

DOC CODE-IMMS

Small Entity Declaration

PATENT
IN THE UNITED STATES PATENT AND TRADEMARK OFFICE

Application Number: 14/000,442

Current Date: January 27, 2023

Filing Date: August 20, 2013

Patent Number: 9,191,648

Issue Date: November 17, 2015

ASSERTION OF SMALL ENTITY STATUS
PURSUANT TO 37 C.F.R. §1.27 (c)(1)

Commissioner for Patents
Mail Stop M Correspondence
P.O. Box 1450
Alexandria, VA 22313-1450

Sir:

This communication hereby asserts that the above-identified patent is entitled to small entity status.

COMPANY or FIRM
NAME AND ADDRESS:

MEDIT CORP.
35, GAEUNSA-GIL, SEONGBUK-GU,
SEOUL 02842, REPUBLIC OF KOREA

Respectfully submitted,

Seok J. Hyun

Signature *SEOK, JI. Hyun*

Printed Name *Terminator of IP Term*

Title

3SHAPE EXHIBIT 1002
3Shape v. Medit

FAX COVER SHEET

TO

COMPANY

FAXNUMBER 15712736500

FROM Data Verification CPA Global

DATE 2023/02/08 10:51:38 GMT

RE US Small Entity Fax Cover Letter (2)

COVER MESSAGE

Confidentiality note: This e-mail may contain confidential information from Clarivate. If you are not the intended recipient, be aware that any disclosure, copying, distribution or use of the contents of this e-mail is strictly prohibited. If you have received this e-mail in error, please delete this e-mail and notify the sender immediately.



UNITED STATES PATENT AND TRADEMARK OFFICE

UNITED STATES DEPARTMENT OF COMMERCE
United States Patent and Trademark Office
Address: COMMISSIONER FOR PATENTS
P.O. Box 1450
Alexandria, Virginia 22313-1450
www.uspto.gov

APPLICATION NO.	ISSUE DATE	PATENT NO.	ATTORNEY DOCKET NO.	CONFIRMATION NO.
14/000,442	11/17/2015	9191648	67245US004	8005

32692 7590 10/28/2015
3M INNOVATIVE PROPERTIES COMPANY
PO BOX 33427
ST. PAUL, MN 55133-3427

ISSUE NOTIFICATION

The projected patent number and issue date are specified above.

Determination of Patent Term Adjustment under 35 U.S.C. 154 (b) (application filed on or after May 29, 2000)

The Patent Term Adjustment is 323 day(s). Any patent to issue from the above-identified application will include an indication of the adjustment on the front page.

If a Continued Prosecution Application (CPA) was filed in the above-identified application, the filing date that determines Patent Term Adjustment is the filing date of the most recent CPA.

Applicant will be able to obtain more detailed information by accessing the Patent Application Information Retrieval (PAIR) WEB site (<http://pair.uspto.gov>).

Any questions regarding the Patent Term Extension or Adjustment determination should be directed to the Office of Patent Legal Administration at (571)-272-7702. Questions relating to issue and publication fee payments should be directed to the Application Assistance Unit (AAU) of the Office of Data Management (ODM) at (571)-272-4200.

APPLICANT(s) (Please see PAIR WEB site <http://pair.uspto.gov> for additional applicants):

Ilya A. Kriveshko, Littleton, MA;
Benjamin Frantzdale, Shrewsbury, MA;

The United States represents the largest, most dynamic marketplace in the world and is an unparalleled location for business investment, innovation, and commercialization of new technologies. The USA offers tremendous resources and advantages for those who invest and manufacture goods here. Through SelectUSA, our nation works to encourage and facilitate business investment. To learn more about why the USA is the best country in the world to develop technology, manufacture products, and grow your business, visit SelectUSA.gov.

PART B - FEE(S) TRANSMITTAL

Complete and send this form, together with applicable fee(s), to: **Mail** Mail Stop ISSUE FEE
Commissioner for Patents
P.O. Box 1450
Alexandria, Virginia 22313-1450
 or **Fax** (571)-273-2885

INSTRUCTIONS: This form should be used for transmitting the ISSUE FEE and PUBLICATION FEE (if required). Blocks 1 through 5 should be completed where appropriate. All further correspondence including the Patent, advance orders and notification of maintenance fees will be mailed to the current correspondence address as indicated unless corrected below or directed otherwise in Block 1, by (a) specifying a new correspondence address; and/or (b) indicating a separate "FEE ADDRESS" for maintenance fee notifications.

CURRENT CORRESPONDENCE ADDRESS (Note: Use Block 1 for any change of address)

32622 7590 09/10/2015
3M INNOVATIVE PROPERTIES COMPANY
PO BOX 33427
ST. PAUL, MN 55133-3427

Note: A certificate of mailing can only be used for domestic mailings of the Fee(s) Transmittal. This certificate cannot be used for any other accompanying papers. Each additional paper, such as an assignment or formal drawing, must have its own certificate of mailing or transmission.

Certificate of Mailing or Transmission

I hereby certify that this Fee(s) Transmittal is being deposited with the United States Postal Service with sufficient postage for first class mail in an envelope addressed to the Mail Stop ISSUE FEE address above, or being facsimile transmitted to the USPTO (571) 273-2885, on the date indicated below.

(Depositor's name)
(Signature)
(Date)

APPLICATION NO.	FILING DATE	FIRST NAMED INVENTOR	ATTORNEY DOCKET NO.	CONFIRMATION NO.
14/000,442	08/20/2013	Ilya A. Kriveshko	672451/S004	8005

TITLE OF INVENTION: HYBRID STITCHING

APPL. TYPE	ENTITY STATUS	ISSUE FEE DUE	PUBLICATION FEE DUE	PREV. PAID ISSUE FEE	TOTAL FEE(S) DUE	DATE DUE
nonprovisional	UNDISCOUNTED	\$960	\$0	\$0	\$960	12/10/2015

EXAMINER	ART UNIT	CLASS-SUBCLASS
WONG, ALLEN C	2488	348-050000

1. Change of correspondence address or indication of "Fee Address" (37 CFR 1.363).

☐ Change of correspondence address (or Change of Correspondence Address form PTO/SB/122) attached.

☐ "Fee Address" indication (or "Fee Address" Indication form PTO/SB/47; Rev 03-02 or more recent) attached. **Use of a Customer Number is required.**

2. For printing on the patent front page, list

(1) The names of up to 3 registered patent attorneys or agents OR, alternatively,

(2) The name of a single firm (having as a member a registered attorney or agent) and the names of up to 2 registered patent attorneys or agents. If no name is listed, no name will be printed.

1. _____
 2. _____
 3. _____

3. ASSIGNEE NAME AND RESIDENCE DATA TO BE PRINTED ON THE PATENT (print or type)

PLEASE NOTE: Unless an assignee is identified below, no assignee data will appear on the patent. If an assignee is identified below, the document has been filed for recordation as set forth in 37 CFR 3.11. Completion of this form is NOT a substitute for filing an assignment.

(A) NAME OF ASSIGNEE

3M INNOVATIVE PROPERTIES COMPANY

(B) RESIDENCE: (CITY and STATE OR COUNTRY)

SAINT PAUL, MINNESOTA

Please check the appropriate assignee category or categories (will not be printed on the patent): ☐ Individual ☒ Corporation or other private group entity ☐ Government

4a. The following fee(s) are submitted:

- ☒ Issue Fee
☐ Publication Fee (No small entity discount permitted)
☐ Advance Order - # of Copies _____

4b. Payment of Fee(s): (Please first reapply any previously paid issue fee shown above)

- ☐ A check is enclosed.
☐ Payment by credit card. Form PTO-2038 is attached. / any additional
☒ The director is hereby authorized to charge ~~any~~ **any** deficiency, or credits any overpayment, to Deposit Account Number **13-3723** ~~on a copy of this form~~

5. Change in Entity Status (from status indicated above)

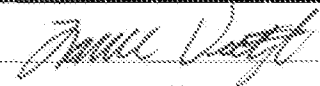
- ☐ Applicant certifying micro entity status. See 37 CFR 1.29
☐ Applicant asserting small entity status. See 37 CFR 1.27
☐ Applicant changing to regular undiscounted fee status.

NOTE: Absent a valid certification of Micro Entity Status (see forms PTO/SB/15A and 15B), issue fee payment in the micro entity amount will not be accepted at the risk of application abandonment.

NOTE: If the application was previously under micro entity status, checking this box will be taken to be a notification of loss of entitlement to micro entity status.

NOTE: Checking this box will be taken to be a notification of loss of entitlement to small or micro entity status, as applicable.

NOTE: This form must be signed in accordance with 37 CFR 1.31 and 1.33. See 37 CFR 1.4 for signature requirements and certifications.

Authorized Signature 

Date 10/14/15

Typed or printed name Lance L. Vietzke

Registration No. 36,708

Electronic Patent Application Fee Transmittal				
Application Number:		14000442		
Filing Date:		20-Aug-2013		
Title of Invention:		HYBRID STITCHING		
First Named Inventor/Applicant Name:		Ilya A. Kriveshko		
Filer:		Lance L. Vietzke/Paula Bick		
Attorney Docket Number:		67245US004		
Filed as Large Entity				
Filing Fees for U.S. National Stage under 35 USC 371				
Description	Fee Code	Quantity	Amount	Sub-Total in USD(\$)
Basic Filing:				
Pages:				
Claims:				
Miscellaneous-Filing:				
Petition:				
Patent-Appeals-and-Interference:				
Post-Allowance-and-Post-Issuance:				
Utility Appl Issue Fee	1501	1	960	960

Description	Fee Code	Quantity	Amount	Sub-Total in USD(\$)
Extension-of-Time:				
Miscellaneous:				
Total in USD (\$)				960

Electronic Acknowledgement Receipt

EFS ID:	23780434
Application Number:	14000442
International Application Number:	
Confirmation Number:	8005
Title of Invention:	HYBRID STITCHING
First Named Inventor/Applicant Name:	Ilya A. Kriveshko
Customer Number:	32692
Filer:	Lance L. Vietzke/Paula Bick
Filer Authorized By:	Lance L. Vietzke
Attorney Docket Number:	67245US004
Receipt Date:	14-OCT-2015
Filing Date:	20-AUG-2013
Time Stamp:	13:59:34
Application Type:	U.S. National Stage under 35 USC 371

Payment information:

Submitted with Payment	yes
Payment Type	Deposit Account
Payment was successfully received in RAM	\$960
RAM confirmation Number	108
Deposit Account	133723
Authorized User	3M COMPANY

The Director of the USPTO is hereby authorized to charge indicated fees and credit any overpayment as follows:

Charge any Additional Fees required under 37 C.F.R. 1.492 (National application filing, search, and examination fees)

Charge any Additional Fees required under 37 C.F.R. Section 1.77 (Patent application and reexamination processing fees)

Charge any Additional Fees required under 37 C.F.R. Section 1.19 (Document supply fees)

Charge any Additional Fees required under 37 C.F.R. Section 1.20 (Post Issuance fees)

Charge any Additional Fees required under 37 C.F.R. Section 1.21 (Miscellaneous fees and charges)

File Listing:

Document Number	Document Description	File Name	File Size(Bytes)/ Message Digest	Multi Part /.zip	Pages (if appl.)
1	Issue Fee Payment (PTO-85B)	Issue_Fee_Trans_67245US004.pdf	412376	no	1
			1d5d58f5fc3687e9a454b1f4d6d2fc9e0ec4351a		

Warnings:

Information:

2	Fee Worksheet (SB06)	fee-info.pdf	30620	no	2
			998ff46c83e2b30f1316391bd3b6b84e5fd196eb		

Warnings:

Information:

Total Files Size (in bytes):	442996
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This Acknowledgement Receipt evidences receipt on the noted date by the USPTO of the indicated documents, characterized by the applicant, and including page counts, where applicable. It serves as evidence of receipt similar to a Post Card, as described in MPEP 503.

New Applications Under 35 U.S.C. 111

If a new application is being filed and the application includes the necessary components for a filing date (see 37 CFR 1.53(b)-(d) and MPEP 506), a Filing Receipt (37 CFR 1.54) will be issued in due course and the date shown on this Acknowledgement Receipt will establish the filing date of the application.

National Stage of an International Application under 35 U.S.C. 371

If a timely submission to enter the national stage of an international application is compliant with the conditions of 35 U.S.C. 371 and other applicable requirements a Form PCT/DO/EO/903 indicating acceptance of the application as a national stage submission under 35 U.S.C. 371 will be issued in addition to the Filing Receipt, in due course.

New International Application Filed with the USPTO as a Receiving Office

If a new international application is being filed and the international application includes the necessary components for an international filing date (see PCT Article 11 and MPEP 1810), a Notification of the International Application Number and of the International Filing Date (Form PCT/RO/105) will be issued in due course, subject to prescriptions concerning national security, and the date shown on this Acknowledgement Receipt will establish the international filing date of the application.



UNITED STATES PATENT AND TRADEMARK OFFICE

UNITED STATES DEPARTMENT OF COMMERCE
United States Patent and Trademark Office
Address: COMMISSIONER FOR PATENTS
P.O. Box 1450
Alexandria, Virginia 22313-1450
www.uspto.gov

NOTICE OF ALLOWANCE AND FEE(S) DUE

32692 7590 09/10/2015
3M INNOVATIVE PROPERTIES COMPANY
PO BOX 33427
ST. PAUL, MN 55133-3427

EXAMINER

WONG, ALLEN C

ART UNIT

PAPER NUMBER

2488

DATE MAILED: 09/10/2015

APPLICATION NO.	FILING DATE	FIRST NAMED INVENTOR	ATTORNEY DOCKET NO.	CONFIRMATION NO.
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14/000,442

08/20/2013

Ilya A. Kriveshko

67245US004

8005

TITLE OF INVENTION: HYBRID STITCHING

APPLN. TYPE	ENTITY STATUS	ISSUE FEE DUE	PUBLICATION FEE DUE	PREV. PAID ISSUE FEE	TOTAL FEE(S) DUE	DATE DUE
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nonprovisional

UNDISCOUNTED

\$960

\$0

\$0

\$960

12/10/2015

THE APPLICATION IDENTIFIED ABOVE HAS BEEN EXAMINED AND IS ALLOWED FOR ISSUANCE AS A PATENT. PROSECUTION ON THE MERITS IS CLOSED. THIS NOTICE OF ALLOWANCE IS NOT A GRANT OF PATENT RIGHTS. THIS APPLICATION IS SUBJECT TO WITHDRAWAL FROM ISSUE AT THE INITIATIVE OF THE OFFICE OR UPON PETITION BY THE APPLICANT. SEE 37 CFR 1.313 AND MPEP 1308.

THE ISSUE FEE AND PUBLICATION FEE (IF REQUIRED) MUST BE PAID WITHIN THREE MONTHS FROM THE MAILING DATE OF THIS NOTICE OR THIS APPLICATION SHALL BE REGARDED AS ABANDONED. THIS STATUTORY PERIOD CANNOT BE EXTENDED. SEE 35 U.S.C. 151. THE ISSUE FEE DUE INDICATED ABOVE DOES NOT REFLECT A CREDIT FOR ANY PREVIOUSLY PAID ISSUE FEE IN THIS APPLICATION. IF AN ISSUE FEE HAS PREVIOUSLY BEEN PAID IN THIS APPLICATION (AS SHOWN ABOVE), THE RETURN OF PART B OF THIS FORM WILL BE CONSIDERED A REQUEST TO REAPPLY THE PREVIOUSLY PAID ISSUE FEE TOWARD THE ISSUE FEE NOW DUE.

HOW TO REPLY TO THIS NOTICE:

I. Review the ENTITY STATUS shown above. If the ENTITY STATUS is shown as SMALL or MICRO, verify whether entitlement to that entity status still applies.

If the ENTITY STATUS is the same as shown above, pay the TOTAL FEE(S) DUE shown above.

If the ENTITY STATUS is changed from that shown above, on PART B - FEE(S) TRANSMITTAL, complete section number 5 titled "Change in Entity Status (from status indicated above)".

For purposes of this notice, small entity fees are 1/2 the amount of undiscounted fees, and micro entity fees are 1/2 the amount of small entity fees.

II. PART B - FEE(S) TRANSMITTAL, or its equivalent, must be completed and returned to the United States Patent and Trademark Office (USPTO) with your ISSUE FEE and PUBLICATION FEE (if required). If you are charging the fee(s) to your deposit account, section "4b" of Part B - Fee(s) Transmittal should be completed and an extra copy of the form should be submitted. If an equivalent of Part B is filed, a request to reapply a previously paid issue fee must be clearly made, and delays in processing may occur due to the difficulty in recognizing the paper as an equivalent of Part B.

III. All communications regarding this application must give the application number. Please direct all communications prior to issuance to Mail Stop ISSUE FEE unless advised to the contrary.

IMPORTANT REMINDER: Utility patents issuing on applications filed on or after Dec. 12, 1980 may require payment of maintenance fees. It is patentee's responsibility to ensure timely payment of maintenance fees when due.

PART B - FEE(S) TRANSMITTAL

Complete and send this form, together with applicable fee(s), to: **Mail** **Mail Stop ISSUE FEE**
Commissioner for Patents
P.O. Box 1450
Alexandria, Virginia 22313-1450
or Fax (571)-273-2885

INSTRUCTIONS: This form should be used for transmitting the ISSUE FEE and PUBLICATION FEE (if required). Blocks 1 through 5 should be completed where appropriate. All further correspondence including the Patent, advance orders and notification of maintenance fees will be mailed to the current correspondence address as indicated unless corrected below or directed otherwise in Block 1, by (a) specifying a new correspondence address; and/or (b) indicating a separate "FEE ADDRESS" for maintenance fee notifications.

CURRENT CORRESPONDENCE ADDRESS (Note: Use Block 1 for any change of address)

Note: A certificate of mailing can only be used for domestic mailings of the Fee(s) Transmittal. This certificate cannot be used for any other accompanying papers. Each additional paper, such as an assignment or formal drawing, must have its own certificate of mailing or transmission.

32692 7590 09/10/2015
3M INNOVATIVE PROPERTIES COMPANY
PO BOX 33427
ST. PAUL, MN 55133-3427

Certificate of Mailing or Transmission

I hereby certify that this Fee(s) Transmittal is being deposited with the United States Postal Service with sufficient postage for first class mail in an envelope addressed to the Mail Stop ISSUE FEE address above, or being facsimile transmitted to the USPTO (571) 273-2885, on the date indicated below.

(Depositor's name)
(Signature)
(Date)

APPLICATION NO.	FILING DATE	FIRST NAMED INVENTOR	ATTORNEY DOCKET NO.	CONFIRMATION NO.
14/000,442	08/20/2013	Ilya A. Kriveshko	67245US004	8005

TITLE OF INVENTION: HYBRID STITCHING

APPLN. TYPE	ENTITY STATUS	ISSUE FEE DUE	PUBLICATION FEE DUE	PREV. PAID ISSUE FEE	TOTAL FEE(S) DUE	DATE DUE
nonprovisional	UNDISCOUNTED	\$960	\$0	\$0	\$960	12/10/2015

EXAMINER	ART UNIT	CLASS-SUBCLASS
WONG, ALLEN C	2488	348-050000

1. Change of correspondence address or indication of "Fee Address" (37 CFR 1.363).

- ☐ Change of correspondence address (or Change of Correspondence Address form PTO/SB/122) attached.
- ☐ "Fee Address" indication (or "Fee Address" Indication form PTO/SB/47; Rev 03-02 or more recent) attached. **Use of a Customer Number is required.**

2. For printing on the patent front page, list

- (1) The names of up to 3 registered patent attorneys or agents OR, alternatively, 1 _____
- (2) The name of a single firm (having as a member a registered attorney or agent) and the names of up to 2 registered patent attorneys or agents. If no name is listed, no name will be printed. 2 _____
- 3 _____

3. ASSIGNEE NAME AND RESIDENCE DATA TO BE PRINTED ON THE PATENT (print or type)

PLEASE NOTE: Unless an assignee is identified below, no assignee data will appear on the patent. If an assignee is identified below, the document has been filed for recordation as set forth in 37 CFR 3.11. Completion of this form is NOT a substitute for filing an assignment.

(A) NAME OF ASSIGNEE

(B) RESIDENCE: (CITY and STATE OR COUNTRY)

Please check the appropriate assignee category or categories (will not be printed on the patent): ☐ Individual ☐ Corporation or other private group entity ☐ Government

4a. The following fee(s) are submitted:

- ☐ Issue Fee
- ☐ Publication Fee (No small entity discount permitted)
- ☐ Advance Order - # of Copies _____

4b. Payment of Fee(s): (Please first reapply any previously paid issue fee shown above)

- ☐ A check is enclosed.
- ☐ Payment by credit card. Form PTO-2038 is attached.
- ☐ The director is hereby authorized to charge the required fee(s), any deficiency, or credits any overpayment, to Deposit Account Number _____ (enclose an extra copy of this form).

5. Change in Entity Status (from status indicated above)

- ☐ Applicant certifying micro entity status. See 37 CFR 1.29
- ☐ Applicant asserting small entity status. See 37 CFR 1.27
- ☐ Applicant changing to regular undiscounted fee status.

NOTE: Absent a valid certification of Micro Entity Status (see forms PTO/SB/15A and 15B), issue fee payment in the micro entity amount will not be accepted at the risk of application abandonment.

NOTE: If the application was previously under micro entity status, checking this box will be taken to be a notification of loss of entitlement to micro entity status.

NOTE: Checking this box will be taken to be a notification of loss of entitlement to small or micro entity status, as applicable.

NOTE: This form must be signed in accordance with 37 CFR 1.31 and 1.33. See 37 CFR 1.4 for signature requirements and certifications.

Authorized Signature _____

Date _____

Typed or printed name _____

Registration No. _____



UNITED STATES PATENT AND TRADEMARK OFFICE

UNITED STATES DEPARTMENT OF COMMERCE
United States Patent and Trademark Office
Address: COMMISSIONER FOR PATENTS
P.O. Box 1450
Alexandria, Virginia 22313-1450
www.uspto.gov

APPLICATION NO.	FILING DATE	FIRST NAMED INVENTOR	ATTORNEY DOCKET NO.	CONFIRMATION NO.
14/000,442	08/20/2013	Ilya A. Kriveshko	67245US004	8005

32692	7590	09/10/2015
3M INNOVATIVE PROPERTIES COMPANY		
PO BOX 33427		
ST. PAUL, MN 55133-3427		

EXAMINER	
WONG, ALLEN C	

ART UNIT	PAPER NUMBER
2488	

DATE MAILED: 09/10/2015

Determination of Patent Term Adjustment under 35 U.S.C. 154 (b) (Applications filed on or after May 29, 2000)

The Office has discontinued providing a Patent Term Adjustment (PTA) calculation with the Notice of Allowance.

Section 1(h)(2) of the AIA Technical Corrections Act amended 35 U.S.C. 154(b)(3)(B)(i) to eliminate the requirement that the Office provide a patent term adjustment determination with the notice of allowance. See Revisions to Patent Term Adjustment, 78 Fed. Reg. 19416, 19417 (Apr. 1, 2013). Therefore, the Office is no longer providing an initial patent term adjustment determination with the notice of allowance. The Office will continue to provide a patent term adjustment determination with the Issue Notification Letter that is mailed to applicant approximately three weeks prior to the issue date of the patent, and will include the patent term adjustment on the patent. Any request for reconsideration of the patent term adjustment determination (or reinstatement of patent term adjustment) should follow the process outlined in 37 CFR 1.705.

Any questions regarding the Patent Term Extension or Adjustment determination should be directed to the Office of Patent Legal Administration at (571)-272-7702. Questions relating to issue and publication fee payments should be directed to the Customer Service Center of the Office of Patent Publication at 1-(888)-786-0101 or (571)-272-4200.

OMB Clearance and PRA Burden Statement for PTOL-85 Part B

The Paperwork Reduction Act (PRA) of 1995 requires Federal agencies to obtain Office of Management and Budget approval before requesting most types of information from the public. When OMB approves an agency request to collect information from the public, OMB (i) provides a valid OMB Control Number and expiration date for the agency to display on the instrument that will be used to collect the information and (ii) requires the agency to inform the public about the OMB Control Number's legal significance in accordance with 5 CFR 1320.5(b).

The information collected by PTOL-85 Part B is required by 37 CFR 1.311. The information is required to obtain or retain a benefit by the public which is to file (and by the USPTO to process) an application. Confidentiality is governed by 35 U.S.C. 122 and 37 CFR 1.14. This collection is estimated to take 12 minutes to complete, including gathering, preparing, and submitting the completed application form to the USPTO. Time will vary depending upon the individual case. Any comments on the amount of time you require to complete this form and/or suggestions for reducing this burden, should be sent to the Chief Information Officer, U.S. Patent and Trademark Office, U.S. Department of Commerce, P.O. Box 1450, Alexandria, Virginia 22313-1450. DO NOT SEND FEES OR COMPLETED FORMS TO THIS ADDRESS. SEND TO: Commissioner for Patents, P.O. Box 1450, Alexandria, Virginia 22313-1450. Under the Paperwork Reduction Act of 1995, no persons are required to respond to a collection of information unless it displays a valid OMB control number.

Privacy Act Statement

The Privacy Act of 1974 (P.L. 93-579) requires that you be given certain information in connection with your submission of the attached form related to a patent application or patent. Accordingly, pursuant to the requirements of the Act, please be advised that: (1) the general authority for the collection of this information is 35 U.S.C. 2(b)(2); (2) furnishing of the information solicited is voluntary; and (3) the principal purpose for which the information is used by the U.S. Patent and Trademark Office is to process and/or examine your submission related to a patent application or patent. If you do not furnish the requested information, the U.S. Patent and Trademark Office may not be able to process and/or examine your submission, which may result in termination of proceedings or abandonment of the application or expiration of the patent.

The information provided by you in this form will be subject to the following routine uses:

1. The information on this form will be treated confidentially to the extent allowed under the Freedom of Information Act (5 U.S.C. 552) and the Privacy Act (5 U.S.C. 552a). Records from this system of records may be disclosed to the Department of Justice to determine whether disclosure of these records is required by the Freedom of Information Act.
2. A record from this system of records may be disclosed, as a routine use, in the course of presenting evidence to a court, magistrate, or administrative tribunal, including disclosures to opposing counsel in the course of settlement negotiations.
3. A record in this system of records may be disclosed, as a routine use, to a Member of Congress submitting a request involving an individual, to whom the record pertains, when the individual has requested assistance from the Member with respect to the subject matter of the record.
4. A record in this system of records may be disclosed, as a routine use, to a contractor of the Agency having need for the information in order to perform a contract. Recipients of information shall be required to comply with the requirements of the Privacy Act of 1974, as amended, pursuant to 5 U.S.C. 552a(m).
5. A record related to an International Application filed under the Patent Cooperation Treaty in this system of records may be disclosed, as a routine use, to the International Bureau of the World Intellectual Property Organization, pursuant to the Patent Cooperation Treaty.
6. A record in this system of records may be disclosed, as a routine use, to another federal agency for purposes of National Security review (35 U.S.C. 181) and for review pursuant to the Atomic Energy Act (42 U.S.C. 218(c)).
7. A record from this system of records may be disclosed, as a routine use, to the Administrator, General Services, or his/her designee, during an inspection of records conducted by GSA as part of that agency's responsibility to recommend improvements in records management practices and programs, under authority of 44 U.S.C. 2904 and 2906. Such disclosure shall be made in accordance with the GSA regulations governing inspection of records for this purpose, and any other relevant (i.e., GSA or Commerce) directive. Such disclosure shall not be used to make determinations about individuals.
8. A record from this system of records may be disclosed, as a routine use, to the public after either publication of the application pursuant to 35 U.S.C. 122(b) or issuance of a patent pursuant to 35 U.S.C. 151. Further, a record may be disclosed, subject to the limitations of 37 CFR 1.14, as a routine use, to the public if the record was filed in an application which became abandoned or in which the proceedings were terminated and which application is referenced by either a published application, an application open to public inspection or an issued patent.
9. A record from this system of records may be disclosed, as a routine use, to a Federal, State, or local law enforcement agency, if the USPTO becomes aware of a violation or potential violation of law or regulation.

Notice of Allowability	Application No. 14/000,442	Applicant(s) KRIVESHKO ET AL.	
	Examiner ALLEN WONG	Art Unit 2488	AIA (First Inventor to File) Status No

-- The MAILING DATE of this communication appears on the cover sheet with the correspondence address--

All claims being allowable, PROSECUTION ON THE MERITS IS (OR REMAINS) CLOSED in this application. If not included herewith (or previously mailed), a Notice of Allowance (PTOL-85) or other appropriate communication will be mailed in due course. **THIS NOTICE OF ALLOWABILITY IS NOT A GRANT OF PATENT RIGHTS.** This application is subject to withdrawal from issue at the initiative of the Office or upon petition by the applicant. See 37 CFR 1.313 and MPEP 1308.

1. ☐ This communication is responsive to _____.
☐ A declaration(s)/affidavit(s) under **37 CFR 1.130(b)** was/were filed on _____.

2. ☐ An election was made by the applicant in response to a restriction requirement set forth during the interview on _____; the restriction requirement and election have been incorporated into this action.

3. ☒ The allowed claim(s) is/are 1-24. As a result of the allowed claim(s), you may be eligible to benefit from the **Patent Prosecution Highway** program at a participating intellectual property office for the corresponding application. For more information, please see http://www.uspto.gov/patents/init_events/pph/index.jsp or send an inquiry to PPHfeedback@uspto.gov.

4. ☐ Acknowledgment is made of a claim for foreign priority under 35 U.S.C. § 119(a)-(d) or (f).

Certified copies:

a) ☐ All b) ☐ Some *c) ☐ None of the:

1. ☐ Certified copies of the priority documents have been received.
2. ☐ Certified copies of the priority documents have been received in Application No. _____.
3. ☐ Copies of the certified copies of the priority documents have been received in this national stage application from the International Bureau (PCT Rule 17.2(a)).

* Certified copies not received: _____.

Applicant has THREE MONTHS FROM THE "MAILING DATE" of this communication to file a reply complying with the requirements noted below. Failure to timely comply will result in ABANDONMENT of this application.
THIS THREE-MONTH PERIOD IS NOT EXTENDABLE.

5. ☐ CORRECTED DRAWINGS (as "replacement sheets") must be submitted.
☐ including changes required by the attached Examiner's Amendment / Comment or in the Office action of Paper No./Mail Date _____.

Identifying indicia such as the application number (see 37 CFR 1.84(c)) should be written on the drawings in the front (not the back) of each sheet. Replacement sheet(s) should be labeled as such in the header according to 37 CFR 1.121(d).

6. ☐ DEPOSIT OF and/or INFORMATION about the deposit of BIOLOGICAL MATERIAL must be submitted. Note the attached Examiner's comment regarding REQUIREMENT FOR THE DEPOSIT OF BIOLOGICAL MATERIAL.

Attachment(s)

1. ☒ Notice of References Cited (PTO-892)	5. ☐ Examiner's Amendment/Comment
2. ☒ Information Disclosure Statements (PTO/SB/08), Paper No./Mail Date _____	6. ☒ Examiner's Statement of Reasons for Allowance
3. ☐ Examiner's Comment Regarding Requirement for Deposit of Biological Material	7. ☐ Other _____
4. ☐ Interview Summary (PTO-413), Paper No./Mail Date _____	

/ALLEN WONG/ Primary Examiner, Art Unit 2488	
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DETAILED ACTION

The present application is being examined under the pre-AIA first to invent provisions.

Information Disclosure Statement

The information disclosure statement (IDS) submitted on 3/14/14 and 4/15/15 is in compliance with the provisions of 37 CFR 1.97. Accordingly, the information disclosure statement has been considered by the examiner.

Allowable Subject Matter

Claims 1-24 are allowed.

The following is an examiner's statement of reasons for allowance: the instant invention pertains to generation of three-dimensional surface imaging.

Hausler (US 2010/0303341) discloses a method comprising: obtaining a first three-dimensional model including a first plurality of sets of three-dimensional points spatially related to one another by a first camera path (paragraph 74 and 95, claim 2, note first and second set of 3D data is obtained); obtaining a second three-dimensional model including a second plurality of sets of three-dimensional points spatially related to one another by a second camera path (paragraph 74 and 95, claim 2, note first and second set of 3D data is obtained); registering one of the first plurality of sets of three-dimensional points to one of the second plurality of sets of three-dimensional points to place the first three-dimensional model and the second three-dimensional model in a shared coordinate system (paragraph 96).

Lopes (US 2010/0194863) discloses a method comprising: obtaining a first three-dimensional model including a first plurality of sets of three-dimensional points spatially related to one another by a first camera path (paragraph 104, note virtual 3D modeling is obtained of the scene, wherein a camera viewpoint can be obtained to obtain a first set of 3D data); obtaining a second three-dimensional model including a second plurality of sets of three-dimensional points spatially related to one another by a second camera path (paragraph 104, note virtual 3D modeling is obtained, and multiple camera viewpoints are obtained in including first and second sets of 3D data); registering one of the first plurality of sets of three-dimensional points to one of the second plurality of sets of three-dimensional points to

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place the first three-dimensional model and the second three-dimensional model in a shared coordinate system (paragraph 5).

The prior art, either singularly or in combination, does not disclose the limitations “to create a virtual stitch graph that spatially relates the first plurality of sets and the second plurality of sets, thereby providing a combined model that includes the first plurality of sets and the second plurality of sets all spatially related by the virtual stitch graph”, “to refine the combined model with a global motion optimization of the virtual stitch graph” and “a display configured to render the combined model”. Thus, the prior art does not disclose the aforementioned limitations used in combination with all of the other limitations of claim 23. Claims 1, 12 and 24 are patentable for at least similar reasons as claim 23.

Any comments considered necessary by applicant must be submitted no later than the payment of the issue fee and, to avoid processing delays, should preferably accompany the issue fee. Such submissions should be clearly labeled “Comments on Statement of Reasons for Allowance.”

Contact Information

Any inquiry concerning this communication or earlier communications from the examiner should be directed to ALLEN WONG whose telephone number is (571)272-7341. The examiner can normally be reached on Flex Monday to Thursday 8am-6pm.

If attempts to reach the examiner by telephone are unsuccessful, the examiner's supervisor, SATH PERUNGAVOOR can be reached on (571) 272-7455. The fax phone number for the organization where this application or proceeding is assigned is 571-273-8300.

Information regarding the status of an application may be obtained from the Patent Application Information Retrieval (PAIR) system. Status information for published applications may be obtained from either Private PAIR or Public PAIR. Status information for unpublished applications is available through Private PAIR only. For more information about the PAIR system, see <http://pair-direct.uspto.gov>. Should you have questions on access to the Private PAIR system, contact the Electronic Business Center (EBC) at 866-217-9197 (toll-free). If you would like assistance from a USPTO Customer Service Representative

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or access to the automated information system, call 800-786-9199 (IN USA OR CANADA) or 571-272-1000.

/ALLEN WONG/

Primary Examiner, Art Unit 2488

Notice of References Cited	Application/Control No. 14/000,442		Applicant(s)/Patent Under Reexamination KRIVESHKO ET AL.	
	Examiner ALLEN WONG		Art Unit 2488	Page 1 of 1

U.S. PATENT DOCUMENTS

*		Document Number Country Code-Number-Kind Code	Date MM-YYYY	Name	CPC Classification	US Classification
*	A	US-2010/0303341 A1	12-2010	Hausler; Gerd	A61B5/0062	382/154
*	B	US-2010/0194863 A1	08-2010	Lopes; Goncalo Cardoso	G06T7/0061	348/50
	C	US-				
	D	US-				
	E	US-				
	F	US-				
	G	US-				
	H	US-				
	I	US-				
	J	US-				
	K	US-				
	L	US-				
	M	US-				

FOREIGN PATENT DOCUMENTS

*		Document Number Country Code-Number-Kind Code	Date MM-YYYY	Country	Name	CPC Classification
	N					
	O					
	P					
	Q					
	R					
	S					
	T					

NON-PATENT DOCUMENTS

*		Include as applicable: Author, Title Date, Publisher, Edition or Volume, Pertinent Pages)
	U	
	V	
	W	
	X	

*A copy of this reference is not being furnished with this Office action. (See MPEP § 707.05(a).)
Dates in MM-YYYY format are publication dates. Classifications may be US or foreign.

<i>Index of Claims</i> 	Application/Control No. 14000442	Applicant(s)/Patent Under Reexamination KRIVESHKO ET AL.
	Examiner ALLEN WONG	Art Unit 2488

✓	Rejected	-	Cancelled	N	Non-Elected	A	Appeal
=	Allowed	÷	Restricted	I	Interference	O	Objected

☐ Claims renumbered in the same order as presented by applicant			☐ CPA			☐ T.D.			☐ R.1.47		
CLAIM		DATE									
Final	Original	09/02/2015									
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3	3	=									
4	4	=									
5	5	=									
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22	22	=									
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24	24	=									

EAST Search History

EAST Search History (Prior Art)

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L1	2	"20100303341".pn.	US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO; DERWENT; IBM_TDB	OR	OFF	2015/09/01 18:48
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L4	561	register\$4 with (3D or three-dimension\$3 or 3-D) with (coordinate\$1 or point\$1) with model	US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO; DERWENT; IBM_TDB	OR	OFF	2015/09/01 19:05
L5	15	L4 and L3	US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO; DERWENT; IBM_TDB	OR	OFF	2015/09/01 19:05
L6	2744	A61B1/24.CPC.	US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO; DERWENT; IBM_TDB	OR	OFF	2015/09/01 19:05
L7	6376	(3D or three-dimension\$3 or 3-D) near\$5 model\$4 with camera	US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO; DERWENT; IBM_TDB	OR	OFF	2015/09/01 19:05
L8	8	L7 and L6	US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO; DERWENT; IBM_TDB	OR	OFF	2015/09/01 19:05
L9	5328	A61B1/00009.CPC.	US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO; DERWENT; IBM_TDB	OR	OFF	2015/09/01 19:06
L10	33	L7 and L9	US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO; DERWENT; IBM_TDB	OR	OFF	2015/09/01 19:06
L11	521	348/50.OCLS.	US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO; DERWENT; IBM_TDB	OR	OFF	2015/09/01 19:06
L12	56	L7 and L11	US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO; DERWENT; IBM_TDB	OR	OFF	2015/09/01 19:06
S1	521	348/50.OCLS.	US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO; DERWENT; IBM_TDB	OR	OFF	2015/09/01 12:43

S2	1737	H04N13/0203.CPC.	US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO; DERWENT; IBM_TDB	OR	OFF	2015/09/01 12:44
S3	2559	G06T7/0024.CPC.	US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO; DERWENT; IBM_TDB	OR	OFF	2015/09/01 12:44
S4	8865	G06T19/00.CPC.	US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO; DERWENT; IBM_TDB	OR	OFF	2015/09/01 12:45
S5	570	G06T2207/20072.CPC.	US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO; DERWENT; IBM_TDB	OR	OFF	2015/09/01 12:45
S6	863	G06T2207/30036.CPC.	US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO; DERWENT; IBM_TDB	OR	OFF	2015/09/01 12:45
S7	3635	G06T2207/10028.CPC.	US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO; DERWENT; IBM_TDB	OR	OFF	2015/09/01 12:45
S8	5328	A61B1/00009.CPC.	US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO; DERWENT; IBM_TDB	OR	OFF	2015/09/01 12:46
S9	2098	A61B1/00193.CPC.	US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO; DERWENT; IBM_TDB	OR	OFF	2015/09/01 12:46
S10	1452	A61B1/00039.CPC.	US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO; DERWENT; IBM_TDB	OR	OFF	2015/09/01 12:46
S11	2744	A61B1/24.CPC.	US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO; DERWENT; IBM_TDB	OR	OFF	2015/09/01 12:46
S12	2788	A61B1/0005.CPC.	US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO; DERWENT; IBM_TDB	OR	OFF	2015/09/01 12:46
S13	78	(3D or three-dimension\$3 or 3-D) near5 model\$4 with camera near4 (path or trajector\$3)	US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO; DERWENT; IBM_TDB	OR	OFF	2015/09/01 12:49
S14	6376	(3D or three-dimension\$3 or 3-D) near5 model\$4 with camera	US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO; DERWENT; IBM_TDB	OR	OFF	2015/09/01 12:49
S15	18839	(3D or three-dimension\$3 or 3-D) near5 model\$4 with (coordinate\$1 or point\$1)	US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO; DERWENT; IBM_TDB	OR	OFF	2015/09/01 12:50
S16	6	virtual adj stitch adj graph\$1	US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO; DERWENT;	OR	OFF	2015/09/01 12:50

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S17	12	stitch adj graph\$1	US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO; DERWENT; IBM_TDB	OR	OFF	2015/09/01 12:50
S18	0	hybrid adj stitch with (3D or three-dimension\$3 or 3-D)	US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO; DERWENT; IBM_TDB	OR	OFF	2015/09/01 12:51
S19	0	hybrid adj stitch same (3D or three-dimension\$3 or 3-D)	US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO; DERWENT; IBM_TDB	OR	OFF	2015/09/01 12:51
S20	0	hybrid near4 stitch same (3D or three-dimension\$3 or 3-D)	US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO; DERWENT; IBM_TDB	OR	OFF	2015/09/01 12:51
S21	4	hybrid near4 stitch and (3D or three-dimension\$3 or 3-D)	US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO; DERWENT; IBM_TDB	OR	OFF	2015/09/01 12:52
S22	9	S13 and S1	US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO; DERWENT; IBM_TDB	OR	OFF	2015/09/01 12:52
S23	1	S13 and S2	US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO; DERWENT; IBM_TDB	OR	OFF	2015/09/01 12:52
S24	1	S13 and S3	US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO; DERWENT; IBM_TDB	OR	OFF	2015/09/01 12:52
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S28	3	S13 and S7	US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO; DERWENT; IBM_TDB	OR	OFF	2015/09/01 12:52
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S33	4	S13 and S12	US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO; DERWENT; IBM_TDB	OR	OFF	2015/09/01 12:53
S35	38	S14 and S2	US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO; DERWENT; IBM_TDB	OR	OFF	2015/09/01 12:53
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S42	19	S14 and S9	US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO; DERWENT; IBM_TDB	OR	OFF	2015/09/01 12:53
S43	18	S14 and S10	US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO; DERWENT; IBM_TDB	OR	OFF	2015/09/01 12:53
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S56	6	S17 and S11	US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO; DERWENT; IBM_TDB	OR	OFF	2015/09/01 12:54
S57	6	S17 and S12	US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO; DERWENT; IBM_TDB	OR	OFF	2015/09/01 12:54
S59	561	register\$4 with (3D or three- dimension\$3 or 3-D) with (coordinate\$1 or point\$1) with model	US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO; DERWENT; IBM_TDB	OR	OFF	2015/09/01 13:01
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S61	1	S59 and S2	US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO; DERWENT; IBM_TDB	OR	OFF	2015/09/01 13:01
S62	26	S59 and S3	US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO; DERWENT; IBM_TDB	OR	OFF	2015/09/01 13:01
S63	17	S59 and S4	US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO; DERWENT; IBM_TDB	OR	OFF	2015/09/01 13:02
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S67	2	S59 and S8	US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO; DERWENT; IBM_TDB	OR	OFF	2015/09/01 13:02
S68	1	S59 and S9	US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO; DERWENT; IBM_TDB	OR	OFF	2015/09/01 13:02
S69	1	S59 and S10	US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO; DERWENT; IBM_TDB	OR	OFF	2015/09/01 13:02
S70	1	S59 and S11	US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO; DERWENT; IBM_TDB	OR	OFF	2015/09/01 13:02
S71	1	S59 and S12	US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO; DERWENT; IBM_TDB	OR	OFF	2015/09/01 13:02

EAST Search History (Interference)

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9/ 1/ 2015 7:23:53 PM
C:\ Users\ awong1\ Documents\ EAST\ Workspaces\ 14000442_090115.wsp

EAST Search History

EAST Search History (Prior Art)

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L1	13	set\$1 near2 (three-dimension\$3 or 3-D or 3D) with point\$1 with graph\$1	US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO; DERWENT; IBM_TDB	OR	OFF	2015/09/02 13:04
L2	1	set\$1 near2 (three-dimension\$3 or 3-D or 3D) with point\$1 with stitch near2 graph\$1	US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO; DERWENT; IBM_TDB	OR	OFF	2015/09/02 13:05

EAST Search History (Interference)

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9/ 2/ 2015 1:06:40 PM
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INFORMATION DISCLOSURE STATEMENT BY APPLICANT (Use as many sheets as necessary) Page 1 of 2	Application Number 14/000442
	Filing Date 17-FEB-2012
	First Named Inventor Kriveshko, Ilya A
	Confirmation Number 8005
	Attorney Case Number 67245US004

United States Patent Documents					
Exam. Init.*	Cite No.	Document Number	Publication Date MM-DD-YYYY	Name of Patentee or Applicant of Cited Document	Pages, Columns, Lines, Where Relevant Passages or Relevant Figures Appear
		Doc. Number-(Kind Code if Known)			
	A1	2003-0151604	08-14-2003	Kaufman	
	A2	2004-0155975	08-12-2004	Hart	
	A3	2006-0139470	06-29-2006	McGowan	
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	A5	2007-0171220	07-26-2007	Kriveshko	
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INFORMATION DISCLOSURE STATEMENT BY APPLICANT

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Page 2 of 2

Application Number

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4214000442 - GAU: 2488

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17-FEB-2012

First Named Inventor

Kriveshko, Ilya A

Confirmation Number

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BIB DATA SHEET

CONFIRMATION NO. 8005

SERIAL NUMBER 14/000,442	FILING or 371(c) DATE 08/20/2013 RULE	CLASS 348	GROUP ART UNIT 2488	ATTORNEY DOCKET NO. 67245US004		
APPLICANTS INVENTORS Ilya A. Kriveshko, Littleton, MA; Benjamin Frantzdale, Shrewsbury, MA; ** CONTINUING DATA ***** This application is a 371 of PCT/US12/25554 02/17/2012 which claims benefit of 61/445,464 02/22/2011 ** FOREIGN APPLICATIONS ***** ** IF REQUIRED, FOREIGN FILING LICENSE GRANTED ** 08/29/2013						
Foreign Priority claimed ☐ Yes ☒ No 35 USC 119(a-d) conditions met ☐ Yes ☒ No Verified and Acknowledged <u>/ALLEN C WONG/</u> Examiner's Signature		☐ Met after Allowance Initials	STATE OR COUNTRY MA	SHEETS DRAWINGS 9	TOTAL CLAIMS 24	INDEPENDENT CLAIMS 4
ADDRESS 3M INNOVATIVE PROPERTIES COMPANY PO BOX 33427 ST. PAUL, MN 55133-3427 UNITED STATES						
TITLE HYBRID STITCHING						
FILING FEE RECEIVED 2220	FEES: Authority has been given in Paper No. _____ to charge/credit DEPOSIT ACCOUNT No. _____ for following:			☐ All Fees ☐ 1.16 Fees (Filing) ☐ 1.17 Fees (Processing Ext. of time) ☐ 1.18 Fees (Issue) ☐ Other _____ ☐ Credit		

Search Notes 	Application/Control No. 14000442	Applicant(s)/Patent Under Reexamination KRIVESHKO ET AL.
	Examiner ALLEN WONG	Art Unit 2488

CPC- SEARCHED		
Symbol	Date	Examiner
G06T 2207/30036, A61B 1/24, A61B 1/00009, H04N 13/0203, G06T 7/0024, G06T 19/00, G06T 2207/20072, G06T 2207/30036, G06T 2207/10028, A61B 1/00193, A61B 1/00039, A61B 1/24, A61B 1/0005	9/1/15	AW

CPC COMBINATION SETS - SEARCHED		
Symbol	Date	Examiner

US CLASSIFICATION SEARCHED			
Class	Subclass	Date	Examiner
348	50	9/1/15	AW
		9/1/15	AW

SEARCH NOTES		
Search Notes	Date	Examiner

INTERFERENCE SEARCH			
US Class/ CPC Symbol	US Subclass / CPC Group	Date	Examiner
348	50	9/2/15	AW
G06T	2207/30036, 7/0024, 19/00, 2207/20072, 2207/30036,	9/2/15	AW
H04N	13/0203	9/2/15	AW
A61B	1/24, 1/00009, 1/00193, 1/00039, 1/24, 1/0005	9/2/15	AW

	/ALLEN WONG/ Primary Examiner.Art Unit 2488
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Issue Classification 	Application/Control No. 14000442	Applicant(s)/Patent Under Reexamination KRIVESHKO ET AL.	
	Examiner ALLEN WONG	Art Unit 2488	

CPC						
Symbol					Type	Version
H04N		13	/	0203	F	2013-01-01
A61B		1	/	00009	I	2013-01-01
A61B		1	/	00039	I	2013-01-01
A61B		1	/	0005	I	2013-01-01
A61B		1	/	00193	I	2013-01-01
A61B		1	/	24	I	2013-01-01
G06T		19	/	00	I	2013-01-01
G06T		7	/	0024	I	2013-01-01
G06T		2207	/	10028	A	2013-01-01
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G06T		2207	/	30036	A	2013-01-01
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CPC Combination Sets				
Symbol	Type	Set	Ranking	Version

NONE		Total Claims Allowed: 24	
(Assistant Examiner)	(Date)		
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(Primary Examiner)	(Date)	1	1

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	Examiner ALLEN WONG	Art Unit 2488

US ORIGINAL CLASSIFICATION						INTERNATIONAL CLASSIFICATION												
CLASS		SUBCLASS				CLAIMED					NON-CLAIMED							
348		50				H	0	4	N	13 / 02 (2006.01.01)								
CROSS REFERENCE(S)																		
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(Primary Examiner)	(Date)	1	1

Issue Classification 	Application/Control No. 14000442	Applicant(s)/Patent Under Reexamination KRIVESHKO ET AL.
	Examiner ALLEN WONG	Art Unit 2488

☐ Claims renumbered in the same order as presented by applicant ☐ CPA ☐ T.D. ☐ R.1.47															
Final	Original	Final	Original	Final	Original	Final	Original	Final	Original	Final	Original	Final	Original	Final	Original
1	1	17	17												
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Page 1 of 1

Application Number

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First Named Inventor

Ilya Kriveshko

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United States Patent Documents

Exam. Init.*	Cite No.	Document Number	Publication Date MM-DD-YYYY	Name of Patentee or Applicant of Cited Document	Pages, Columns, Lines, Where Relevant Passages or Relevant Figures Appear
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	A12				

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		Ctry. Code	Number-Kind Code (If known)				
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	C1		
	C2		
	C3		

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ALL REFERENCES CONSIDERED EXCEPT WHERE LINED THROUGH. /AW/

Substitute for form 1449A/PTO (modified) INFORMATION DISCLOSURE STATEMENT BY APPLICANT (Use as many sheets as necessary) Page 1 of 1	Application Number	14/000442
	Filing Date	17-FEB-2012
	First Named Inventor	Ilya Kriveshko
	Confirmation Number	8005
	Attorney Case Number	67245US004

United States Patent Documents					
Exam. Init.*	Cite No.	Document Number	Publication Date MM-DD-YYYY	Name of Patentee or Applicant of Cited Document	Pages, Columns, Lines, Where Relevant Passages or Relevant Figures Appear
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	A2				
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Foreign Patent Documents							
Exam. Init.*	Cite No.	Foreign Patent Document		Publication Date MM-DD-YYYY	Name of Patentee or Applicant of Cited Document	Pages, Columns, Lines, Where Relevant Passages or Relevant Figures Appear	Translation (Check if yes)
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	B1	CN	101799293	08-11-2010			Abst.
	B2						
	B3						
	B4						
	B5						
	B6						

OTHER DOCUMENTS			
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**Espacenet****Bibliographic data: CN101799293 (A) — 2010-08-11**

Satellite-borne three-non-colinear TDI CCD (Time Delayed and Integration Charge Coupled Device) image splicing method based on segmented affine transformation

Inventor(s): FEN HU; SHUYING JIN; MI WANG ± (HU FEN, ; JIN SHUYING, ; WANG MI)

Applicant(s): UNIV WUHAN ± (WUHAN UNIVERSITY)

Classification: - international: **G01C11/04**
- cooperative:

Application number: CN20101119968 20100305

Priority number(s): CN20101119968 20100305

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Abstract of CN101799293 (A)

The invention relates to a satellite-borne three-non-colinear TDI CCD image splicing method based on segmented affine transformation. The spliced virtual scanning scene is regarded as a scene acquired by three virtual CCD linear arrays connected end to end on a focal plane, wherein virtual CCD linear arrays at both sides are consistent with the true TDI CCD, the virtual CCD linear array in the middle fills in a gap between the virtual CCD linear arrays at both sides, the image face transformation models of TDI CCD imaging data and virtual CCD imaging data are established through following the principle of references at both side and transformation in the middle according to the joints among slices, a virtual scanning scene is outputted through image resampling, and therefore, the invention effectively improves the splicing efficiency, precision and reliability of internal view fields.



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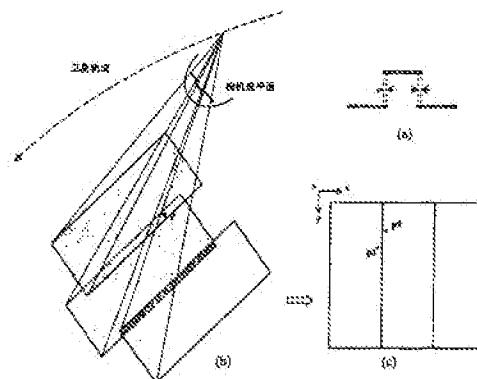
权利要求书 2 页 说明书 6 页 附图 2 页

(54) 发明名称

基于分段仿射变换的星载三片非共线TDICCD
影像拼接方法

(57) 摘要

本发明涉及一种基于分段仿射变换的星载三片非共线TDICCD影像拼接方法,将拼接后的虚拟扫描景看作是由焦面上首尾相连的三片虚拟CCD线阵所获取,其中,两侧的虚拟CCD与真实的TDICCD保持一致,中间虚拟CCD线阵则填充两侧虚拟CCD线阵的间隙,遵循“两边参考、中间变换”的原则,根据片间连接点建立TDICCD成像数据与虚拟CCD成像数据的像面变换模型,经影像重采样输出虚拟拼接扫描景,从而有效地改善了内视场拼接的效率、精度和可靠性。



1. 基于分段仿射变换的星载三片非共线 TDI CCD 影像拼接方法, 包括以下步骤: 一、确定虚拟拼接景的行数和列数: 令星载三片非共线 TDI CCD 影像的左片 TDI CCD1、中片 TDI CCD2 和右片 TDI CCD3 的长度即像元个数分别为 S_1 、 S_2 和 S_3 , 由三片非共线 TDI CCD 获取的原始影像的扫描行数为 L , 列数为 S , 其中 $S = S_1 + S_2 + S_3$; 令虚拟拼接景的扫描行数为 L_v , 列数为 S_v , 则有:

$$\begin{aligned} L_v &= L \\ S_v &= S - O_{12} - O_{23} \end{aligned} \quad (1)$$

式中, O_{12} 为 TDI CCD1 和 TDI CCD2 重叠像元设计个数, 其中 $0 < O_{12} < \min(S_1, S_2)$;

O_{23} 为 TDI CCD2 和 TDI CCD3 重叠像元设计个数, 其中 $0 < O_{23} < \min(S_2, S_3)$;

当 $S_1 \leq S_2$, $\min(S_1, S_2) = S_1$; 否则, $\min(S_1, S_2) = S_2$;

当 $S_2 \leq S_3$, $\min(S_2, S_3) = S_2$; 否则, $\min(S_2, S_3) = S_3$;

二、提取每相邻两片 TDI CCD 影像的连接点;

三、将虚拟拼接景看作是由焦面上首尾相连的三片虚拟 CCD 线阵即 CCD1、CCD2 和 CCD3 所获取, 其中, CCD1、CCD3 保持 TDI CCD1、TDI CCD3 原有摆放位置不变, CCD2 则填充 CCD1 和 CCD3 的空隙; 按照下列步骤建立 TDI CCD2 影像与虚拟 CCD2 影像间的分段仿射变换关系:

1) 根据影像辅助数据判断景内是否存在行积分时间跳变, 如果存在, 找到行积分时间发生跳变的扫描行位置 T_i , 其中 $0 < T_i < L$, $i = 1, 2, \dots, n$, n 表示行积分时间跳变次数;

2) 将 TDI CCD2 影像分为 N 段, $N = n+1$; 每段影像的起始扫描行号和终止扫描行号分别为 LS_i 和 LE_i , 有:

$$\begin{aligned} LS_1 &= 0 \\ LE_1 &= T_1 & (i=1) \\ LS_i &= T_{i-1} - 1 \\ LE_i &= T_i & (i=2, \dots, N-1) \\ LS_i &= T_i - 1 \\ LE_i &= L & (i=N) \end{aligned} \quad (2)$$

3) 利用 TDI CCD2 影像与 TDI CCD1 影像和 TDI CCD3 影像的连接点约束条件, 计算虚拟 CCD2 影像到 TDI CCD2 影像的分段仿射变换系数: 令提取的每对连接点在原始影像坐标系 xoy 中的像点坐标为 (x, y) 和 (x', y') , 且 (x', y') 对应于 TDI CCD2 影像上的点, (x, y) 对应于 TDI CCD1 或 TDI CCD3 影像上的点, 根据公式 (3), 计算 (x, y) 在虚拟拼接景坐标系 sol 中的坐标为 (s, l) :

$$\begin{aligned} s &= x & (x \leq S_1) \\ l &= y \\ s &= x - O_{12} - O_{23} & (x > S_1 + S_2) \\ l &= y \end{aligned} \quad (3)$$

4) 基于 (s, l) 与 (x', y') 的同名点对应关系, 基于公式 (4) 列误差方程式最小二乘平差解算 CCD2 影像到 TDI CCD2 影像的分段仿射变换系数 $a_{0i}, a_{1i}, a_{2i}, b_{0i}, b_{1i}, b_{2i}$ ($i = 1, 2, \dots, N$):

$$\begin{aligned} x' &= a_{0i} + a_{1i} \times s + a_{2i} \times l \\ y' &= b_{0i} + b_{1i} \times s + b_{2i} \times l \end{aligned} \quad (4)$$

四、对原始影像进行重采样,生成虚拟拼接扫描景:

1) 确定虚拟拼接景上三片虚拟 CCD 影像的拼接线位置:令 col_s 对应 CCD2 影像在虚拟拼接景上的起始列号, col_e 对应 CCD2 影像在虚拟拼接景上的终止列号,其中, col_s = S_1 , col_e = $S_v - S_3$;

2) 对于虚拟拼接景上的任意像点 (s, l), 按公式 (5) 计算其在原始影像上的像点坐标 (x', y'):

$$\begin{aligned} & \text{当 } s \leq \text{col_s} \text{ 时, } \begin{cases} x' = s \\ y' = l \end{cases} \\ & \text{当 } \text{col_s} < s \leq \text{col_e} \text{ 时, } \begin{cases} x' = a_{0i} + a_{1i} \times s + a_{2i} \times l \\ y' = b_{0i} + b_{1i} \times s + b_{2i} \times l \end{cases} \quad (i=1,2,\dots,N; \text{Ls}_i \leq l < \text{Le}_i) \\ & \text{当 } s > \text{col_e} \text{ 时, } \begin{cases} x' = s + O_{12} + O_{23} \\ y' = l \end{cases} \end{aligned} \quad (5)$$

根据像点坐标 (x', y') 经重采样得到像点的灰度值。

基于分段仿射变换的星载三片非共线 TDI CCD 影像拼接方法

技术领域

[0001] 本发明属于测绘科学与技术领域,涉及一种基于分段仿射变换的星载三片非共线 TDI CCD 影像拼接方法。

背景技术

[0002] 对于星载高分辨率光学相机而言,为了解决由相对孔径减小和成像曝光时间变短等因素所引起的光学系统像面光谱能量不足的问题,采用延时积分电荷耦合元件(TDI CCD)作为成像传感器是目前一种主要的技术途径。TDI CCD 是利用电荷延时积分原理成像的新型光电成像器件,与普通的单积分线阵 CCD 相比,能以多重延时积分成像的方式对地物多次曝光,成倍提升系统收集能量的能力,从而在低照度条件下获得高灵敏度、高输出速率、高空间分辨率、大的动态范围和相对较高的信噪比。受单片 TDI CCD 像元个数的限制,星载高分辨率光学相机通常以多片 TDI CCD 视场拼接的方式获取较大的成像视场。由于每片 TDI CCD 在物理结构上是一个小面阵,加上受外壳包装等限制,多片 TDI CCD 无法在焦面上按照一条直线进行物理排列,而通常采用三片品字形或多片上下交错形的非共线设计,其典型特征可以描述为:将多片 TDI CCD 在焦面上排成两列,与相机的整机推扫方向垂直;第二列填充由第一列形成的间隙,同一列 TDI CCD 的首尾像元分别对齐,相邻两片 TDI CCD 有一定的像元重叠。非共线 TDI CCD 已成为当前国内外高分辨率光学卫星影像获取的主要传感器,IKONOS, QuickBird, Geoeye-1, Worldview II, ALOS, OrbView-3, Formosat-2 等国外高分辨率商业卫星和我国遥感二号、资源一号 02B 卫星以及未来即将发射的多颗高分辨率卫星都采用了非共线 TDI CCD 相机作为成像载荷。

[0003] 与普通的单线阵 CCD 相比,非共线 TDI CCD 特殊的物理结构和成像方式给高分辨率卫星影像高精度和高质量的几何处理带来了新的问题。多片 TDI CCD 宽视场成像所获取的原始数据是按照每片 TDI CCD 成像单独记录的,受传感器的视场摆放位置、地形起伏、行积分时间变化等因素的影响,无法直接形成一个完整的扫描景影像。需要在影像预处理环节对非共线 TDI CCD 成像数据进行内视场拼接处理以形成空间上连续无缝的完整扫描景,满足后续影像产品的生产和制作要求。总体看来,国内外文献对星载非共线 TDI CCD 成像数据内视场拼接理论和算法的介绍很少。目前主要的技术途径是由连接点统计相邻影像的水平和垂直偏移量,然后进行片间平移拼接。IKONOS 和 Quickbird 等国外高分辨率商业卫星的光学相机大多采用多片交错形焦面设计,相邻 TDI CCD 对同一地物的成像时间延迟很短,使得地形起伏和行积分时间变化等因素对非共线 TDI CCD 成像的影响几乎可以忽略不计,只需要简单的片间平移即可满足亚像素级的拼接精度(K. Jacobsen, Calibration of Optical Satellite Sensors[C], International Calibration and Orientation Workshop EuroCOW 2006, Casteldefels, 2006, 6S., CD.; K. Jacobsen, 2008, Satellite image orientation[C], International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences, Vol. XXXVII, Part B1 (WGI/5): 703-709.)。对于采用

三片品字形焦面设计的星载非共线 TDI CCD 相机,成像受地形起伏和行积分时间变化等因素的影响较为明显,使得拼接处理的情况要相对复杂。岳庆兴等(岳庆兴,周强,张春玲,尤淑樟,贾永红,邱振戈, CBERS-02B 星全色影像的平差方法[J], 国土资源遥感, 2009, 79(1): 60-63.) 指出 CBERS-02B 卫星 HR 相机的两侧 TDI CCD 与中间 TDI CCD 成像数据间存在拼接错位问题,但没有对此展开研究;李世威等(李世威,刘团结,王宏琦, 基于图像匹配的 CBERS-02B 卫星 HR 相机图像拼接方法, 遥感技术与应用, 2009, 24(3): 374-378.) 提出了基于图像匹配的资源一号 02B 卫星高分辨率(HR)相机影像拼接方法,其本质也是基于大量连接点统计相邻影像间的水平和垂直偏移量,然后对多片影像进行两两平移拼接。但是,传统的平移拼接方法无法顾及景内可能存在的行积分时间跳变,且拼接处理只能在相邻两片 TDI CCD 成像数据间依次进行。

[0004] 因此,亟需深入开展非共线 TDI CCD 成像数据的内视场拼接理论和技术的研究,并针对目前较为典型的三片品字形设计情况,不断提出对原始成像数据进行拼接预处理即虚拟拼接景生成的新方法、新思路,以改善拼接处理的可靠性、效率和精度,这对于保证卫星影像产品的辐射质量和几何质量等具有十分重要的意义。

发明内容

[0005] 本发明所要解决的问题是:实现一种基于分段仿射变换的星载三片非共线 TDI CCD 影像拼接方法,该方法可完成对三片非共线 TDI CCD 成像数据的高效内视场拼接,以形成空间上连续无缝的完整虚拟扫描景。

[0006] 本发明提供的技术方案是:对于星载三片非共线 TDI CCD 成像数据的内视场拼接问题,将拼接后的虚拟扫描景看成是由焦面上首尾相连的三片虚拟 CCD 线阵获取到的,其中两侧虚拟 CCD 线阵的位置与真实的两侧 TDI CCD 保持一致,中间虚拟 CCD 线阵则填充两侧虚拟 CCD 线阵的间隙;根据行积分时间的变化情况,利用片间连接点构建中间虚拟 CCD 影像与中间 TDI CCD 影像的分段仿射变换关系,然后遵循这种“两边参考、中间变换”的影像重采样原则,对三片非共线 TDI CCD 成像数据进行内视场拼接以形成空间上连续无缝的完整扫描景。该技术方案包括以下步骤:

[0007] 一、确定虚拟拼接景的行数和列数;令星载三片非共线 TDI CCD 影像的左片 TDI CCD1、中片 TDI CCD2 和右片 TDI CCD3 的长度即像元个数分别为 S_1 、 S_2 和 S_3 ,由三片非共线 TDI CCD 获取的原始影像的扫描行数为 L ,列数为 S ,其中 $S = S_1 + S_2 + S_3$;令虚拟拼接景的扫描行数为 L_v ,列数为 S_v ,则有:

$$[0008] \quad L_v = L$$

$$[0009] \quad (1)$$

$$[0010] \quad S_v = S - O_{12} - O_{23}$$

[0011] 式中, O_{12} 为 TDI CCD1 和 TDI CCD2 重叠像元设计个数,其中 $0 < O_{12} < \min(S_1, S_2)$;

[0012] O_{23} 为 TDI CCD2 和 TDI CCD3 重叠像元设计个数,其中 $0 < O_{23} < \min(S_2, S_3)$;

[0013] 当 $S_1 \leq S_2$, $\min(S_1, S_2) = S_1$;否则, $\min(S_1, S_2) = S_2$;

[0014] 当 $S_2 \leq S_3$, $\min(S_2, S_3) = S_2$;否则, $\min(S_2, S_3) = S_3$;

[0015] 二、提取每相邻两片 TDI CCD 影像的连接点;

[0016] 三、将虚拟拼接景看作是由焦面上首尾相连的三片虚拟 CCD 线阵即 CCD1、CCD2 和

CCD3 所获取,其中, CCD1、CCD3 保持 TDI CCD1、TDI CCD3 原有摆放位置不变, CCD2 则填充 CCD1 和 CCD3 的空隙;按照下列步骤建立 TDI CCD2 影像与虚拟 CCD2 影像间的分段仿射变换关系:

[0017] 1) 根据影像辅助数据判断景内是否存在行积分时间跳变,如果存在,找到行积分时间发生跳变的扫描行位置 T_i ,其中 $0 < T_i < L, i = 1, 2, \dots, n, n$ 表示行积分时间跳变次数;

[0018] 2) 将 TDI CCD2 影像分为 N 段, $N = n+1$;每段影像的起始扫描行号和终止扫描行号分别为 LS_i 和 LE_i ,有:

$$[0019] \quad LS_1 = 0$$

$$[0020] \quad (i = 1)$$

$$[0021] \quad LE_i = T_i$$

$$[0022] \quad LS_i = T_{i-1}$$

$$[0023] \quad (i = 2, \dots, N-1)$$

$$[0024] \quad LE_i = T_i$$

$$[0025] \quad LS_i = T_{i-1}$$

$$[0026] \quad (i = N) \quad (2)$$

$$[0027] \quad LE_N = L$$

[0028] 3) 利用 TDI CCD2 影像与 TDI CCD1 影像和 TDI CCD3 影像的连接点约束条件,计算虚拟 CCD2 影像到 TDI CCD2 影像的分段仿射变换系数;令提取的每对连接点在原始影像坐标系 xoy 中的像点坐标为 (x, y) 和 (x', y') ,且 (x', y') 对应于 TDI CCD2 影像上的点, (x, y) 对应于 TDI CCD1 或 TDI CCD3 影像上的点,根据公式 (3),计算 (x, y) 在虚拟拼接景坐标系 sol 中的坐标为 (s, l) :

$$[0029] \quad s = x$$

$$[0030] \quad (x \leq S_1) \quad (3)$$

$$[0031] \quad l = y$$

$$[0032] \quad s = x - 0_{12} - 0_{23}$$

$$[0033] \quad (x > S_1 + S_2)$$

$$[0034] \quad l = y$$

[0035] 4) 基于 (s, l) 与 (x', y') 的同名点对应关系,基于公式 (4) 列误差方程式最小二乘平差解算 CCD2 影像到 TDI CCD2 影像的分段仿射变换系数 $a_{0i}, a_{1i}, a_{2i}, b_{0i}, b_{1i}, b_{2i} (i = 1, 2, \dots, N)$;

$$[0036] \quad x' = a_{0i} + a_{1i} \times s + a_{2i} \times l$$

$$[0037] \quad (4)$$

$$[0038] \quad y' = b_{0i} + b_{1i} \times s + b_{2i} \times l$$

[0039] 四、对原始影像进行重采样,生成虚拟拼接扫描景:

[0040] 1. 确定虚拟拼接景上三片虚拟 CCD 影像的拼接线位置;令 col_s 对应 CCD2 影像在虚拟拼接景上的起始列号, col_e 对应 CCD2 影像在虚拟拼接景上的终止列号,其中, $col_s = S_1, col_e = S_1 + S_2$;

[0041] 2. 对于虚拟拼接景上的任意像点 (s, l) ,按公式 (5) 计算其在原始影像上的像点

坐标 (x', y') , 根据像点坐标 (x', y') 经重采样得到像点的灰度值。

[0042] 当 $s \leq \text{col_s}$ 时,
$$\begin{aligned} x' &= s \\ y' &= l \end{aligned}$$

[0043] 当 $\text{col_s} < s \leq \text{col_e}$ 时,
$$\begin{aligned} x' &= a_{0i} + a_{1i} \times s + a_{2i} \times l \\ y' &= b_{0i} + b_{1i} \times s + b_{2i} \times l \end{aligned} \quad (i=1, 2, \dots, N; Ls_i \leq l < Le_i) \quad (5)$$

[0044] 当 $s > \text{col_e}$ 时,
$$\begin{aligned} x' &= s + O_{12} + O_{23} \\ y' &= l \end{aligned}$$

[0045] 本发明将拼接后的虚拟扫描景看作是由焦面上首尾相连的三片虚拟 CCD 线阵所获取, 其中, 两侧虚拟 CCD 线阵的位置与真实的两侧 TDI CCD 保持一致, 中间虚拟 CCD 线阵则填充两侧虚拟 CCD 线阵的间隙; 根据行积分时间的变化情况, 基于片间连接点构建中间虚拟 CCD 成像数据与中间 TDI CCD 成像数据之间的分段仿射变换关系, 然后遵循这种“两边参考、中间变换”的影像重采样原则, 实现三片非共线 TDI CCD 成像数据的高效内视场拼接, 以形成空间上连续无缝的完整虚拟扫描景。

附图说明

[0046] 图 1 是三片非共线 TDI CCD 成像原理的示意图; (a) 相机焦面结构; (b) 推扫成像模式; (c) 原始影像坐标系;

[0047] 图 2 给出了虚拟拼接景物理含义的示意图;

[0048] 图 3 给出了拼接原理的示意图。

具体实施方式

[0049] 下面结合附图对本发明做进一步详细描述。

[0050] 如图 1 所示, 三片 TDI CCD 按品字形偏场排列于相机焦平面 (图 1(a)), 沿卫星轨道推扫成像时三片 TDI CCD 共享一套轨道姿态参数 (图 1(b)), M 为三片 TDI CCD 成像数据按时间 (行计数) 对齐后的原始影像 (图 1(c))。例如, p1 和 p2 为 TDI CCD1 影像和 TDI CCD2 影像间的一对同名点, 点 P 为其对应的物点。概括起来, 基于分段仿射变换的星载三片非共线 TDI CCD 影像拼接方法, 其实施过程可以分为四个阶段:

[0051] 第一阶段: 确定虚拟拼接景的行数和列数

[0052] 令星载三片非共线 TDI CCD 影像的左片 TDI CCD1、中片 TDI CCD2 和右片 TDI CCD3 的长度即像元个数分别为 S_1 、 S_2 和 S_3 , 由三片非共线 TDI CCD 获取的原始影像的扫描行数为 L , 列数为 S , 其中 $S = S_1 + S_2 + S_3$; 令虚拟拼接景的扫描行数为 L_v , 列数为 S_v , 则有:

[0053] $L_v = L$

[0054] $S_v = S - O_{12} - O_{23} \quad (1)$

[0055] 式中, O_{12} 为 TDI CCD1 和 TDI CCD2 重叠像元设计个数, 其中 $0 < O_{12} < \min(S_1, S_2)$;

[0056] O_{23} 为 TDI CCD2 和 TDI CCD3 重叠像元设计个数, 其中 $0 < O_{23} < \min(S_2, S_3)$;

[0057] 当 $S_1 \leq S_2$, $\min(S_1, S_2) = S_1$; 否则, $\min(S_1, S_2) = S_2$;

[0058] 当 $S_2 \leq S_3$, $\min(S_2, S_3) = S_2$; 否则, $\min(S_2, S_3) = S_3$;

[0059] 第二阶段: 提取相邻 TDI CCD 影像的连接点

[0060] 通过现有技术中的目视判读或影像自动匹配技术提取每相邻两片 TDI CCD 影像的

连接点。

[0061] 第三阶段：建立虚拟 CCD2 影像与 TDI CCD2 影像的分段仿射变换关系

[0062] 原始影像由相机焦平面上三片品字形排列的 TDI CCD (如图 2(a)) 所获取, 若对 TDI CCD2 影像进行像面变换, 使之与两侧 TDI CCD 影像无缝拼接, 那么根据中心投影几何关系, 所构成的虚拟拼接景可以看作是由焦面上三片首尾相连的虚拟 CCD 线阵即 CCD1、CCD2 和 CCD3 所获取, 如图 2(b) 所示, CCD1、CCD3 保持 TDI CCD1、TDI CCD3 原有位置不变, CCD2 填充 CCD1 和 CCD3 的空隙。于是, 按照下列步骤建立虚拟 CCD2 影像到 TDI CCD2 影像的分段仿射变换关系:

[0063] 1. 根据影像辅助数据判断景内是否存在行积分时间跳变, 如果存在, 找到行积分时间发生跳变的扫描行位置 T_i , 其中 $0 < T_i < L, i = 1, 2, \dots, n, n$ 表示行积分时间跳变次数;

[0064] 2. 将 TDI CCD2 影像分为 N 段, $N = n+1$; 每段影像的起始扫描行号和终止扫描行号分别为 LS_i 和 LE_i , 有:

$$[0065] \quad LS_i = 0$$

$$[0066] \quad (i = 1)$$

$$[0067] \quad LE_i = T_i$$

$$[0068] \quad LS_i = T_i - 1$$

$$[0069] \quad (i = 2, \dots, N-1)$$

$$[0070] \quad LE_i = T_i$$

$$[0071] \quad LS_i = T_i - 1$$

$$[0072] \quad (i = N) \quad (2)$$

$$[0073] \quad LE_i = L$$

[0074] 3. 利用 TDI CCD2 影像与 TDI CCD1 影像、TDI CCD3 影像的连接点约束条件, 计算虚拟 CCD2 影像到 TDI CCD2 影像的分段仿射变换系数; 如图 3(a) 所示, 令提取的每对连接点在原始影像坐标系 xoy 中的像点坐标为 (x, y) 和 (x', y') , 且 (x', y') 对应于 TDI CCD2 影像上的点, (x, y) 对应于 TDI CCD1 或 TDI CCD3 影像上的点; 如图 3(b), 令虚拟拼接景影像坐标系为 $so1$, 则按照公式 (3) 计算 (x, y) 在虚拟拼接景上对应的像点坐标 (s, l) :

$$[0075] \quad s = x$$

$$[0076] \quad (x \leq S_i) \quad (3)$$

$$[0077] \quad l = y$$

$$[0078] \quad s = x - O_{12} - O_{23}$$

$$[0079] \quad (x > S_i + S_{i+1})$$

$$[0080] \quad l = y$$

[0081] 4. 基于 (s, l) 与 (x', y') 的同名点对应关系, 基于公式 (4) 列误差方程式最小二乘平差解算 CCD2 影像到 TDI CCD2 影像的分段仿射变换系数 $a_{0i}, a_{1i}, a_{2i}, b_{0i}, b_{1i}, b_{2i} (i = 1, 2, \dots, N)$:

$$[0082] \quad x' = a_{0i} + a_{1i} \times s + a_{2i} \times l$$

$$[0083] \quad (4)$$

$$[0084] \quad y' = b_{0i} + b_{1i} \times s + b_{2i} \times l$$

[0085] 第四阶段:对原始影像进行重采样,生成虚拟拼接扫描景。

[0086] 1. 确定虚拟拼接景上三片虚拟 CCD 影像的拼接线位置,如图 3(b) 所示:令 col_s 对应 CCD2 影像在虚拟拼接景上的起始列号, col_e 对应 CCD2 影像在虚拟拼接景上的终止列号,为了最大程度地保留 TDI CCD1 影像和 TDI CCD3 影像,这里, col_s = S_1 , col_e = $S_2 - S_3$;

[0087] 2. 对于虚拟拼接景上的任意像点 (s, l), 按公式 (5) 计算其在原始影像上的像点坐标 (x' , y'), 经重采样得到像点的灰度值。

[0088] 当 $s \leq \text{col_s}$ 时,
$$\begin{aligned} x' &= s \\ y' &= l \end{aligned}$$

[0089] 当 $\text{col_s} < s \leq \text{col_e}$ 时,
$$\begin{aligned} x' &= a_{0i} + a_{1i} \times s + a_{2i} \times l \\ y' &= b_{0i} + b_{1i} \times s + b_{2i} \times l \end{aligned} \quad (i=1,2,\dots,N; L_{S_i} \leq l < L_{E_i}) \quad (5)$$

[0090] 当 $s > \text{col_e}$ 时,
$$\begin{aligned} x' &= s + O_{12} + O_{23} \\ y' &= l \end{aligned}$$

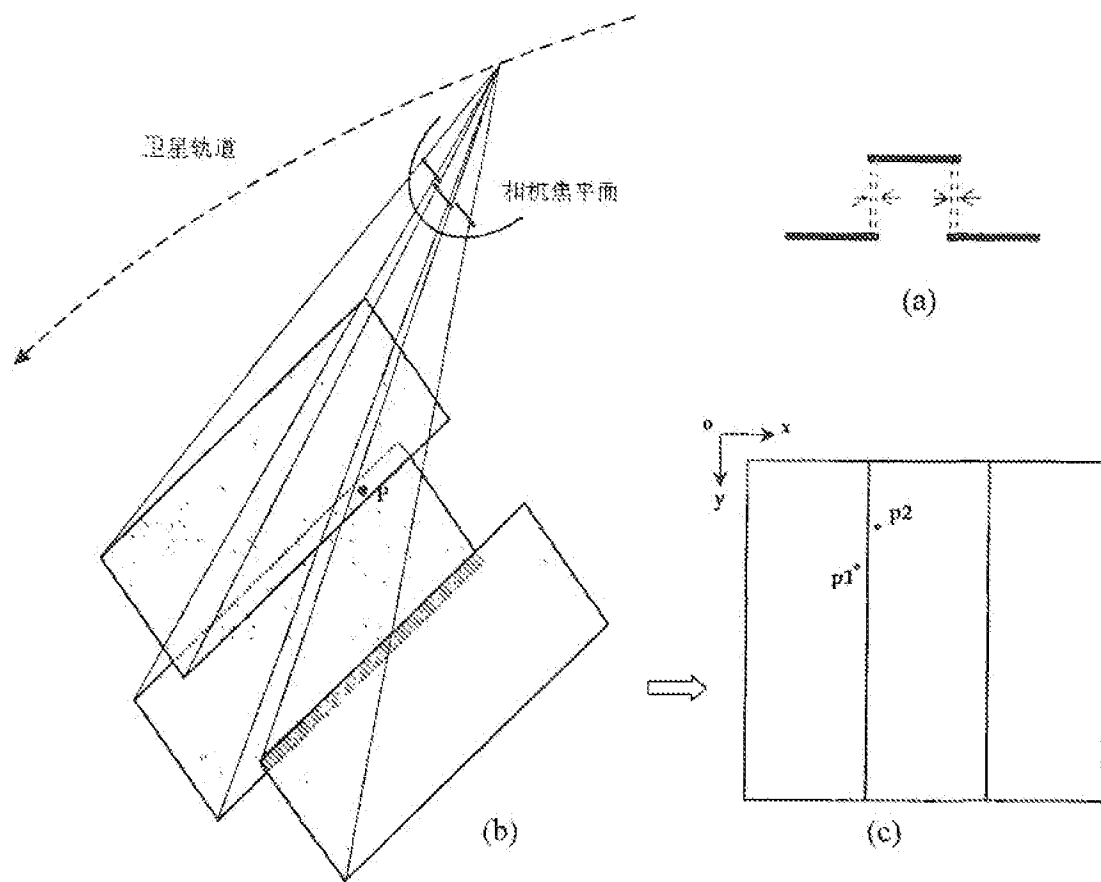


图 1

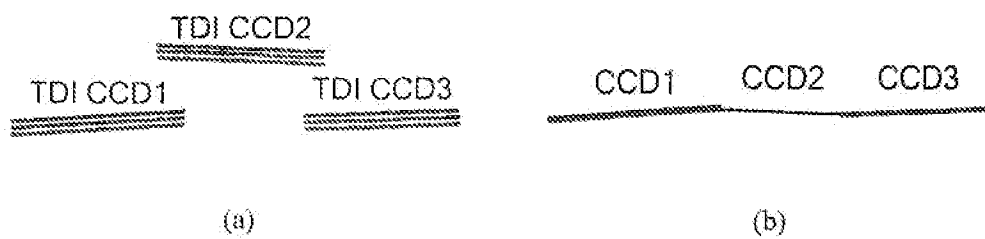


图 2

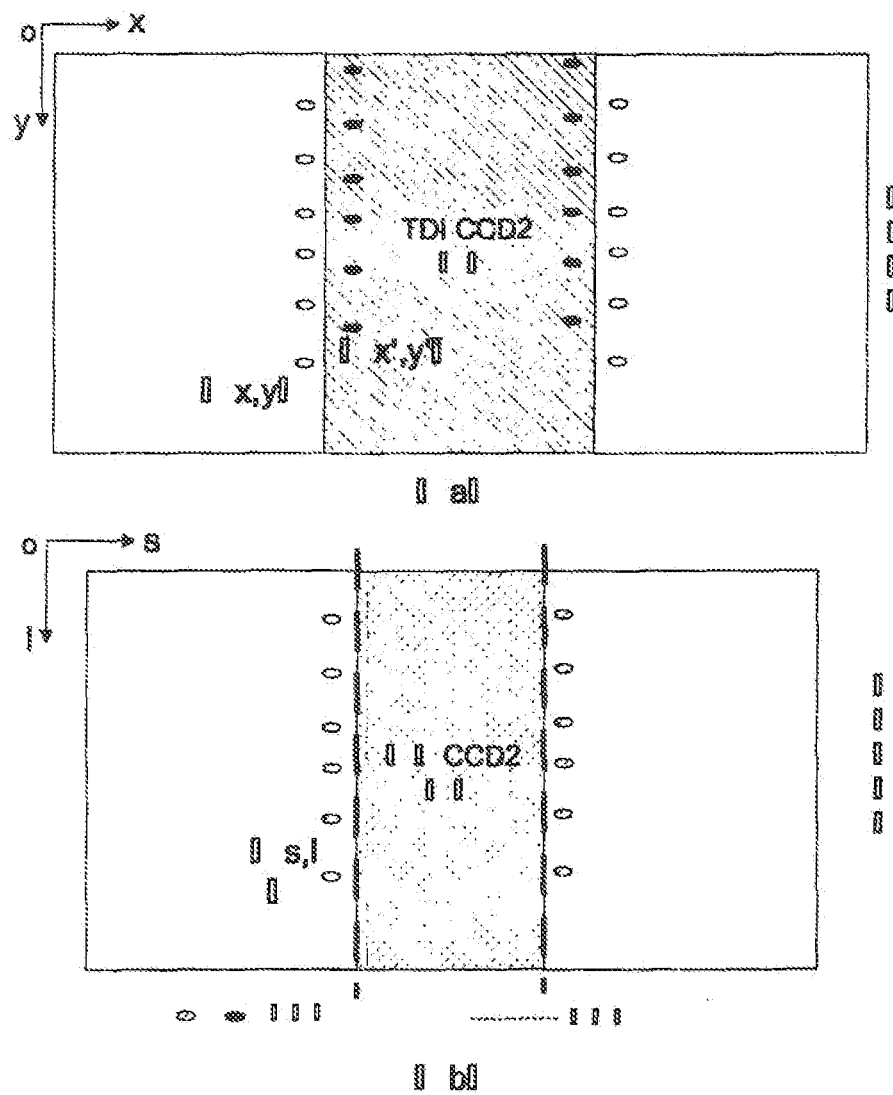


图 3

Electronic Acknowledgement Receipt

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International Application Number:	
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Title of Invention:	HYBRID STITCHING
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1	Transmittal Letter	IDS2_67245US004.pdf	76915 88b9be3182199447b7a6e8b3b400c6b888a5a9ea	no	2

Warnings:

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2	Information Disclosure Statement (IDS) Form (SB08)	IDS2_1449_67245US004.pdf	77093 bc4cf81c59a65616195bcd9188b28766b3 9cd3c	no	1
Warnings:					
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3	Foreign Reference	CN101799293_abst.pdf	2645724 7c64c098d8dad6aca208fe37797f0b01e810 29f9	no	12
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32692
Customer Number

Patent
Case No.: 67245US004

IN THE UNITED STATES PATENT AND TRADEMARK OFFICE

First Named Inventor: ILYA KRIVESHKO

Application No.: 14/000442

Confirmation No.: 8005

Filed: 17-FEB-2012

Title HYBRID STITCHING

INFORMATION DISCLOSURE STATEMENT

Mail Stop: Amendment
Commissioner for Patents
P.O. Box 1450
Alexandria, VA 22313-1450

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I hereby certify that this correspondence is being:

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April 14, 2015

/Paula J. Bick/

Date

Signed by: Paula J. Bick

Dear Commissioner:

Pursuant to 37 CFR §§ 1.56, 1.97, and 1.98, enclosed is a completed Form PTO-1449, citing references submitted for consideration by the Examiner. It is respectfully requested that the Examiner initial and return the enclosed Form PTO-1449 to indicate that each reference has been considered.

This Information Disclosure Statement is being filed within three months of the filing date of the application, or within three months of entry into the national stage, or before the mailing of a first Office Action on the merits.

Fees

- ☒ It is believed that no fee is due; however, in the event a fee is required, please charge the fee to Deposit Account No. 13-3723.
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Copies of Documents

Copies of any cited foreign patents, foreign publications, non-patent literature documents, and any pending U.S. applications filed before June 30, 2003, are enclosed. Copies of any pending U.S. applications filed after June 30, 2003 that can be accessed on the USPTO's IFW system are not enclosed as per USPTO Waiver dated September 21, 2004. Copies of any U.S. patents and published U.S. patent applications are not enclosed.

Respectfully submitted,

April 14, 2015

Date

By: /Lance Vietzke/

Lance L. Vietzke, Reg. No.: 36,708

Telephone No.: 651-737-2180

Office of Intellectual Property Counsel
3M Innovative Properties Company
Facsimile No.: 651-736-3833

Substitute for form 1449A/PTO (modified) INFORMATION DISCLOSURE STATEMENT BY APPLICANT (Use as many sheets as necessary) Page 1 of 2	Application Number	14/000442
	Filing Date	17-FEB-2012
	First Named Inventor	Kriveshko, Ilya A
	Confirmation Number	8005
	Attorney Case Number	67245US004

United States Patent Documents					
Exam. Init.*	Cite No.	Document Number	Publication Date MM-DD-YYYY	Name of Patentee or Applicant of Cited Document	Pages, Columns, Lines, Where Relevant Passages or Relevant Figures Appear
		Doc. Number-(Kind Code if Known)			
	A1	2003-0151604	08-14-2003	Kaufman	
	A2	2004-0155975	08-12-2004	Hart	
	A3	2006-0139470	06-29-2006	McGowan	
	A4	2007-0103460	05-10-2007	Zhang	
	A5	2007-0171220	07-26-2007	Kriveshko	
	A6	2007-0172101	07-26-2007	Kriveshko	
	A7	2010-0066364	03-18-2010	Huwer	
	A8	2010-0281370	11-04-2010	Rohaly	
	A9	2010-0303341	12-02-2010	Hausler	
	A10	5,410,614	04-25-1995	Chou	
	A11	7,372,642	05-13-2008	Rohaly	

Foreign Patent Documents						
Exam. Init.*	Cite No.	Foreign Patent Document		Publication Date MM-DD-YYYY	Name of Patentee or Applicant of Cited Document	Pages, Columns, Lines, Where Relevant Passages or Relevant Figures Appear
		Ctry. Code	Number-Kind Code (if known)			
	B1	WO	2007-084589	07-26-2007	Kriveshko	
	B2	WO	2012-115862	08-30-2012	Mcqueston	

OTHER DOCUMENTS			
Exam. Init.*	Cite No.	Include name of the author (in CAPITAL LETTERS), title of the article (when appropriate), title of the item (book, magazine, journal, serial, symposium, catalog, etc.), date, page(s), volume-issue number(s), publisher, city and/or country where published	Translation (Check if yes)
	C1	BENJEMAA, "A Solution for the Registration of Multiple 3D Point Sets Using Unit Quaternions", ECCV98, 5 th European Conference on Computer Vision, June 1998, Vol. II, pp. 34-50.	
	C2	DORST, "First Order Error Propagation of the Procrustes Method for 3D Attitude Estimation", IEEE Transactions on Pattern Analysis and Machine Intelligence, February 2005, Vol.27, No. 2, pp. 221-229.	
	C3	GOVINDU "Combining Two-View Constraints For Motion Estimation," ,Proc. of the Int. Conf. on Computer Vision and Pattern Recognition, July 2001, Vol. 2, pp. 218-225..	
	C4	KRISHNAN, "Global Registration of Multiple 3D Point Sets via Optimization-on-a-Manifold", Eurographics Symposium on. Geometry Processing, 2005, 11 pages.	
	C5	WILLIAMS, "Simultaneous Registration Of Multiple Corresponding Point Sets", Computer Vision and Image Understanding, January 2001, Vol. 81, No. 1, pp. 117-142.	

*Examiner:	Date Considered:
EXAMINER: Initial if reference considered, whether or not citation is in conformance with MPEP 609. Draw line through citation if not in conformance and not considered. Include copy of this form with next communication to applicant.	

Substitute for form 1449A/PTO (modified) INFORMATION DISCLOSURE STATEMENT BY APPLICANT (Use as many sheets as necessary) Page 2 of 2	Application Number	14/000442
	Filing Date	17-FEB-2012
	First Named Inventor	Kriveshko, Ilya A
	Confirmation Number	8005
	Attorney Case Number	67245US004

OTHER DOCUMENTS			
Exam. Init.*	Cite No.	Include name of the author (in CAPITAL LETTERS), title of the article (when appropriate), title of the item (book, magazine, journal, serial, symposium, catalog, etc.), date, page(s), volume-issue number(s), publisher, city and/or country where published	Translation (Check if yes)
	C6	International Search Report for International PCT Application No.PCT/US2012/025554 Mailed on September 26, 2012, 3 pages.	

*Examiner:	Date Considered:
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	Filing Date	17-FEB-2012
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	A4	2007-0103460	05-10-2007	Zhang	
	A5	2007-0171220	07-26-2007	Kriveshko	
	A6	2007-0172101	07-26-2007	Kriveshko	
	A7	2010-0066364	03-18-2010	Huwer	
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	A9	2010-0303341	12-02-2010	Hausler	
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(71) Applicant (for all designated States except US): **3M INNOVATIVE PROPERTIES COMPANY** [US/US];
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(74) Agents: **EDMAN, Sean, J.** et al.; 3M Center, Office of Intellectual Property Counsel, Post Office Box 33427, Saint Paul, Minnesota 55133-3427 (US).

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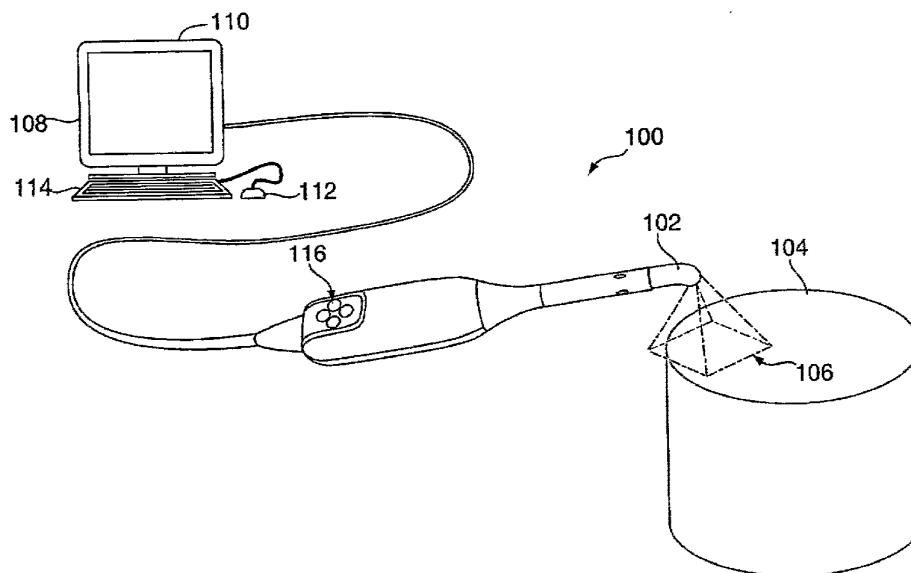
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For two-letter codes and other abbreviations, refer to the "Guidance Notes on Codes and Abbreviations" appearing at the beginning of each regular issue of the PCT Gazette.

(54) Title: THREE-DIMENSIONAL SCAN RECOVERY



(57) Abstract: A scanning system that acquires three-dimensional images as an incremental series of fitted three-dimensional data sets is improved by testing for successful incremental fits in real time and providing a variety of visual user cues and process modifications depending upon the relationship of newly acquired data to previously acquired data. The system may be used to aid in error-free completion of three-dimensional scans. The methods and systems described herein may also usefully be employed to scan complex surfaces including occluded or obstructed surfaces by maintaining a continuous three-dimensional scan across separated subsections of the surface. In one useful dentistry application, a full three-dimensional surface scan may be obtained for two dental arches in occlusion.



WO 2007/084589 A2

THREE-DIMENSIONAL SCAN RECOVERY

RELATED APPLICATIONS

[0001] This application claims priority to U.S. App. No. 11/337,182 filed on
5 January 20, 2006.

BACKGROUND

1. Field of the Invention.

[0002] The invention relates to three-dimensional scanning, and more
10 particularly to techniques for resuming a three-dimensional scan after losing data acquisition.

2. Description of the Related Art.

[0003] A wide range of techniques exist for acquiring three-dimensional data
15 from a subject. These techniques range from techniques using structured laser illumination or other controlled stimulus (such as x-rays, ultrasound, or magnetic resonance) to techniques that operate directly on video data captured from one or more cameras. While many criteria can be devised for sorting and comparing these techniques, one broad category employs continuous scanning in which incremental three-dimensional
20 data is acquired and assembled into a full three-dimensional model.

[0004] In this latter category, regardless of the particular sensing technology, a scanning process can be divided into abstract steps of incremental data capture, incremental derivation of three-dimensional data, and registration of the incremental data to a common coordinate system. The final registration step brings the incremental data
25 together into a single three-dimensional model of a scan subject. Typical implementations separate acquisition from registration, with registration being performed in a post-processing step after completion of the data acquisition. While this permits relatively exhaustive processing, it poses a significant disadvantage because accuracy and completeness of the overall scan cannot be evaluated until after the scan has been
30 terminated. Unrecoverable errors or gaps in incremental data cannot be identified and fixed without initiating a new scan -- possibly a full scan to completely replace the

defective results. In commercial applications, this may create delays and inconvenience that increase the effective cost of scanning.

[0005] In certain instances, recovery of lost or unusable scan segments may be addressed by using robotics, independent references, or other techniques that can reliably position a scanning device within a global coordinate system. In addition to imposing further equipment costs, this approach can only be used to continue a previous scan if the subject of the scan has also retained its position and orientation within the same global coordinate system.

[0006] There remains a need for processing techniques that identify and aid in recovery from errors in incremental scans. There also remains a need for real time feedback systems to support recovery from a lost scanning sequence while the scan is in progress.

SUMMARY

[0007] A scanning system that acquires three-dimensional images as an incremental series of fitted three-dimensional data sets is improved by testing for successful incremental fits in real time and providing a variety of visual user cues and process modifications depending upon the relationship of newly acquired data to previously acquired data. The system may be used to aid in error-free completion of three-dimensional scans. The methods and systems described herein may also usefully be employed to scan complex surfaces including occluded or obstructed surfaces by maintaining a continuous three-dimensional scan across separated subsections of the surface. In one useful dentistry application, a full three-dimensional surface scan may be obtained for two dental arches in occlusion.

[0008] In one aspect, a method disclosed herein may include acquiring three-dimensional surface data from a subject as a sequence of three-dimensional images, each one of the sequence of three-dimensional images fitted to at least one previous one of the sequence of three-dimensional images, and acquiring an image set for a next three-dimensional image. When the image set can be converted into the next three-dimensional image and the next three-dimensional image can be fitted to the three-dimensional surface data, the three-dimensional surface data and the next three-dimensional image are superimposed onto a two-dimensional image of the subject in a display. Further, when the

image set cannot be converted into the next three-dimensional image or the next three-dimensional image cannot be fitted to the three-dimensional surface data, a recover mode is entered. The recover mode may include superimposing a current two-dimensional image of the subject onto a previous two-dimensional image of the subject in the display.

5 The two-dimensional image represents a view of the subject from a position from which one of the sequence of three-dimensional images was acquired. Additionally the current two-dimensional image represents a view of the subject from a position from which the image set was acquired. The recover mode further may include acquiring at least one subsequent three-dimensional image and test fitting it to one or more of the sequence of

10 three-dimensional images.

[0009] The method may further include adding the next three-dimensional image to the three-dimensional surface data when the image set can be converted into the next three-dimensional image and the next three-dimensional image can be fit to the three-dimensional surface data. In the method, the previous two-dimensional image and the

15 current two-dimension image may include video frames. The method may further include manually entering the recover mode in response to a user input. Also, the method may further include automatically entering the recover mode in response to a detection of a lost acquisition. The detection of a lost acquisition may include, for example, a detection of motion blur. The detection of lost acquisition may also include a detection of an

20 insufficient recovery of three-dimensional data. In the method, the recover mode may include the step of highlighting a region on the subject for attempting a recovery. Also the highlighted region may include a plurality of previous ones of the sequence of three-dimensional images. The recover mode may include the step of test fitting at least one subsequent three-dimensional image to one or more additional images acquired during the

25 recover mode and test fitting may include selecting a reference image from the sequence of three-dimensional images based on a suitability for test fitting. The suitability for test fitting may be based upon an entropy of image data in the previous three-dimensional image. Also, the suitability for test fitting may be based upon an amount of three-dimensional data in the previous three-dimensional image. Also, or instead, the suitability

30 for test fitting may be based upon a placement of three-dimensional data within a range and a field of view of an imaging device. Determining the suitability for test fitting may be based upon a temporal proximity of the at least one subsequent three-dimensional image to

one or more of the sequence of three-dimensional images. Determining the suitability for test fitting may be based upon a spatial proximity of the at least one subsequent three-dimensional image to one or more of the sequence of three-dimensional images. The recover mode may include the step of manually selecting one or more of the sequence of three-dimensional images. The recover mode may also include selecting a reference image from a beginning or an end of the sequence of three-dimensional images.

[0010] In another aspect, a method is disclosed herein may include providing three-dimensional surface data for a subject, and acquiring an image set for a three-dimensional image of the subject. When the image set cannot be fitted to the three-dimensional surface data, the method may enter a landing mode which may include superimposing a current two-dimensional image of the subject onto a previous two-dimensional image of the subject in the display, the current two-dimensional image representing a view of the subject from a position from which the image set was acquired, and the previous two-dimensional image representing a view of the subject from which at least a portion of the three-dimensional surface data was acquired; acquiring at least one subsequent three-dimensional image; fitting the at least one subsequent three-dimensional image to a second three-dimensional surface reconstruction; and test fitting the at least one subsequent three-dimensional image to the three-dimensional surface data. When the image set can be fitted to the three-dimensional surface data, the method superimposes the three-dimensional surface data and the next three-dimensional image onto a two-dimensional image of the subject in a display and adds the second three-dimensional surface reconstruction to the three-dimensional surface data.

[0011] In the method, the previous two-dimensional image and the current two-dimensional image may include video frames. The method may further include manually entering the landing mode in response to a user input. In the landing mode, the method may include highlighting a region on the subject for attempting a landing. The highlighted region may include a portion of the three-dimensional surface data. Test fitting may include selecting a reference image from the three-dimensional surface data based on the reference image's suitability for test fitting. Suitability for testing may be based on any one or more of the following: entropy of image data in the previous three-dimensional image, amount of three-dimensional data in the previous three-dimensional image, placement of three-dimensional data within a range and a field of view of an imaging

device, and spatial proximity of the image set to a portion of the three-dimensional surface data. The method may further include manually selecting a region of the three-dimensional surface data for test fitting. Test fitting may include selecting a reference image from a beginning or an end of a sequence of three-dimensional images used to
5 construct the three-dimensional surface data. The previous two-dimensional image and the current two-dimension image may include video frames. The method may further include manually entering the recover mode in response to a user input. Additionally, the method may further include manually selecting a region from the three-dimensional surface data for test fitting.

10 [0012] In another aspect, a system is disclosed herein may include a scanning device that acquires three-dimensional surface data from a subject as a sequence of three-dimensional images, each one of the sequence of three-dimensional images fitted to at least one previous one of the sequence of three-dimensional images. The scanning device may include an acquisition mode in which one or more additional three-dimensional
15 images are acquired and added to the three-dimensional surface data. Additionally the device may include a recovery mode in which one or more additional three-dimensional images are test fit to one or more of the sequence of three-dimensional images to recover the acquisition mode, and a display may be adapted to provide one or more visual indicators distinguishing between the acquisition mode and the recovery mode.

20 [0013] In the system, the display may be further adapted to provide guidance to an operator in manipulating the subject in the recovery mode.

[0014] In another aspect, a method is disclosed herein including performing a first acquisition of a first set of three-dimensional data from a first subject, placing a second subject in a fixed orientation relative to the first subject, and performing a second
25 acquisition of a second set of three-dimensional data starting at a location on a surface of the first subject and including at least a portion of the second subject. In the method, the first subject and the second subject each may be a rigid body.

[0015] In the method, the location on the surface of the first subject may include a plurality of spatially proximate ones of a sequence of three-dimensional images used to
30 derive the three-dimensional data from the first subject. Also, in the method, the location on the surface of the first subject may include a plurality of temporally proximate ones of a sequence of three-dimensional images used to derive the three-dimensional data from the

first subject. Alternatively, in the method, the first subject may include a first dental arch. At least a portion of the second set of three-dimensional data may be fitted to at least a portion of the first set of three-dimensional data to provide a unified set of three-dimensional data.

5 **[0016]** The method may further include terminating the second acquisition at a location on a surface of the second subject, removing the first subject, and performing a third acquisition of three-dimensional data starting at the location on the surface of the second subject. The location on the surface of the second subject may include a plurality of spatially proximate ones of a sequence of three-dimensional images used to derive the three-dimensional data from the second subject. Alternatively, the location on the surface of the second subject may include a plurality of temporally proximate ones of the sequence of three-dimensional images used to derive the three-dimensional data from the second subject.

15 **[0017]** The method may further include combining the first set of three-dimensional data, the second set of three-dimensional data, and the third set of three-dimensional data into a unified set of three-dimensional data. In the method, the second subject may include a second dental arch, and the fixed orientation may include the first dental arch and the second dental arch in occlusion.

20 **[0018]** In another aspect, a system disclosed herein may include an acquisition means for performing a first acquisition of a first set of three-dimensional data from a first subject, and a positioning means for placing a second subject in a fixed orientation relative to the first subject. In the system, the acquisition means may include a means for performing a second acquisition of a second set of three-dimensional data starting at a location on a surface of the first subject and including at least a portion of the second subject. In the system, the first subject and the second subject each may be a rigid body.

25 **[0019]** In the system, the location on the surface of the first subject may include a plurality of spatially proximate ones of a sequence of three-dimensional images used to derive the three-dimensional data from the first subject. Alternatively, the location on the surface of the first subject may include a plurality of temporally proximate ones of a sequence of three-dimensional images used to derive the three-dimensional data from the first subject. The first subject may include a first dental arch. At least a portion of the second set of three-dimensional data may be fitted to at least a portion of the first set of

three-dimensional data to provide a unified set of three-dimensional data. The system may further include a control means for terminating the second acquisition at a location on a surface of the second subject, the positioning means may include a means for removing the first subject; and the acquisition means may include a means for performing a third acquisition of three-dimensional data starting at the location on the surface of the second subject. The location on the surface of the second subject may include a plurality of spatially proximate ones of a sequence of three-dimensional images used to derive the three-dimensional data from the second subject. Alternatively, the location on the surface of the second subject may include a plurality of temporally proximate ones of the sequence of three-dimensional images used to derive the three-dimensional data from the second subject. The system may further include a computing means for combining the first set of three-dimensional data, the second set of three-dimensional data, and the third set of three-dimensional data into a unified set of three-dimensional data. In the system, the second subject may include a second dental arch, and the fixed orientation may include the first dental arch and the second dental arch in occlusion.

[0020] In another aspect, a method disclosed herein may include placing a first subject in a fixed orientation relative to a second subject, acquiring a first set of three-dimensional data including a first portion of the first subject and a first portion of the second subject, acquiring a second set of three-dimensional data from the first subject in isolation starting at a location on a surface of the first subject and including a second portion of the first subject different from the first portion of the first subject, and combining the first set of three-dimensional data with the second set of three-dimensional data.

[0021] In the method, the first subject and the second subject may be a rigid body. Alternatively, the first subject may include a first dental arch. The location on the surface of the first subject may include a plurality of spatially proximate ones of a sequence of three-dimensional images used to derive the three-dimensional data from the first subject. Alternatively, the location on the surface of the first subject may include a plurality of temporally proximate ones of a sequence of three-dimensional images used to derive the three-dimensional data from the first subject. The method may further include acquiring a third set of three-dimensional data from the second subject in isolation starting at a location on a surface of the second subject and including a second portion of the

second subject, and combining the third set of three-dimensional data with the first and second sets of three-dimensional data. The location on the surface of the second subject may include a plurality of spatially proximate ones of a sequence of three-dimensional images used to derive the three-dimensional data from the second subject. Alternatively, the location on the surface of the second subject may include a plurality of temporally proximate ones of the sequence of three-dimensional images used to derive the three-dimensional data from the second subject. The second subject may include a second dental arch, and the fixed orientation may include the first dental arch and the second dental arch in occlusion.

[0022] In another aspect, a method disclosed herein may include providing a first set of three-dimensional data from a subject, scanning the subject to acquire one or more additional three-dimensional images, test fitting each one of the one or more additional three-dimensional images to the set of three dimensional data, and upon a successful fit, adding the one or more additional three-dimensional images to the set of three-dimensional data.

[0023] The method may include fitting each new one of the one or more additional three-dimensional images to one another to provide a second set of three-dimensional data, and upon a successful fit, adding the second set of three-dimensional data to the first set of three-dimensional data. The three-dimensional data may include three-dimensional surface data. Alternatively, the one or more additional three-dimensional images may include surface data derived from two-dimensional image sets of the subject. In the method, the set of three-dimensional data may include three-dimensional surface data acquired from a subject as a sequence of three-dimensional images, each one of the sequence of three-dimensional images fitted to at least one previous one of the sequence of three-dimensional images.

[0024] In another aspect, a system disclosed herein may include a storage means for providing a first set of three-dimensional data from a subject, an acquisition means for scanning the subject to acquire one or more additional three-dimensional images, and a computing means for test fitting each one of the one or more additional three-dimensional images to the set of three dimensional data. The computing means may further include a means for detecting a successful fit and, upon detecting a successful fit, may add the one or more additional three-dimensional images to the set of three-dimensional data.

[0025] In the system, the computing means may include a means for fitting each new one of the one or more additional three-dimensional images to one another to provide a second set of three-dimensional data, and upon a successful fit, may add the second set of three-dimensional data to the first set of three-dimensional data. In the system, the three-dimensional data may include three-dimensional surface data. Alternatively in the system, the one or more additional three-dimensional images may include surface data derived from two-dimensional image sets of the subject. The set of three-dimensional data may include three-dimensional surface data acquired from a subject as a sequence of three-dimensional images, each one of the sequence of three-dimensional images may be fitted to at least one previous one of the sequence of three-dimensional images.

[0026] In another aspect, a computer program product disclosed herein may include computer executable code which may be embodied on a computer readable medium that, when executing on one or more computing devices, performs the steps of providing a first set of three-dimensional data from a subject, scanning the subject to acquire one or more additional three-dimensional images, test fitting each one of the one or more additional three-dimensional images to the set of three dimensional data, and upon a successful fit, adding the one or more additional three-dimensional images to the set of three-dimensional data.

[0027] The computer program product may further include code to perform the steps of fitting each new one of the one or more additional three-dimensional images to one another to provide a second set of three-dimensional data, and upon a successful fit, adding the second set of three-dimensional data to the first set of three-dimensional data.

[0028] In the computer program product, the three-dimensional data may include three-dimensional surface data. Alternatively, in the computer program product, the one or more additional three-dimensional images may include surface data derived from two-dimensional image sets of the subject. The set of three-dimensional data may include three-dimensional surface data acquired from a subject as a sequence of three-dimensional images, each one of the sequence of three-dimensional images may be fitted to at least one previous one of the sequence of three-dimensional images.

[0029] In another aspect, a method disclosed herein may include providing a first set of three-dimensional data from a subject, scanning the subject to acquire one or more additional three-dimensional images, test fitting each one of the one or more additional

three-dimensional images to the first set of three-dimensional data in real time, and providing real time visual feedback to a user relating to the test fitting.

[0030] In the method, providing real time visual feedback may include superimposing the first set of three-dimensional data and the one or more additional three-dimensional images on a video image of the subject when a test fit is successful. Providing
5 real time visual feedback may include displaying one or more navigation cues when a test fit is unsuccessful. When the test fitting is unsuccessful, the method may further include fitting each new one of the one or more additional three-dimensional images to one another to provide a second set of three-dimensional data. Upon a successful fit, the
10 method may further include adding the second set of three-dimensional data to the first set of three-dimensional data. The three-dimensional data may include three-dimensional surface data. The one or more additional three-dimensional images may include surface data derived from two-dimensional image sets of the subject. Additionally, the set of three-dimensional data may include three-dimensional surface data acquired from a
15 subject as a sequence of three-dimensional images, each one of the sequence of three-dimensional images fitted to at least one previous one of the sequence of three-dimensional images.

[0031] In another aspect, a system disclosed herein may include a storage means for providing a first set of three-dimensional data from a subject, an acquisition means for
20 scanning the subject to acquire one or more additional three-dimensional images, a computing means for test fitting each one of the one or more additional three-dimensional images to the first set of three-dimensional data in real time, and a display means for providing real time visual feedback to a user relating to the test fitting.

[0032] In the system, providing real time visual feedback may include
25 superimposing the first set of three-dimensional data and the one or more additional three-dimensional images on a video image of the subject when a test fit is successful. Alternatively, providing real time visual feedback may include displaying one or more navigation cues when a test fit is unsuccessful. The computing means may include means for, when the test fitting is unsuccessful, fitting each new one of the one or more
30 additional three-dimensional images to one another to provide a second set of three-dimensional data, and upon a successful fit, adding the second set of three-dimensional data to the first set of three-dimensional data. Alternatively, the three-dimensional data

may include three-dimensional surface data. The one or more additional three-dimensional images may include surface data derived from two-dimensional image sets of the subject. The set of three-dimensional data may include three-dimensional surface data acquired from a subject as a sequence of three-dimensional images, each one of the sequence of three-dimensional images fitted to at least one previous one of the sequence of three-dimensional images.

[0033] In another aspect, a computer program product disclosed herein may include computer executable code embodied on a computer readable medium that, when executing on one or more computing devices, performs the steps of providing a first set of three-dimensional data from a subject, scanning the subject to acquire one or more additional three-dimensional images, test fitting each one of the one or more additional three-dimensional images to the first set of three-dimensional data in real time, and providing real time visual feedback to a user relating to the test fitting.

[0034] In the computer program product, providing real time visual feedback may include superimposing the first set of three-dimensional data and the one or more additional three-dimensional images on a video image of the subject when a test fit is successful. Alternatively, providing real time visual feedback may include displaying one or more navigation cues when a test fit is unsuccessful. The computer program product may further include computer code that performs the steps of, when the test fitting is unsuccessful, fitting each new one of the one or more additional three-dimensional images to one another to provide a second set of three-dimensional data, and upon a successful fit, adding the second set of three-dimensional data to the first set of three-dimensional data. The three-dimensional data may include three-dimensional surface data. The one or more additional three-dimensional images may include surface data derived from two-dimensional image sets of the subject. The set of three-dimensional data may include three-dimensional surface data acquired from a subject as a sequence of three-dimensional images, each one of the sequence of three-dimensional images fitted to at least one previous one of the sequence of three-dimensional images.

BRIEF DESCRIPTION OF THE FIGURES

[0035] The invention and the following detailed description of certain embodiments thereof may be understood by reference to the following figures.

[0036] Fig. 1 shows an image capture system.

[0037] Fig. 2 shows a process for operating an image capture system.

[0038] Fig. 3 shows a process for operating an image capture system.

[0039] Fig. 4 depicts a view of a user interface for an image capture system.

5 [0040] Fig. 5 depicts a view of a user interface for an image capture system in an acquisition mode.

[0041] Fig. 6 depicts a view of a user interface for an image capture system in an acquisition mode.

10 [0042] Fig. 7 depicts a view of a user interface for an image capture system in a recover mode.

[0043] Fig. 8 depicts a view of a user interface for an image capture system in a recover mode.

[0044] Fig. 9 depicts a view of a user interface for an image capture system after reacquiring a scan.

15 [0045] Fig. 10 is a three-dimensional view of a first component of a scanning subject.

[0046] Fig. 11 is a three-dimensional view of a first and second component of a scanning subject.

20 [0047] Fig. 12 is a three-dimensional view of a second component of a scanning subject.

DETAILED DESCRIPTION

[0048] Described below is a technique for providing real time visual feedback to a user operating an incremental three-dimensional scanning device. However, it will be appreciated that the inventive concepts disclosed herein are not limited to such applications, and may be usefully employed in a number of imaging applications. For example, while visible light, video-based systems are described in some detail, the techniques described herein may be usefully applied to other imaging modalities based on, for example, x-rays, infrared or ultraviolet light, ultrasound, laser light, and so forth. As another example, the systems described herein may be usefully employed in two-dimensional imaging systems or other applications where user feedback and correction might be augmented by real time visual feedback. As a further example, the systems and

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methods described herein may be employed in an automated, robotic system to automate rescanning of regions of a subject where incremental image data has been lost or degrades in quality below a predetermined threshold. All such variations and alternative embodiments as would be apparent to one of ordinary skill in the art are intended to fall within the scope of this disclosure.

[0049] In the following description, the term “image” generally refers to a set of two-dimensional pixels forming a two-dimensional view of a subject within an image plane. The term “image set” generally refers to a set of related two dimensional images that might be resolved into three-dimensional data. The term “point cloud” generally refers to a set of three-dimensional points forming a three-dimensional view of the subject reconstructed from a number of two-dimensional views. In a three-dimensional image capture system, a number of such point clouds may also be registered and combined into an aggregate point cloud constructed from images captured by a moving camera. Thus it will be understood that pixels generally refer to two-dimensional data and points generally refer to three-dimensional data, unless another meaning is specifically indicated or clear from the context.

[0050] Fig. 1 shows an image capture system. In general, the system 100 may include a scanner 102 that captures images of a subject 104 within an image plane 106, and forwards the images to a computer 108, which may include a display 110 and one or more user input devices such as a mouse 112 or a keyboard 114.

[0051] The scanner 102 may include any camera or camera system suitable for capturing images from which a three-dimensional point cloud may be recovered. For example, the camera 102 may employ a multi-aperture system as disclosed, for example, in U.S. Pat. Pub. No. 20040155975 to Hart et al., the entire contents of which is incorporated herein by reference. While Hart discloses one multi-aperture system, it will be appreciated that any multi-aperture system suitable for reconstructing a three-dimensional point cloud from a number of two-dimensional images may similarly be employed. In one multi-aperture embodiment, the scanner 102 may include a plurality of apertures including a center aperture positioned along a center optical axis of a lens and any associated imaging hardware. The scanner 102 may also, or instead, include a stereoscopic, triscopic or other multi-camera or other configuration in which a number of cameras or optical paths are maintained in fixed relation to one another to obtain two-

dimensional images of an object from a number of slightly different perspectives. The scanner 102 may include suitable processing for deriving a three-dimensional point cloud from an image set or a number of image sets, or each two-dimensional image set may be transmitted to an external processor such as contained in the computer 108 described
5 below. In other embodiments, the scanner 102 may employ structured light, laser scanning, direct ranging, or any other technology suitable for acquiring three-dimensional data, or two-dimensional data that can be resolved into three-dimensional data. In one embodiment, the scanner 102 is a handheld, freely positionable probe having at least one user input device, such as a button, lever, dial, thumb wheel, switch, or the like, for user
10 control of the image capture system 100 such as starting and stopping scans.

[0052] Although not shown in Fig. 1, it will be appreciated that a number of supplemental lighting systems may be usefully employed during image capture. For example, environmental illumination may be enhanced with one or more spotlights illuminating the subject 104 to speed image acquisition and improve depth of field (or
15 spatial resolution depth). The scanner 102 may also, or instead, include a strobe, flash, or other light source to supplement illumination of the subject 104 during image acquisition.

[0053] The subject 104 may be any object, collection of objects, portion of an object, or other subject matter. While illustrated in Fig. 1 as a simple geometric form, the subject 104 may include much more complex surfaces, and any number of separate
20 elements. For example, in a dental imaging application, the subject 104 may include a tooth, a quadrant of teeth, or a full collection of teeth including two opposing arches from which a virtual dental impression is desired. The subject 104 may also, or instead, include a dental prosthesis such as an inlay, a crown, or any other dental prosthesis, implant, or the like. The subject 104 may include a dental model, such as a plaster cast, wax-up,
25 impression, or negative impression of a tooth, teeth, soft tissue, or some combination of these. In certain instances, an optical or textured imaging agent may be applied to surfaces of the subject 104 to improve capture of three dimensional points. In other embodiments, the subject 104 may be a human head, or a portion thereof, from which a three-dimensional model is desired for custom fitting of a hearing aid, eyeglasses, goggles, or
30 the like. In other embodiments, the subject 104 may be a physical model of an object for use in digital animation, such as a miniature, physical model for use in a three-dimensional digital animation process. From the preceding examples, it will be apparent that a system

using the techniques described herein may be suitably adapted to a wide range of applications for relatively short range, high resolution three-dimensional image acquisition. However, one skilled in the art will appreciate that suitable adaptations to the image capture system 100 may be made for a variety of other three-dimensional imaging applications based upon multi-aperture or multi-camera systems, as well as other three-dimensional imaging systems and technologies, and all such variations are intended to fall within the scope of this disclosure.

[0054] The image plane 106 may include a two-dimensional field of view of the camera 102. It will be appreciated that the term "image plane" as used in this paragraph, refers to a plane in the imaging environment rather than a plane within an optical sensor (such as film or sensors) where an image is captured. Though illustrated as a rectangle the image plane 106 may, for example, form a square, a circle, or any other geometry provided by the scanner 102. In general, the scanner 102 will have a depth of field or range of depth resolution for image acquisition within the image plane 106 determined by the physical construction of the scanner 102 and environmental conditions such as ambient light.

[0055] The computer 108 may be, for example, a personal computer or other processing device. In one embodiment, the computer 108 includes a personal computer with a dual 2.8GHz Opteron central processing unit, 2 gigabytes of random access memory, a TYAN Thunder K8WE motherboard, and a 250 gigabyte, 10,000 rpm hard drive. This system may be operated to capture approximately 1,500 points per image set in real time using the techniques described herein, and store an aggregated point cloud of over one million points. More generally, processing capabilities of the computer 108 may vary according to the size of the subject 104, the speed of image acquisition, and the desired spatial resolution of three-dimensional points. The computer 108 may also include peripheral devices such as a keyboard 114, display 110, and mouse 112 for user interaction with the camera system 100. The display 110 may be a touch screen display capable of receiving user input through direct, physical interaction with the display 110.

[0056] Communications between the computer 108 and the scanner 102 may use any suitable communications link including, for example, a wired connection or a wireless connection based upon, for example, IEEE 802.11 (also known as wireless Ethernet), Bluetooth, or any other suitable wireless standard using, e.g., a radio frequency, infrared,

or other wireless communication medium. In medical imaging or other sensitive applications, wireless image transmission from the scanner 102 to the computer 108 may be secured. The computer 108 may generate control signals to the scanner 102 which, in addition to image acquisition commands, may include conventional camera controls such as focus or zoom.

[0057] In an example of general operation of a three-dimensional image capture system 100, the scanner 102 may acquire two-dimensional image sets while the scanner 102 is passed over a surface of the subject. The two-dimensional image sets may be forwarded to the computer 108 for derivation of three-dimensional point clouds. The three-dimensional data for each newly acquired two-dimensional image set may be derived and fitted or "stitched" to existing three-dimensional data using a number of different techniques. One useful example of such a technique is described in commonly-owned U.S. App. No. 11/270,135, filed on November 9, 2005, the entire contents of which is incorporated herein by reference. However, it will be appreciated that this example is not limiting, and that the principles described herein may be applied to a wide range of three-dimensional image capture systems.

[0058] From time to time in such incremental data acquisition systems, the fitting or stitch may fail for reasons described in greater detail below. In such situations, a user may be notified through visual feedback that a recover mode has been entered. In the recover mode, the system 100 may seek to reacquire the previous scan by test fitting new scan data to previously acquired data, and providing visual feedback to a user to assist in navigating back to a scan location on the subject where the re-acquisition is being attempted. In a related landing mode, a user may attempt to initiate a new scan registered or connected to an existing three-dimensional model. Similar visual feedback tools may be provided to guide a user to an appropriate scan location, and notify a user when the scan has been reacquired. These techniques are now described in greater detail, beginning with a detailed description of the processes for a stitch recovery and a landing, described with reference to Figs. 2 and 3. The corresponding user interface is described in greater detail with reference to Figs. 4 et seq.

[0059] Fig. 2 depicts a process for three-dimensional scanning. The process 200 may begin 202 by acquiring a candidate frame from a sensor, such as an image set from the scanner 102 described above, as shown in step 204. During this phase of the process

200, a video image such as a video image of the subject from a position or point of view of the scanning device, may be rendered on the display 110. This view may assist a user of the image capture system 100 in positioning the scanner 102 relative to the subject 104. In such embodiments, the view will continuously shift as the user moves the scanner 102
5 about the subject 104, always maintaining a visual display of the point of view of the scanner 102 on the subject 104. In other embodiments, the subject 104 may be displayed in a static, non-moving orientation within the display 110, while a visual cue may be provided within the user interface as to a position and orientation of the scanner.

[0060] As shown in step 206, three-dimensional data may be derived from the
10 candidate frame. Stated alternatively, the two-dimensional data, such as an image set, may be converted into three-dimensional data or a three-dimensional image. As used herein, the terms three-dimensional data, three-dimensional representation, three-dimensional model, three-dimensional image, three-dimensional surface map, and the like are used interchangeably to describe the three-dimensional representation assembled from
15 incremental scan results captured by the scanning device, or a portion thereof, unless a different meaning to these phrases is explicitly stated or clear from the context.

[0061] A number of techniques may be employed to calculate three-dimensional
point values from the candidate frame. For example, stereoscopic matching techniques include probabilistic measures of image similarity such as mutual information or
20 correlation of pixel intensities. Other types of suitable derivations include, for example, optical flow using spatial and/or temporal gradients. In a stereoscopic camera configuration, for example, the image set typically includes two images. However, three or more images may be included in an image set using a multi-aperture camera configuration, such as a three or four aperture camera, or similar camera systems. It
25 should also be appreciated that each set of three-dimensional data need not include all, or even most, of the points that might be recovered from the candidate frame. The point cloud may, for example, be calculated from a sparse mesh of a candidate frame image set (relative to the pixel density of the original image set). This arrangement may be particularly suitable for accelerating processing in real time imaging applications. The
30 sparse mesh may be obtained from any subset of pixels in the image set. Regular rectangular grids, for example, are particularly suited to hierarchical methods using subsampling of images. However, other meshes may be used, such as triangular, square,

quadrilateral, or the like, to select regularly or irregularly spaced pixels within the image set for derivation of a point cloud. In some embodiments, a relatively sparse subset of pixel data may be employed for real time rendering and feedback, while a denser or complete version of pixel data is stored for use in a more computationally intensive post-processing step, which might yield greater accuracy and density.

[0062] It will be appreciated that three-dimensional surface data consisting of a point cloud of three-dimensional points is one type of three-dimensional data that may be readily derived from two-dimensional image sets. However, other forms of three-dimensional data may also be obtained using various techniques known in the art. This may include, for example, three-dimensional surface data consisting of a three-dimensional map of interconnected polygons, such as triangles or other regular or irregular polygons, or volumetric three-dimensional data reflecting interior as well as surface points of the subject. All such variations are intended to fall within the scope of this disclosure.

[0063] As shown in step 208, once three-dimensional data has been derived, it may be evaluated to determine whether the derivation was successful. In general, this tests the recovery of incremental data for internal consistency, rather than by comparison to the full three-dimensional model reconstructed from incremental scans. For example, movement of the scanner laterally off the subject may result in an insufficient amount of derived data, or a complete lack of derived data. Similarly, with certain imaging technologies, rapid scanner motion may cause blurring in acquired two-dimensional image sets that interferes with conversion to three-dimensional data. This motion blur may render an image set unsuitable for derivation of three-dimensional data, or reduce the quality of derived three-dimensional data. Other scanner motions, such as movement outside the scanner's physical scanning range (again, this may be technology dependent), such as too close or too far away from the subject, may result in low quality or insufficient derived three-dimensional data. Other imaging artifacts may similarly render a particular image set unsuitable (or less suitable) for deriving three-dimensional data, such as lack of texture on a surface of the subject, poor optical focus or resolution, illumination anomalies such as specularities or shadows, distortion and aberration artifacts in components in the optical path, and so forth. Other factors such as physical properties of the subject may cause deterioration of data acquisition. For example, highly reflective surfaces may interfere with three-dimensional conversion. Various quantitative measures of success

may be employed, and in various embodiments, numerical thresholds may be user-specified according to a desired accuracy of the resulting three-dimensional model. If it is determined that the two-dimensional data (or other sensor data, as discussed generally above) has been successfully converted into three-dimensional data, then the process 200
5 may proceed to step 210. If it is determined that the two-dimensional data has not been successfully converted into three-dimensional data, then the process may proceed to step 224.

[0064] In step 210, a determination may be made as to whether there is a reference frame or image, such as a previously acquired image set or derived three-dimensional data. In one embodiment, a reference frame will always be available, except
10 when the currently acquired frame is the first frame in a sequence. In various embodiments, different data types may be employed for comparison of incremental data, such as two-dimensional source data, converted three-dimensional data points, and so forth. However, in step 210, the process 200 is only testing for the existence of a
15 reference frame, not the quality of the image frame. If a reference frame is present, the process 200 may proceed to step 212. If a reference frame is not present, the process 200 may proceed to step 220.

[0065] As shown in step 212, the incremental three-dimensional image data may be fitted or stitched to the existing three-dimensional model. In one embodiment, this
20 process is performed by deriving scanner motion between positions or points of view for successive image captures. However, other techniques may be employed, such as direct fitting of features from the new three-dimensional image to the previously acquired three-dimensional model. All such techniques that might usefully be employed to register new three-dimensional data to existing three-dimensional data are intended to fall within the
25 scope of this disclosure. Once a fit has been attempted in step 212, the process 200 may proceed to step 214.

[0066] In step 214, the fit obtained in step 212, which may be considered a test fit until accepted for addition to the previously acquired three-dimensional data, may be tested for success. This test fitting may employ any number of quantitative techniques for
30 comparing some or all of the newly acquired three-dimensional data to the previously acquired three-dimensional data. Tests such as correlation or feature matching may be employed to obtain a confidence score or other objective measure of fitting. Further,

where a quantitative limit or range is employed to measure a successful fit, the limit or range may be user-controlled either by explicit selection of a numeric fit parameter or by selection of a qualitative fit parameter (e.g., tight, moderate, loose, etc.). User evaluation and feedback may also be incorporated into a fitting algorithm, which may, for example, be in response to a frequently recurring failure to fit, or to a specific failure event. It will be appreciated that, while a single test fit is shown in step 214, any number of test fits may be performed during this step. In this manner, a number of sequentially acquired three-dimensional images used in whole or in part to constitute the three-dimensional model may each be test fitted to the newly acquired three-dimensional data. This approach may have particular utility where test fitting employs two-dimensional image set data instead of, or in addition to, any three-dimensional data derived therefrom.

[0067] In one example embodiment, a number of different reference frames (also referred to herein as reference images) may be selected for a test fit. The number of reference frames may be selected using various criteria. For example, reference frames may be selected according to temporal proximity to the new incremental data. That is, a group of most recent image sets or three-dimensional data sets may be employed for test fitting. As another example, reference frames may be selected according to spatial proximity to the new incremental data. That is, a group of image sets or three-dimensional data sets that are physically closest to the last known point on the subject may be used. Other techniques may be suitably employed for selecting candidate reference frames, either alone or in combination, including image entropy, data density, data quantity, and/or scanning parameters (such as focal distance or location within field of view). In one embodiment reference frames may be selected from a beginning of the sequence of incremental three-dimensional images used to create the three-dimensional model, such that a user may attempt reacquisition from where the original scan was initiated. In one embodiment, reference frames may be selected for an end of the sequence of incremental three-dimensional images used to create the three-dimensional model, such that a user may attempt reacquisition from where the original scan was lost. In one embodiment, a user may specifically select a point or region on the three-dimensional model for test fitting. This user selection may be used to derive a pool of candidate frames based upon the techniques described above. Manual selection will be discussed in greater detail with reference to the stitch recover mode in Fig. 3. Generally, the manual selection may be

achieved through operation of the user interface to select one or more points on the existing three-dimensional model.

[0068] If the new three-dimensional data is successfully fitted to the existing three-dimensional data, then the process may proceed to step 216. If the new three-dimensional data is not successfully fitted to the existing three-dimensional data, then the process may proceed to step 226.

[0069] As shown in step 216, new or incremental three-dimensional data may be added to the three-dimensional model. In one embodiment using camera motion estimation, this step may include a rigid transformation of the incremental three-dimensional data to the coordinate system of the three-dimensional model, as depicted in step 218. However, it will be appreciated that any suitable technique for registering new three-dimensional data to existing three-dimensional data may be usefully employed in step 216, and the choice of a particular technique may vary according to the scanning technology and/or sensor data of a particular image capture system.

[0070] As shown in step 220, the new or incremental three-dimensional data may next be selected as a candidate reference frame for subsequent acquisitions of one or more sequential data sets from the scanner 102. At this point, the process 200 may proceed to step 222.

[0071] As shown in step 222, a determination may be made as to whether the scan is finished. This may include, for example, user input received through the input device 116 on the scanner 102, through the mouse 112, the keyboard 114, or, for a touch screen embodiment, through the display 110. It will be appreciated that in certain embodiments, the process 200 may be stopped at any point upon receipt of such a user input. If it is determined that the scan is finished, the process 200 may proceed to step 228 and end. If it is determined that the scan is not finished, the process may return to step 204 where a new candidate frame may be acquired from the scanner 102. In a subsequent pass through the following processing steps, the "newly acquired" three-dimensional data may be used as a reference frame for subsequent fitting steps.

[0072] As shown in step 224, when a derivation of three-dimensional data is unsuccessful (which may also be understood as a species of unsuccessful fitting, discussed with reference to step 214), the process 200 may proceed to determine whether at least one reference frame exists. If no reference frame exists, then the process may proceed to step

222, and subsequently to step 204 where a new candidate frame may be acquired. If a reference frame does exist, the process may proceed to step 226, which more generally represents a stitch recovery mode 226.

[0073] In the stitch recover mode 226 the process 200 may attempt to reacquire or resume a scan by test fitting each newly acquired data set to some portion of the three-dimensional model. During this phase, the process may optionally begin assembling a new three-dimensional model from sequential, incremental three-dimensional data sets. In this manner, once the original scan is reacquired with a successful fit to the original three-dimensional model, all of the three-dimensional data acquired during the recover mode may be immediately registered to the original three-dimensional model. Although not explicitly depicted, it will be appreciated that in certain embodiments a user may manually select the recover mode 226, such as where a scan is purposely interrupted by the user. It will be noted that the terms "reacquire" "resume" and are used interchangeably herein to refer to either scans that have been lost due to signal degradation or scans that have been explicitly stopped through user operation.

[0074] In one aspect, the process 200 described herein, and systems embodying this process, include two operating modes. In an acquisition mode, normal acquisition, conversion to three-dimensional data, and test fitting to the three-dimensional model may take place, as described generally above. In a recover mode, or in the landing mode described below, newly acquired incremental data is test fitted to the three-dimensional model, but may also be fitted to a second model so that useful three-dimensional data may continue to be acquired during the recover mode, which is described in greater detail with reference to Fig. 3.

[0075] In another aspect, visual cues or indicators may be provided to a user through the monitor 110 with respect to whether the image capture system 100 is in a recover mode or a normal acquisition mode. For example, in the normal acquisition mode, the display 110 may show a video image of the subject 104, as viewed from the scanner 102. The computer may render the three-dimensional model, which may be a three-dimensional point cloud of surface data acquired for the subject 104, superimposed on the video image. The surface data may be rendered with shading, or a wireframe or other visual techniques to visualize the three-dimensional shape of the surface data. In this mode, the user experience may be one of virtually spray painting a surface of the subject

104 with points or other surface rendering (such as polygons) that reflects the acquired three-dimensional model. In the recover (or landing) mode, the computer may render the video image of the subject 104 as viewed from the scanner 102; however, the computer 108 may remove or stop rendering the three-dimensional model. This may provide
5 immediate user feedback that acquisition has been lost. In addition, the computer may render a previous video image of the subject 104 from a previous position of the scanner 102, in particular, a previous position or location on the subject 104 selected as a reference frame for re-acquisition, superimposed on the current video image. The superimposed video image from the previous location may be rendered in a different color, or with
10 different opacity to provide a visual offset from the current video image. By superimposing the previous video image, as centered on the location where re-acquisition is being algorithmically test fitted, the system can provide feedback to a user that will assist the user in re-centering the scanner 102 at the desired position on the subject 104. Thus the user may be provided with visual cues as to the acquisition mode and the recover
15 mode. The recover mode, in particular, may provide visual feedback to assist a user in re-acquiring three-dimensional data acquisition for the original three-dimensional model. It will be appreciated that other techniques may be employed, such as directional arrows or verbal cues, to coach a user back to an appropriate location relative to the subject 104. Using the computer 108 described above, the visual cues or indicators may be rendered at
20 a video rate consistent with image capture, so that the system provides real time visual feedback to a user.

[0076] The recover mode will now be described in greater detail.

[0077] As shown in Fig. 3, a recover mode process 300 may begin by entering a stitch recover mode 302. This may occur through any of the circumstances described
25 above with reference to Fig. 2, including manual selection of the recover mode by a user.

[0078] As shown in step 304, a suitable reference frame may be selected. This may include one or more reference frames, which may be selected using any of the techniques described above with reference to step 214 of Fig. 2. It will be appreciated that the reference frames for the recover mode are reference frames selected from the three-
30 dimensional model assembled during the acquisition mode of Fig. 2. After one or more reference frames have been selected, the process 300 may proceed to step 306.

[0079] As shown in step 306, a reference frame may be assigned for display. This may be a video image corresponding to one of the reference frames selected in step 304, as well as any corresponding two-dimensional or three-dimensional data suitable for use in display thereof. More generally, the content of the reference frame may vary
5 according to a particular imaging technology and/or techniques used to fit incremental data.

[0080] As shown in step 308, a new frame of data may be acquired from the scanner 102, including a current video image.

[0081] As shown in step 310, the current video image may be displayed on the
10 monitor 110 superimposed on a reference video image selected in step 306. The images may be superimposed on the monitor 110 as a visual indicator for the user. The reference video image may be superimposed on a current video image captured from a current position of the scanner, with each video image distinguished using a visual cue such as color, opacity, or the like. This superposition may indicate to a user both where the
15 scanner is currently positioned and where the scanner should be positioned in order to reacquire a scan, so that a user may manipulate the scanner to a suitable position for recovery.

[0082] As shown in step 312, three-dimensional data may be derived from the new frame of data, as described for example with reference to step 206 of Fig. 2.

[0083] As shown in step 314, success of the derivation may be evaluated, as
20 described for example with reference to step 208 of Fig. 2. If the derivation is successful, the process 300 may proceed to step 316. If the derivation is unsuccessful, the process 300 may proceed to step 308 where a new frame of data may be acquired.

[0084] As shown in step 316, the newly derived three-dimensional data may be
25 test fitted to the reference frame(s) from the acquisition mode, using techniques such as those described above with reference to step 212 of Fig. 2.

[0085] As shown in step 318, the test fit may be evaluated for success. If new data is successfully test fitted to the reference frame(s), the process 300 may proceed to step 320 and exit the recover mode. If the new data is not successfully test fitted to the
30 reference frame(s), then the process 300 may return to step 308 where a new frame of data may be acquired from the scanner 102. At this point, the newly derived three-dimensional data may be fitted to three-dimensional data previously derived in the recover mode. In

this manner, a new three-dimensional model may be created within the recover mode. When a successful test fit is made to the original (acquisition mode) three-dimensional model, the entire new three-dimensional model, or a selected portion thereof, may be registered to the original three-dimensional model using a transformation based upon the successfully fitted frames or three-dimensional images.

[0086] It will be appreciated that the above steps may be varied, such as by using optical flow techniques to determine correspondence between pixels in adjacent image sets in step 212, and that the order of steps may be changed, such as by providing manual inputs to stop, start, or restart (recover) a scan that override the sequence of steps depicted in Fig. 2, or by performing derivation and test-fitting steps together. As another example, the reference frame selection process may be automated by, for example, capturing a scan from a region of a subject where data has been previously acquired, and registering the newly captured scan to the acquired three-dimensional model. At this point, selection of subsequent reference frames for test fitting and/or fitting may be based upon image sets captured from around the registered location of the newly acquired data. Additionally, certain steps may be added or omitted, or multiple steps may be combined. Similarly, in certain computing environments some steps may be performed in parallel (such as test fitting to multiple reference frames), or certain steps may be distributed among more than one process or processor. In one variation, the scanner may remain in a fixed position, and three-dimensional image capture may be performed by moving the subject within an image plane of the scanner. All such variations and modifications are intended to fall within the scope of this disclosure.

[0087] It will be appreciated that the above process may be realized in hardware, software, or any combination of these suitable for the three-dimensional imaging techniques described herein. The process may be realized in one or more microprocessors, microcontrollers, embedded microcontrollers, programmable digital signal processors or other programmable device, along with internal and/or external memory. The process may also, or instead, include an application specific integrated circuit, a programmable gate array, programmable array logic, or any other device that may be configured to process electronic signals. It will further be appreciated that the process may be realized as computer executable code created using a structured programming language such as C, an object oriented programming language such as C++, or any other high-level or low-

level programming language (including assembly languages, hardware description languages, and database programming languages and technologies) that may be stored, compiled or interpreted to run on one of the above devices, as well as heterogeneous combinations of processors, processor architectures, or combinations of different hardware and software. At the same time, processing may be distributed across the camera and/or computer in a number of ways, or all of the functionality may be integrated into a dedicated, standalone image capture device. All such permutations and combinations are intended to fall within the scope of the present disclosure.

[0088] It will also be appreciated that means for performing the steps associated with the processes described above with reference to Figs. 2 and 3 may include any suitable components of the image capture system 100 described above with reference to Fig. 1, along with any software and/or hardware suitable for controlling operation of same. The following figures describe the systems and methods disclosed herein with reference to a user interface that might be rendered, for example, within the display 110 of the image capture system 100 of Fig. 1.

[0089] Fig. 4 depicts a view of a user interface for an image capture system. The user interface 400 may include a window 402 rendered on a monitor such as the display 110 of Fig. 1. Within the window 402, a video image may be displayed including a field of view of a scanner, such as the scanner 102 of Fig. 1. Within the field of view, a subject 404, such as the subject 104 of Fig. 1 may be displayed, along with one or more user controls 406. Fig. 4 specifically depicts the user interface before any image acquisition steps. As such, there is no rendering of an acquired three-dimensional model or any superposition of reference images onto the current video image.

[0090] The user controls 406 may generally include one or more controls for manipulating the three-dimensional model (e.g., rotating, scaling, panning, and the like), selecting a landing target, controlling operation of the image capture system (e.g., starting or stopping an acquisition), and so forth. The one or more controls may be manipulated, for example, using any of the user input devices described above with reference to Fig. 1, including physical interaction with the monitor, where the display 110 includes a touch screen.

[0091] Fig. 5 depicts a view of a user interface for an image capture system, such as described above with reference to Fig. 4, in acquisition mode. In this view, an initial

acquisition of a three-dimensional image 502 consisting of a set of three-dimensional points has occurred. The three-dimensional image, a first element of a three-dimensional model, may be rendered within the user interface as superimposed on the video image of the subject 104, as depicted by a number of X's in Fig. 5. It will be appreciated that, while shown as X's for purposes of distinguishing from subsequent three-dimensional images, these points may, in practice, be rendered simply as points or pixels within the user interface. In such a rendering, techniques such as shading of pixels in accordance with simulated lighting may be used, or any other techniques that provide visual cues to contours of the captured three-dimensional points so that a human viewer can more readily interpret the three-dimensional shape captured by the scan.

[0092] Fig. 6 depicts a view of a user interface for an image capture system, such as described above with reference to Figs. 4-5, in acquisition mode. In this view, a second acquisition of a three-dimensional image 602 consisting of a set of three-dimensional points has occurred. The second set of three-dimensional points in this view have been successfully fitted to the first three-dimensional image 502 and added to a three-dimensional model. It will be appreciated that, while shown as O's for purposes of distinguishing from other three-dimensional images, these points may, in practice, be rendered simply as points or pixels within the user interface. Over a number of successive acquisitions and fits, a large three-dimensional model may be acquired, and the aggregate point cloud may be rendered with shading to simulate a three-dimensional view of the point cloud, all of which may be superimposed on a current video image of the subject.

[0093] Fig. 7 depicts a view of a user interface for an image capture system, such as described above with reference to Figs. 4-6, in a recover mode. In this view, scan acquisition has been lost, such as due to a failure to derive adequate three-dimensional data or a failure to fit a new three-dimensional image to a three-dimensional model. To indicate to a user that the system is in a recover mode, a number of visual cues may be provided. For example, as depicted in Fig. 7, three-dimensional points 502, 602 for the model may be omitted. As another example, a previous video image 702 of the subject may be superimposed on a current video image 404 of the subject. Each image 702, 404 may be rendered in a different color or opacity to indicate its nature. Navigation information is provided in this format. For example, in order to align the current video image 404 with the previous video image 702, a user may move the scanner to the right,

thus shifting the current video image 404 of the subject to the left and into alignment with the previous video image 702. The previous video image 702 may be selected as described generally above with reference to Fig. 3 according to its relationship to one or more reference frames for re-acquisition of a scan. In general, when the previous video image 702 and the current video image are aligned (including scaling and rotation), a newly acquired image set or three-dimensional image should successfully fit to one of the reference frames, or have an elevated probability of successfully fitting to one of the reference frames. It will be appreciated that Fig. 7 may also, or instead, depict a landing mode in which a user seeks to reacquire a scan for a stored three-dimensional model.

[0094] Fig. 8 depicts a view of a user interface for an image capture system, such as described above with reference to Figs. 4-7, in a recover mode. Fig. 8 provides a general comparison to Fig. 7, in which a user has manipulated a scanner to more closely align the current video image 404 to the previous video image 702. It will be appreciated that Fig. 8 may also, or instead, depict a landing mode in which a user seeks to reacquire a scan for a stored three-dimensional model.

[0095] Fig. 9 depicts a view of a user interface for an image capture system, such as described above with reference to Figs. 4-8, after reacquiring a scan. In this figure, a user has realigned the current video image 404 so that a newly acquired three-dimensional image could be successfully fitted to one of the reference images. Upon thus exiting the recover mode, the system returns to acquisition mode and begins acquiring additional three-dimensional data to add to the three-dimensional model. The point cloud 902 of the three-dimensional model, optionally including data acquired during the recover mode, is superimposed on the current video image 404 to communicate reacquisition to a user. This visualization also lets the user know where scanning has been performed and where additional scanning may be appropriate.

[0096] In other embodiments, a landing mode may be provided in which a user attempts to initiate a new scan registered or connected to an existing three-dimensional model. In the landing mode, the system may optionally create a supplemental three-dimensional model by fitting sequential frames to one another before a successful fit to the original three-dimensional model. In various embodiments, the landing mode may also be distinguished by a user's ability to select a point on the original three-dimensional model for re-acquisition of a scan.

[0097] In one aspect, the systems and methods described herein improve real time scanning operations by providing real time user feedback concerning loss and reacquisition of a scan. In another aspect, the systems and methods described herein may be employed in combination with stored three-dimensional models to enhance the functionality of an image capture system. A number of examples of such enhanced functionality are described below.

[0098] In one embodiment multiple scans of an object, including scans taken at different times, may be interpreted as a single scan. For example, in a dental application, a tooth surface may be scanned before and after a surface preparation for dental prosthetic. By starting the second, post-preparation scan, by reacquiring a scan of an unprepared tooth surface, the pre-scan and post-scan structure of the prepared surface may be combined into a single surface representation that encloses a space to be filled by the dental prosthetic.

[0099] In another embodiment, the user interface may be modified to permit reorientation of the scanner. This may be particularly useful in dental applications where a full dental arch scan might be most conveniently performed in two halves, with a user changing hands or scanner orientation around the midpoint of the arch. The scan could be deliberately interrupted, either by rapidly pulling the remote sensor away from the teeth to affect a stitch loss, or by pressing a "pause" button which may be any of the user input devices described above. At this point, a user may reorient the scan, including one or more reference images, by 180 degrees (or some other amount) within the user interface. This may rotate the system coordinates both for the purposes of display and image correlation in the stitch recovery mode. The operator may then rotate the scanner 180 degrees and attempt to recover a stitch using the recover mode described above. Once the stitch is recovered, the scan can proceed in the normal fashion to capture the remaining teeth.

[00100] In another embodiment, the user interface may be modified to permit selection of a point or region of a subject where reacquisition is to be attempted. The interface may, for example, display a point cloud for the three-dimensional model, which a user may rotate, translate, or scale within the interface. A control, which may be accessible using a mouse, keyboard, input device on the scanner, or through a touch screen display, may be provided to select a point or area for recovery of the scan. Using a selection process as described generally above, one or more reference frames may be

selected according to spatial or temporal proximity to the selected point, or according to any other suitable selection criteria. Reference frames, image sets, or three-dimensional data may then be selected from historical scan data according to the user selection. After completion of the selection process, a user may enter the recover mode and attempt to recover a lost stitch using the techniques described above.

[00101] In another embodiment, the techniques described herein may be applied to allow scanning of complex, articulated, closed, or otherwise difficult surfaces with a scanning device that acquires three-dimensional data as a continuous sequence of three-dimensional images. An application of this is illustrated below with reference to a pair of articulated dental arches.

[00102] Fig. 10 is a three-dimensional view of a first component of a scanning subject. The first component 1002 is viewed here in isolation, i.e., separate from a second component (not shown) that relates to the first component 1002. The first component 1002 in this example is a lower arch of human dentition, including surrounding soft tissue. The objective of a scan may be to acquire a surface map of lower and upper arches of dentition in occlusion. A scan of the arch using the image capture system 100 described above may include a continuous scan of exposed tooth surfaces from within a dental patient's mouth, choosing any convenient location 1004 as a starting point, and continuing in a scan path 1006 that passes over any exposed regions, and concluding at another location 1008 on the exterior surface. At this point, the scan may be manually terminated, or terminated through a manipulation such as moving the scanner rapidly outside of scanning range for the first component 1002. According to one of the embodiments of the recover mode described above, one or more reference frames may be established at the end of this scan. By scanning the exposed surfaces, a complete three-dimensional surface scan of the first component 1002, the lower arch, may be acquired. At the same time, a convenient reacquisition point may be established by forcing the system into recovery mode at a desired location. It will be appreciated that, while the scan path 1006 as illustrated passes below the arch, which would be appropriate for a dental model, a live scan of a patient's dentition captured intraorally would typically only pass over exposed surfaces.

[00103] Fig. 11 is a three-dimensional view of a first and second component of a scanning subject. The first component 1002 may be the lower arch of Fig. 10. The second

component 1102 may an upper arch in occlusion with the lower arch. Initiating a second scan from the recover mode, the scan may be reacquired around the location 1008 on the lower arch where the first scan was terminated. The scan may then be continued onto a location 1104 on the second component, where the scan may once again be terminated in
5 recover mode.

[00104] Fig. 12 is a three-dimensional view of a second component of a scanning subject. Fig. 12 depicts the second component 1102 in isolation. An arrow 1201 illustrates a third scan beginning at the location 1104 where the scan was previously terminated. The scan may be reacquired at this location 1104 from within the recover
10 mode. After stitch recovery, the scan may be completed of some or all of the second component 1102, ending at a location 1202 on the surface thereof. While depicted generally as encircling the second component 1102, it will be appreciated that a surface scan such as an intraoral scan of human dentition would typically only be possible for exposed surfaces. Scanning in this manner, a complete, three-dimensional surface map
15 may be obtained for the upper arch and lower arch in occlusion may be obtained from a series of intraoral scans of human dentition. This digital version of a dental bite registration may be useful in the fabrication of dental prosthetics involving one or more occluded tooth surfaces. More generally, this technique may be suitably adapted to a number of scanning environments. For example, this technique may be applied to obtain a
20 full three-dimensional surface scan of the interior and exterior of a closed box with a lid, or any other components that may be separated for access to interior regions.

[00105] While the technique described with reference to Figs. 10-12 takes advantage of a recover mode that selects reference frames from an area where stitching was lost, it will be appreciated that a number of adaptations and variations are possible.
25 For example, in one embodiment test fitting in the recover mode may be performed for the beginning and the end of a scan for which acquisition has been lost. Using such a recover mode, the technique may begin with a scan that spans two objects in fixed relationship, starting on the first object and ending on the second object. When the objects are separated, two separate recoveries may be initiated from the beginning and the end of the
30 initial scan. In another embodiment, a user interface that permits selection of a point for reference frames may be employed to permit a number of different scan orders provided at least one scan spans both objects in their desired orientation. In a further variation, any

number of separate objects may be sequentially or otherwise scanned in one or more orientations by straightforward extension of the techniques described above. Thus there is disclosed herein systems and methods for scanning a plurality of objects, which may be rigid bodies, in a fixed orientation relative to one another.

5 [00106] While the invention has been disclosed in connection with certain preferred embodiments, other embodiments will be recognized by those of ordinary skill in the art, and all such variations, modifications, and substitutions are intended to fall within the scope of this disclosure. Thus, the invention is to be understood with reference to the following claims, which are to be interpreted in the broadest sense allowable by law.

CLAIMS:

What is claimed is:

- 5 1. A method comprising:
 acquiring three-dimensional surface data from a subject as a sequence of three-
 dimensional images, each one of the sequence of three-dimensional images fitted to at
 least one previous one of the sequence of three-dimensional images;
 acquiring an image set for a next three-dimensional image;
10 when the image set can be converted into the next three-dimensional image and the
 next three-dimensional image can be fitted to the three-dimensional surface data,
 superimposing the three-dimensional surface data and the next three-dimensional image
 onto a two-dimensional image of the subject in a display; and
 when the image set cannot be converted into the next three-dimensional image or
15 the next three-dimensional image cannot be fitted to the three-dimensional surface data,
 entering a recover mode comprising the steps of:
 superimposing a current two-dimensional image of the subject onto a
 previous two-dimensional image of the subject in the display, the previous two-
 dimensional image representing a view of the subject from a position from which
20 one of the sequence of three-dimensional images was acquired, and the current
 two-dimensional image representing a view of the subject from a position from
 which the image set was acquired;
 acquiring at least one subsequent three-dimensional image; and
 test fitting the at least one subsequent three-dimensional image to one or
25 more of the sequence of three-dimensional images.
2. The method of claim 1 further comprising adding the next three-dimensional image
 to the three-dimensional surface data when the image set can be converted into the next
 three-dimensional image and the next three-dimensional image can be fit to the three-
30 dimensional surface data.

3. The method of claim 1 wherein the previous two-dimensional image and the current two-dimension image include video frames.

4. The method of claim 1 further comprising manually entering the recover mode in response to a user input.

5. The method of claim 1 further comprising automatically entering the recover mode in response to a detection of a lost acquisition.

6. The method of claim 5 wherein the detection of the lost acquisition includes a detection of a motion blur.

7. The method of claim 5 wherein the detection of the lost acquisition includes a detection of an insufficient recovery of three-dimensional data.

8. The method of claim 1 wherein the recover mode includes the step of highlighting a region on the subject for attempting a recovery.

9. The method of claim 8 wherein the region includes a plurality of previous ones of the sequence of three-dimensional images.

10. The method of claim 1 wherein the recover mode includes the step of test fitting the at least one subsequent three-dimensional image to one or more additional images acquired during the recover mode and test fitting includes selecting a reference image from the sequence of three-dimensional images based on a suitability for test fitting.

11. The method of claim 10 further comprising determining the suitability for test fitting based upon an entropy of image data in the previous three-dimensional image.

12. The method of claim 10 further comprising determining the suitability for test fitting based upon an amount of three-dimensional data in the previous three-dimensional image.

13. The method of claim 10 further comprising determining the suitability for test fitting based upon a placement of three-dimensional data within a range and a field of view of an imaging device.

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14. The method of claim 10 further comprising determining the suitability for test fitting based upon a temporal proximity of the at least one subsequent three-dimensional image to one or more of the sequence of three-dimensional images.

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15. The method of claim 10 further comprising determining the suitability for test fitting based upon a spatial proximity of the at least one subsequent three-dimensional image to one or more of the sequence of three-dimensional images.

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16. The method of claim 1 wherein the recover mode includes the step of manually selecting one or more of the sequence of three-dimensional images.

17. The method of claim 1 wherein the recover mode includes selecting a reference image from a beginning or an end of the sequence of three-dimensional images.

20

18. A method comprising:
providing three-dimensional surface data for a subject;
acquiring an image set for a three-dimensional image of the subject;
when the image set cannot be fitted to the three-dimensional surface data, entering a landing mode comprising the steps of:

25

superimposing a current two-dimensional image of the subject onto a previous two-dimensional image of the subject in the display, the current two-dimensional image representing a view of the subject from a position from which the image set was acquired, and the previous two-dimensional image representing a view of the subject from which at least a portion of the three-dimensional surface data was acquired;

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acquiring at least one subsequent three-dimensional image;

fitting the at least one subsequent three-dimensional image to a second three-dimensional surface reconstruction;

test fitting the at least one subsequent three-dimensional image to the three-dimensional surface data; and

5 when the image set can be fitted to the three-dimensional surface data, superimposing the three-dimensional surface data and the next three-dimensional image onto a two-dimensional image of the subject in a display and adding the second three-dimensional surface reconstruction to the three-dimensional surface data.

10 19. The method of claim 18 wherein the previous two-dimensional image and the current two-dimension image include video frames.

20. The method of claim 18 further comprising manually entering the landing mode in response to a user input.

15 21. The method of claim 18 further comprising, in the landing mode, highlighting a region on the subject for attempting a landing.

20 22. The method of claim 21 wherein the region includes a portion of the three-dimensional surface data.

23. The method of claim 18 wherein test fitting includes selecting a reference image from the three-dimensional surface data based on a suitability for test fitting.

25 24. The method of claim 23 wherein the suitability is based on an entropy of image data in the previous three-dimensional image.

25. The method of claim 23 wherein the suitability is based on an amount of three-dimensional data in the previous three-dimensional image.

30 26. The method of claim 23 wherein the suitability is based on a placement of three-dimensional data within a range and a field of view of an imaging device.

27. The method of claim 23 wherein the suitability is based on a spatial proximity of the image set to a portion of the three-dimensional surface data.

5 28. The method of claim 18 further comprising manually selecting a region of the three-dimensional surface data for test fitting.

29. The method of claim 18 wherein test fitting includes selecting a reference image from a beginning or an end of a sequence of three-dimensional images used to construct
10 the three-dimensional surface data.

30. The method of claim 18 wherein the previous two-dimensional image and the current two-dimension image include video frames.

15 31. The method of claim 18 further comprising manually entering the recover mode in response to a user input.

32. The method of claim 18 further comprising manually selecting a region from the three-dimensional surface data for test fitting.

20 33. A system comprising;
a scanning device that acquires three-dimensional surface data from a subject as a sequence of three-dimensional images, each one of the sequence of three-dimensional images fitted to at least one previous one of the sequence of three-dimensional images, the
25 device including an acquisition mode in which one or more additional three-dimensional images are acquired and added to the three-dimensional surface data, and the device including a recovery mode in which one or more additional three-dimensional images are test fit to one or more of the sequence of three-dimensional images to recover the acquisition mode; and

30 a display adapted to provide one or more visual indicators distinguishing between the acquisition mode and the recovery mode.

34. The system of claim 33, the display further adapted to provide guidance to an operator in manipulating the subject in the recovery mode.

35. A method comprising:

5 performing a first acquisition of a first set of three-dimensional data from a first subject;

placing a second subject in a fixed orientation relative to the first subject; and

10 performing a second acquisition of a second set of three-dimensional data starting at a location on a surface of the first subject and including at least a portion of the second subject.

36. The method of claim 35 wherein each of the first subject and the second subject is a rigid body.

15 37. The method of claim 35 wherein the location on the surface of the first subject includes a plurality of spatially proximate ones of a sequence of three-dimensional images used to derive the three-dimensional data from the first subject.

20 38. The method of claim 35 wherein the location on the surface of the first subject includes a plurality of temporally proximate ones of a sequence of three-dimensional images used to derive the three-dimensional data from the first subject.

39. The method of claim 35 further comprising:

terminating the second acquisition at a location on a surface of the second subject;

25 removing the first subject; and

performing a third acquisition of three-dimensional data starting at the location on the surface of the second subject.

30 40. The method of claim 39 wherein the location on the surface of the second subject includes a plurality of spatially proximate ones of a sequence of three-dimensional images used to derive the three-dimensional data from the second subject.

41. The method of claim 39 wherein the location on the surface of the second subject includes a plurality of temporally proximate ones of the sequence of three-dimensional images used to derive the three-dimensional data from the second subject.

5 42. The method of claim 39 further comprising combining the first set of three-dimensional data, the second set of three-dimensional data, and the third set of three-dimensional data into a unified set of three-dimensional data.

43. The method of claim 35 wherein the first subject includes a first dental arch.

10 44. The method of claim 43 wherein the second subject includes a second dental arch, the fixed orientation including the first dental arch and the second dental arch in occlusion.

15 45. The method of claim 35 wherein at least a portion of the second set of three-dimensional data is fitted to at least a portion of the first set of three-dimensional data to provide a unified set of three-dimensional data.

20 46. A system comprising:
acquisition means for performing a first acquisition of a first set of three-dimensional data from a first subject;
positioning means for placing a second subject in a fixed orientation relative to the first subject; and
the acquisition means including means for performing a second acquisition of a second set of three-dimensional data starting at a location on a surface of the first subject
25 and including at least a portion of the second subject.

47. The system of claim 46 wherein each of the first subject and the second subject is a rigid body.

30 48. The system of claim 46 wherein the location on the surface of the first subject includes a plurality of spatially proximate ones of a sequence of three-dimensional images used to derive the three-dimensional data from the first subject.

49. The system of claim 46 wherein the location on the surface of the first subject includes a plurality of temporally proximate ones of a sequence of three-dimensional images used to derive the three-dimensional data from the first subject.

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50. The system of claim 46 further comprising:
control means for terminating the second acquisition at a location on a surface of the second subject;
the positioning means including means for removing the first subject; and
10 the acquisition means including means for performing a third acquisition of three-dimensional data starting at the location on the surface of the second subject.

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51. The system of claim 50 wherein the location on the surface of the second subject includes a plurality of spatially proximate ones of a sequence of three-dimensional images used to derive the three-dimensional data from the second subject.

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52. The system of claim 50 wherein the location on the surface of the second subject includes a plurality of temporally proximate ones of the sequence of three-dimensional images used to derive the three-dimensional data from the second subject.

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53. The system of claim 50 further comprising computing means for combining the first set of three-dimensional data, the second set of three-dimensional data, and the third set of three-dimensional data into a unified set of three-dimensional data.

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54. The system of claim 46 wherein the first subject includes a first dental arch.

55. The system of claim 54 wherein the second subject includes a second dental arch, the fixed orientation including the first dental arch and the second dental arch in occlusion.

30

56. The system of claim 46 wherein at least a portion of the second set of three-dimensional data is fitted to at least a portion of the first set of three-dimensional data to provide a unified set of three-dimensional data.

57. A method comprising:

placing a first subject in a fixed orientation relative to a second subject;

acquiring a first set of three-dimensional data including a first portion of the first
5 subject and a first portion of the second subject;

acquiring a second set of three-dimensional data from the first subject in isolation
starting at a location on a surface of the first subject and including a second portion of the
first subject different from the first portion of the first subject; and

combining the first set of three-dimensional data with the second set of three-
10 dimensional data.

58. The method of claim 57 wherein each of the first subject and the second subject is
a rigid body.

59. The method of claim 57 wherein the location on the surface of the first subject
15 includes a plurality of spatially proximate ones of a sequence of three-dimensional images
used to derive the three-dimensional data from the first subject.

60. The method of claim 57 wherein the location on the surface of the first subject
20 includes a plurality of temporally proximate ones of a sequence of three-dimensional
images used to derive the three-dimensional data from the first subject.

61. The method of claim 57 further comprising:

acquiring of a third set of three-dimensional data from the second subject in
25 isolation starting at a location on a surface of the second subject and including a second
portion of the second subject; and

combining the third set of three-dimensional data with the first and second sets of
three-dimensional data.

62. The method of claim 61 wherein the location on the surface of the second subject
30 includes a plurality of spatially proximate ones of a sequence of three-dimensional images
used to derive the three-dimensional data from the second subject.

63. The method of claim 61 wherein the location on the surface of the second subject includes a plurality of temporally proximate ones of the sequence of three-dimensional images used to derive the three-dimensional data from the second subject.

5

64. The method of claim 57 wherein the first subject includes a first dental arch.

65. The method of claim 64 wherein the second subject includes a second dental arch, the fixed orientation including the first dental arch and the second dental arch in occlusion.

10

66. A method comprising:

providing a first set of three-dimensional data from a subject;

scanning the subject to acquire one or more additional three-dimensional images;

test fitting each one of the one or more additional three-dimensional images to the

15

set of three dimensional data, and

upon a successful fit, adding the one or more additional three-dimensional images to the set of three-dimensional data.

67. The method of claim 66 further comprising fitting each new one of the one or more additional three-dimensional images to one another to provide a second set of three-dimensional data, and upon a successful fit, adding the second set of three-dimensional data to the first set of three-dimensional data.

20

68. The method of claim 66 wherein the three-dimensional data includes three-dimensional surface data.

25

69. The method of claim 66 wherein the one or more additional three-dimensional images include surface data derived from two-dimensional image sets of the subject.

70. The method of claim 66 wherein the set of three-dimensional data includes three-dimensional surface data acquired from a subject as a sequence of three-dimensional

30

images, each one of the sequence of three-dimensional images fitted to at least one previous one of the sequence of three-dimensional images.

71. A system comprising:

5 storage means for providing a first set of three-dimensional data from a subject; acquisition means for scanning the subject to acquire one or more additional three-dimensional images; and

10 computing means for test fitting each one of the one or more additional three-dimensional images to the set of three dimensional data, the computing means further including means for detecting a successful fit and, upon detecting a successful fit, adding the one or more additional three-dimensional images to the set of three-dimensional data.

15 72. The system of claim 71 wherein the computing means includes means for fitting each new one of the one or more additional three-dimensional images to one another to provide a second set of three-dimensional data, and upon a successful fit, adding the second set of three-dimensional data to the first set of three-dimensional data.

20 73. The system of claim 71 wherein the three-dimensional data includes three-dimensional surface data.

74. The system of claim 71 wherein the one or more additional three-dimensional images include surface data derived from two-dimensional image sets of the subject.

25 75. The system of claim 71 wherein the set of three-dimensional data includes three-dimensional surface data acquired from a subject as a sequence of three-dimensional images, each one of the sequence of three-dimensional images fitted to at least one previous one of the sequence of three-dimensional images.

30 76. A computer program product comprising computer executable code embodied on a computer readable medium that, when executing on one or more computing devices, performs the steps of:

providing a first set of three-dimensional data from a subject;

scanning the subject to acquire one or more additional three-dimensional images;
test fitting each one of the one or more additional three-dimensional images to the
set of three dimensional data, and
upon a successful fit, adding the one or more additional three-dimensional images
5 to the set of three-dimensional data.

77. The computer program product of claim 76 further comprising code to perform the
steps of fitting each new one of the one or more additional three-dimensional images to
one another to provide a second set of three-dimensional data, and upon a successful fit,
10 adding the second set of three-dimensional data to the first set of three-dimensional data.

78. The computer program product of claim 76 wherein the three-dimensional data
includes three-dimensional surface data.

79. The computer program product of claim 76 wherein the one or more additional
15 three-dimensional images include surface data derived from two-dimensional image sets
of the subject.

80. The computer program product of claim 76 wherein the set of three-dimensional
20 data includes three-dimensional surface data acquired from a subject as a sequence of
three-dimensional images, each one of the sequence of three-dimensional images fitted to
at least one previous one of the sequence of three-dimensional images.

81. A method comprising:
25 providing a first set of three-dimensional data from a subject;
scanning the subject to acquire one or more additional three-dimensional images;
test fitting each one of the one or more additional three-dimensional images to the
first set of three-dimensional data in real time, and
providing real time visual feedback to a user relating to the test fitting.
30

82. The method of claim 81 wherein providing real time visual feedback includes superimposing the first set of three-dimensional data and the one or more additional three-dimensional images on a video image of the subject when a test fit is successful.

5 83. The method of claim 81 wherein providing real time visual feedback includes displaying one or more navigation cues when a test fit is unsuccessful.

84. The method of claim 81 further comprising, when the test fitting is unsuccessful, fitting each new one of the one or more additional three-dimensional images to one
10 another to provide a second set of three-dimensional data, and upon a successful fit, adding the second set of three-dimensional data to the first set of three-dimensional data.

85. The method of claim 81 wherein the three-dimensional data includes three-dimensional surface data.

15 86. The method of claim 81 wherein the one or more additional three-dimensional images include surface data derived from two-dimensional image sets of the subject.

87. The method of claim 81 wherein the set of three-dimensional data includes three-dimensional surface data acquired from a subject as a sequence of three-dimensional
20 images, each one of the sequence of three-dimensional images fitted to at least one previous one of the sequence of three-dimensional images.

88. A system comprising:
25 storage means for providing a first set of three-dimensional data from a subject;
acquisition means for scanning the subject to acquire one or more additional three-dimensional images;
computing means for test fitting each one of the one or more additional three-dimensional images to the first set of three-dimensional data in real time, and
30 display means for providing real time visual feedback to a user relating to the test fitting.

89. The system of claim 88 wherein providing real time visual feedback includes superimposing the first set of three-dimensional data and the one or more additional three-dimensional images on a video image of the subject when a test fit is successful.

5 90. The system of claim 88 wherein providing real time visual feedback includes displaying one or more navigation cues when a test fit is unsuccessful.

91. The system of claim 88 wherein the computing means includes means for, when the test fitting is unsuccessful, fitting each new one of the one or more additional three-dimensional images to one another to provide a second set of three-dimensional data, and
10 upon a successful fit, adding the second set of three-dimensional data to the first set of three-dimensional data.

92. The system of claim 88 wherein the three-dimensional data includes three-dimensional surface data.
15

93. The system of claim 88 wherein the one or more additional three-dimensional images include surface data derived from two-dimensional image sets of the subject.

20 94. The system of claim 88 wherein the set of three-dimensional data includes three-dimensional surface data acquired from a subject as a sequence of three-dimensional images, each one of the sequence of three-dimensional images fitted to at least one previous one of the sequence of three-dimensional images.

25 95. A computer program product comprising computer executable code embodied on a computer readable medium that, when executing on one or more computing devices, performs the steps of:

providing a first set of three-dimensional data from a subject;

scanning the subject to acquire one or more additional three-dimensional images;

30 test fitting each one of the one or more additional three-dimensional images to the first set of three-dimensional data in real time, and

providing real time visual feedback to a user relating to the test fitting.

96. The computer program product of claim 95 wherein providing real time visual feedback includes superimposing the first set of three-dimensional data and the one or more additional three-dimensional images on a video image of the subject when a test fit is successful.

97. The computer program product of claim 95 wherein providing real time visual feedback includes displaying one or more navigation cues when a test fit is unsuccessful.

98. The computer program product of claim 95 further comprising computer code that performs the steps of, when the test fitting is unsuccessful, fitting each new one of the one or more additional three-dimensional images to one another to provide a second set of three-dimensional data, and upon a successful fit, adding the second set of three-dimensional data to the first set of three-dimensional data.

99. The computer program product of claim 95 wherein the three-dimensional data includes three-dimensional surface data.

100. The computer program product of claim 95 wherein the one or more additional three-dimensional images include surface data derived from two-dimensional image sets of the subject.

101. The computer program product of claim 95 wherein the set of three-dimensional data includes three-dimensional surface data acquired from a subject as a sequence of three-dimensional images, each one of the sequence of three-dimensional images fitted to at least one previous one of the sequence of three-dimensional images.

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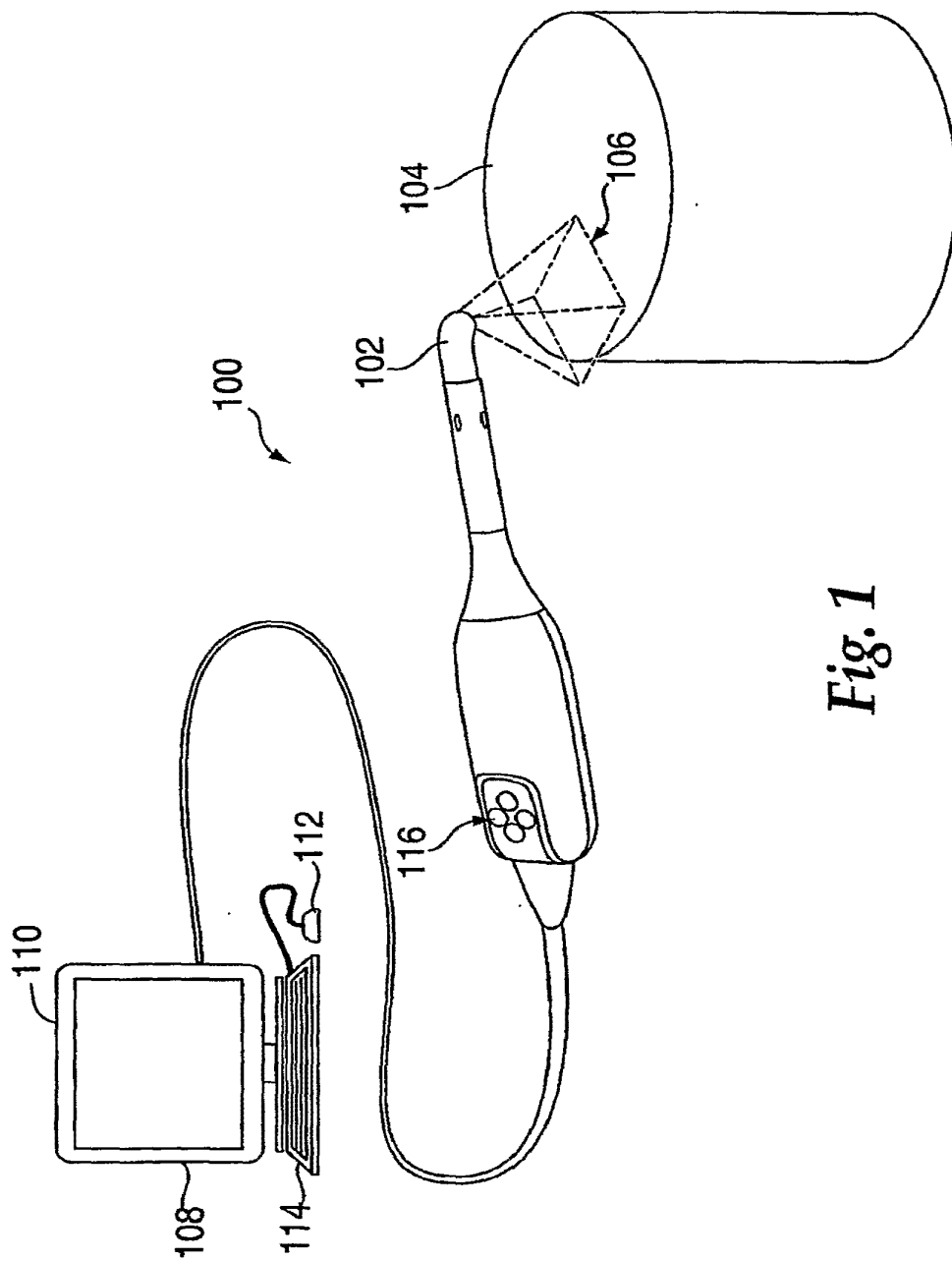
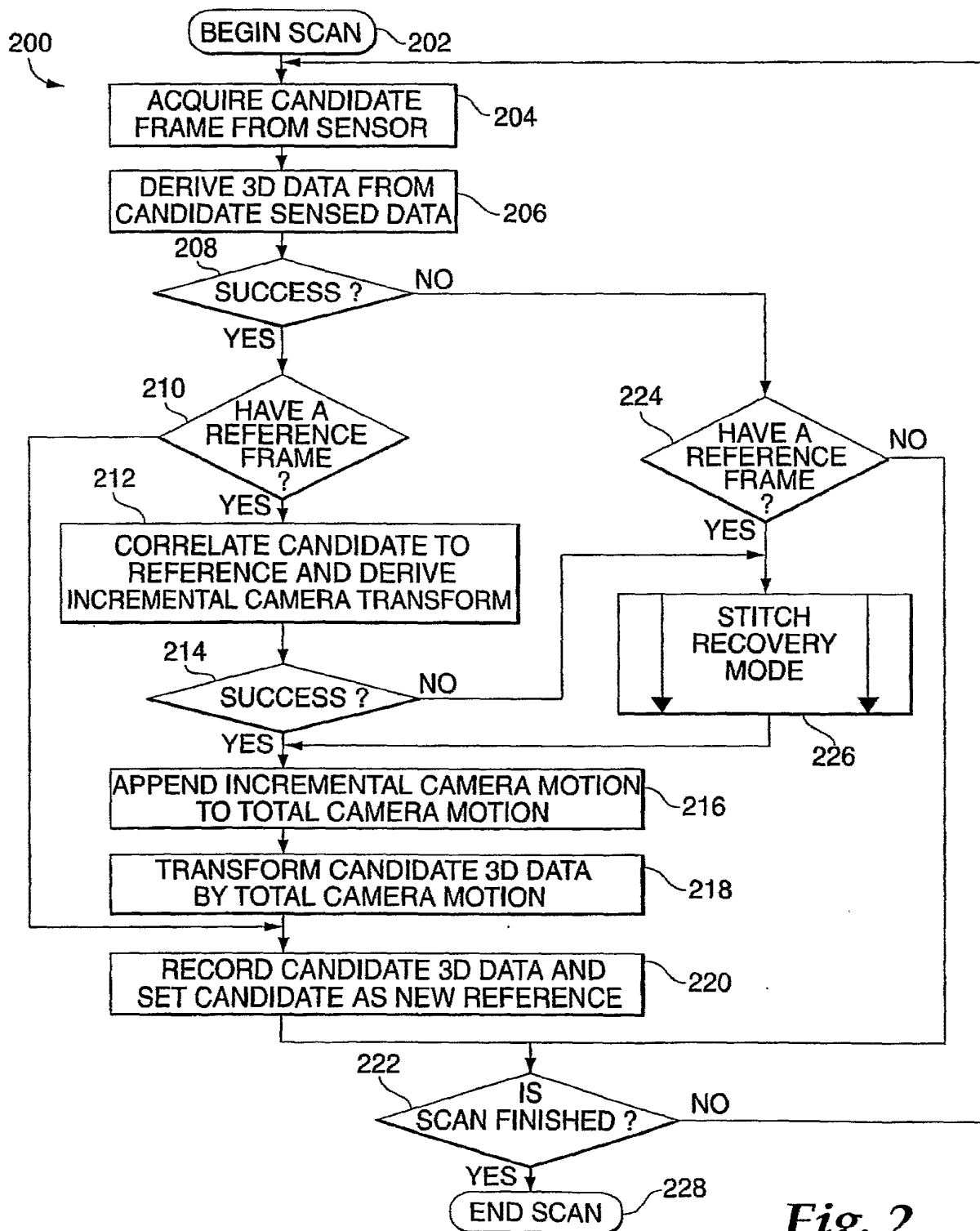
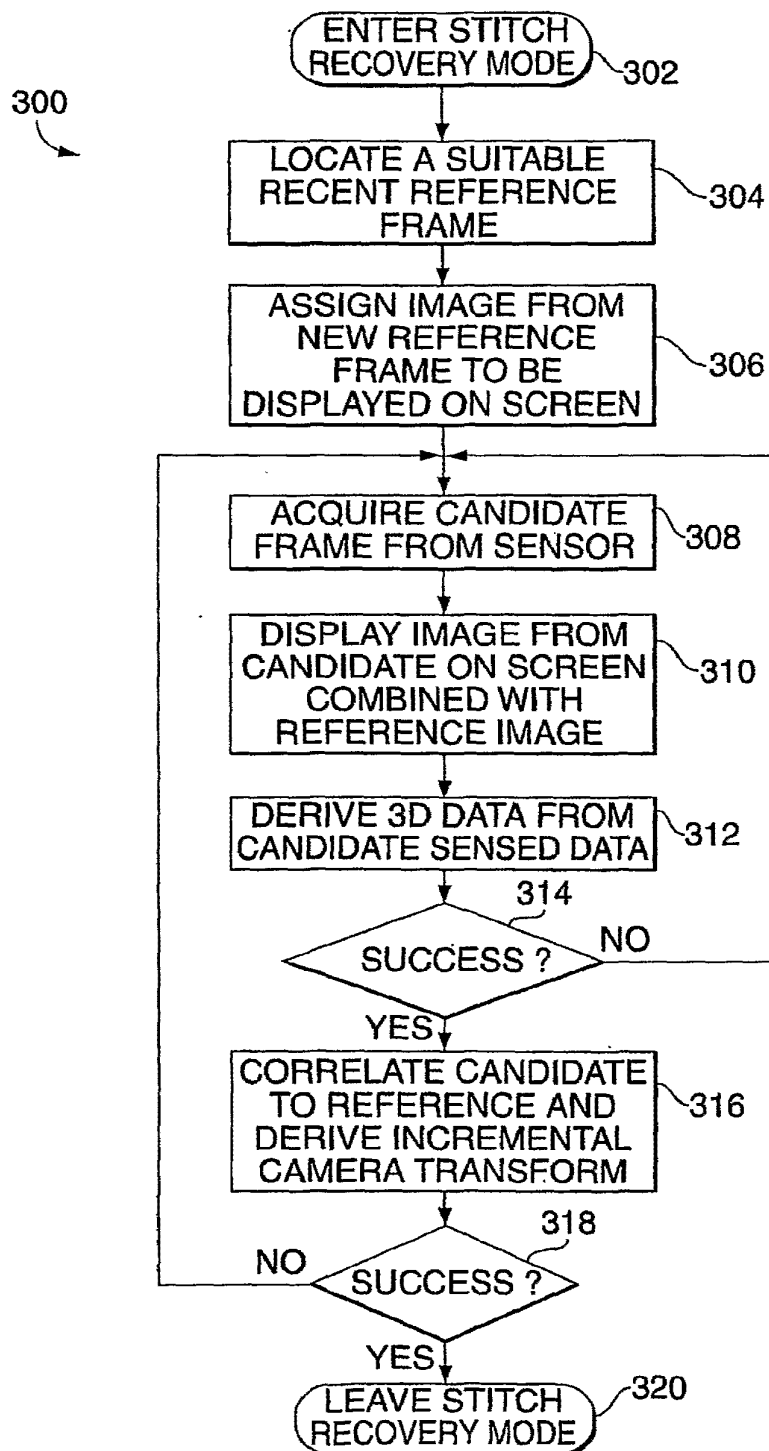


Fig. 1

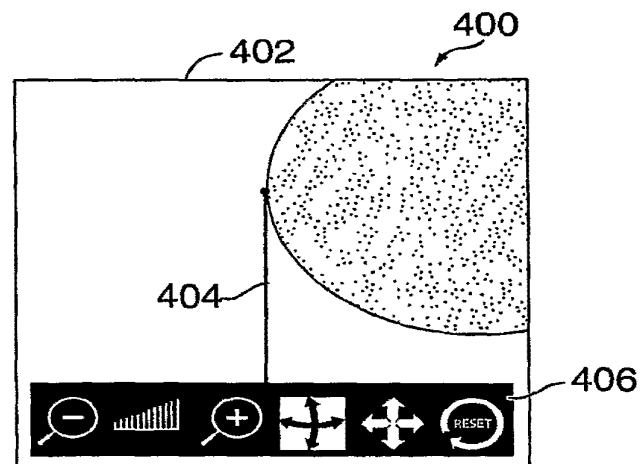
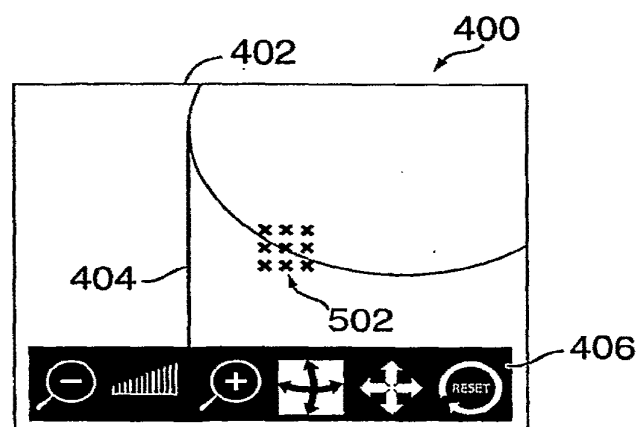
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*Fig. 3*

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*Fig. 4**Fig. 5*

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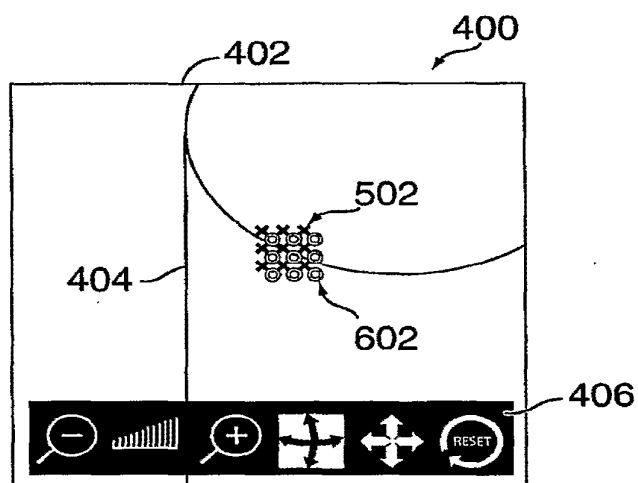


Fig. 6

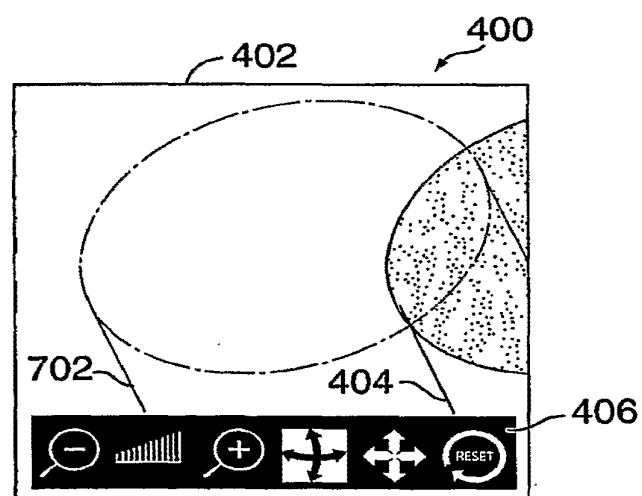
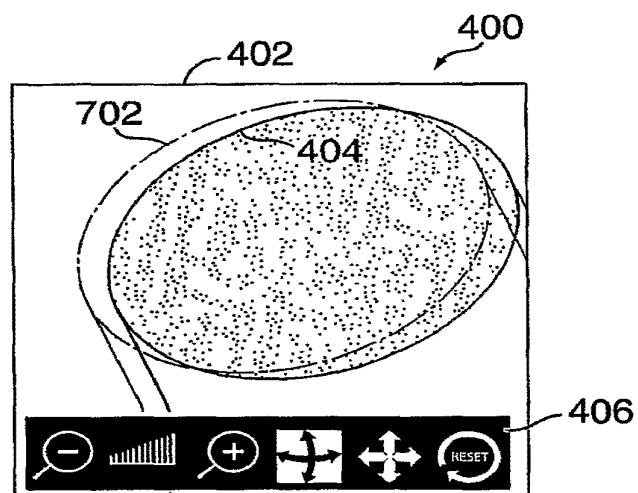
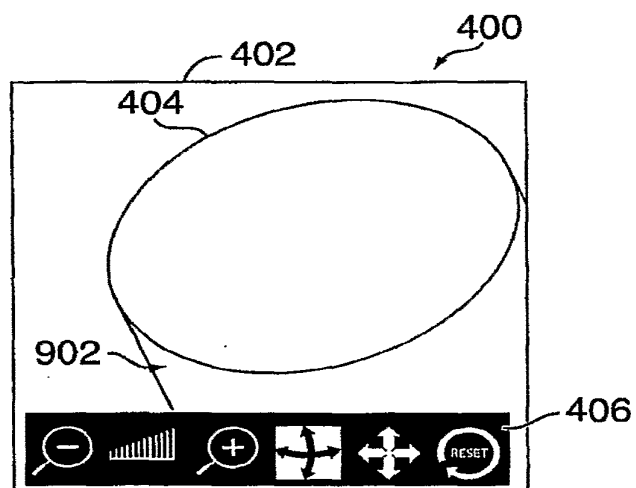


Fig. 7

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*Fig. 8**Fig. 9*

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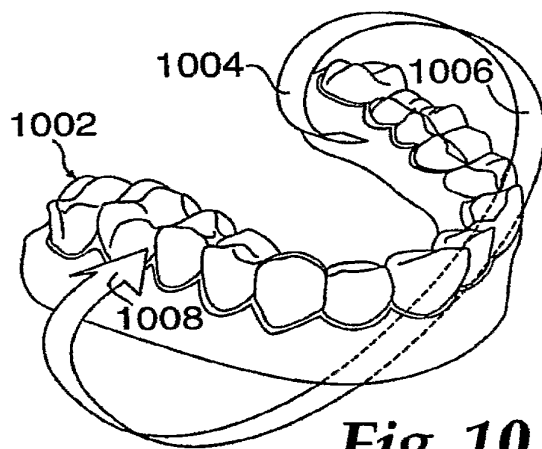


Fig. 10

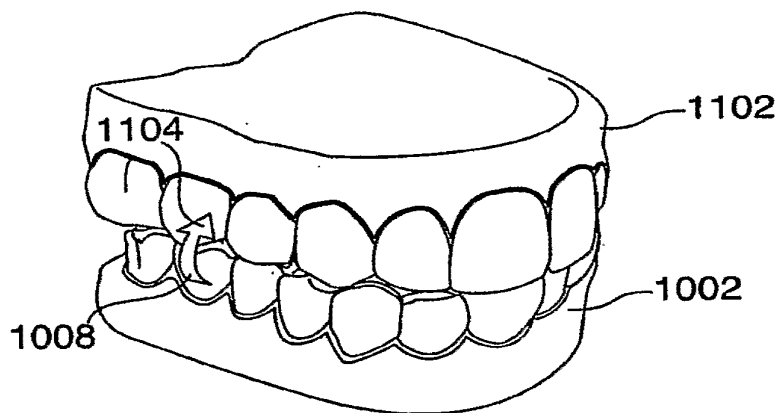


Fig. 11

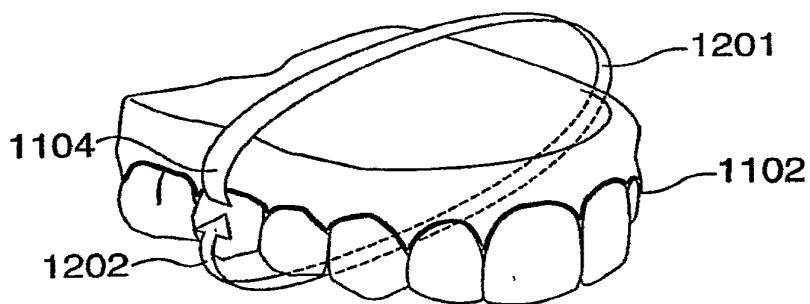


Fig. 12



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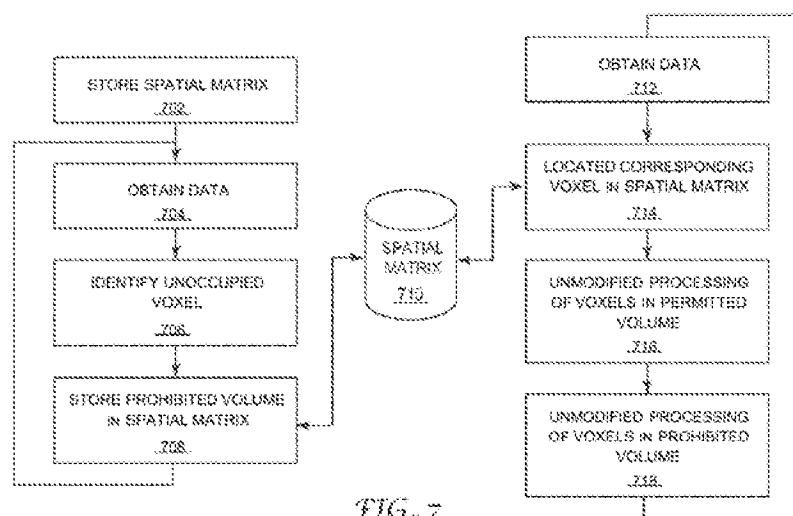


FIG. 7

(57) Abstract: Three-dimensional scanning is improved with the use of space carving to exclude certain scan results from processing and display. Using space carving techniques, a spatial matrix is maintained to store data on volumetric regions (or voxels) known to be empty. By excluding or modifying processing of outlier data from within these unoccupied voxels, a three-dimensional reconstruction process can achieve concurrent improvements in accuracy and speed. In addition, a real time display of scan results can be improved by modifying how such outliers are rendered.

SPACE CARVING IN 3D DATA ACQUISITION

BACKGROUND

1. Field of the Invention.

[0001] The invention relates to the use of space carving to improve three-dimensional data acquisition.

2. Description of the Related Art.

[0002] A wide range of techniques exist for acquiring three-dimensional data from a subject. One broad category of techniques employs continuous scanning in which incremental three-dimensional data is acquired and assembled into a full three-dimensional model. In this latter category, regardless of the particular scanning technology, the calculation and display of three-dimensional data can become encumbered by transient obstructions within a scanning volume. For example, in a dental scan, a patient's tongue or other soft tissue may temporarily obstruct or move adjacent to a scanned surface. A technician may similarly obstruct a scanner's view of the scanned surface with a finger, tongue depressor, or other instrument. There remains a need for techniques to exclude such outliers from a three-dimensional scanning process.

SUMMARY

[0003] Three-dimensional scanning is improved with the use of space carving to exclude certain scan results from processing and display. Using space carving techniques, a spatial matrix is maintained to store data on volumetric regions (or voxels) known to be empty. By excluding or modifying processing of subsequent outlier data from within these unoccupied voxels, a three-dimensional reconstruction process can achieve concurrent improvements in accuracy and speed. In addition, a real time display of scan results can be improved by modifying how such outliers are rendered.

[0004] In one aspect, a method disclosed herein includes storing a spatial matrix in a memory, the spatial matrix including information for a plurality of voxels in a mesh of a scan space; obtaining three-dimensional data from an object within the scan space using a scanner; identifying a one of the plurality of voxels in the mesh that is unoccupied; storing an indication in the spatial matrix for a modified processing of data from the one of the plurality of voxels, thereby identifying a prohibited volume within the scan space; and processing a portion of the three-dimensional data that is not in the prohibited volume according to an unmodified processing and processing a second portion of the three-dimensional data that is in the prohibited volume according to the modified processing.

[0005] Identifying the one of the plurality of voxels may include identifying a plurality of points on a ray between the scanner and the object that are unoccupied. The method may include providing a spatial margin of one or more voxels adjacent to a surface of the object for which processing cannot be prohibited. The spatial margin may be a multiple of a standard deviation of a z-axis measurement for the scanner. The modified processing may include detecting a point in the prohibited volume and displaying the point with a decay time. The modified processing may include omitting any points in the prohibited volume from a surface mesh of the object created with the three-dimensional data. The mesh may divide the scan space into a spatial grid substantially identical to a second spatial grid used to create the surface mesh. The modified processing may include omitting any points in the prohibited volume from a high-accuracy refinement of the three-dimensional data. The mesh of the scan space may be subdivided into voxels having a substantially cubic shape. The substantially cubic shape may measure about 250 microns on each edge. The prohibited volume may include more than one of the plurality of voxels. The spatial matrix may include a binary flag for each one of the plurality of voxels that indicates whether processing is permitted or forbidden for a corresponding volume of the scan space.

[0006] In another aspect, a computer program product disclosed herein includes computer executable code embodied on a non-transitory computer readable medium that, when executing on one or more computing devices, performs the steps of: storing a spatial matrix in a memory, the spatial matrix storing information for a plurality of voxels in a mesh of a scan space; obtaining three-dimensional data from an object within the scan space using a scanner; identifying one of the plurality of voxels in the mesh of the scan space that is unoccupied; storing an indication in the spatial matrix for a modified processing of data from the one of the plurality of voxels that contains the point, thereby identifying a prohibited volume within the scan space; and processing a portion of the three-dimensional data in the prohibited volume according to the modified processing and processing a second portion of the three-dimensional data that is not in the prohibited volume according to an unmodified processing.

[0007] In another aspect, a system disclosed herein includes a scanner configured to obtain three-dimensional data from an object within a scan space; a memory configured to store a spatial matrix that includes information for a plurality of voxels in a mesh of a scan space; and a processor configured to identify a point in the scan space that is unoccupied, to store an indication in the spatial matrix for a modified processing of data from a one of the plurality of voxels that contains the point, thereby identifying a prohibited volume within the scan space, to process a portion of the three-dimensional data that is not in the prohibited volume according to an unmodified processing, and to process a second portion of the three-dimensional data that is in the prohibited volume according to the modified processing.

[0008] In another aspect, a system disclosed herein includes storing means for storing a spatial matrix that includes information for a plurality of voxels in a mesh of a scan space; scanning means for obtaining three-dimensional data from an object within the scan space; and processing means for identifying a point in the scan space that is unoccupied, storing an indication in storing means for a modified processing of data from a one of the plurality of voxels that contains the point, thereby identifying a prohibited volume within the scan space, processing a portion of the three-dimensional data that is not in the prohibited volume according to an unmodified processing and processing a second portion of the three-dimensional data that is in the prohibited volume according to the modified processing.

BRIEF DESCRIPTION OF THE FIGURES

[0009] The invention and the following detailed description of certain embodiments thereof may be understood by reference to the following figures.

[0010] Fig. 1 shows a dental image capture system.

[0011] Fig. 2 depicts a view of a user interface for an image capture system.

[0012] Fig. 3 depicts a view of a user interface for an image capture system.

[0013] Fig. 4 depicts a view of a user interface for an image capture system during an acquisition of three-dimensional data.

[0014] Fig. 5 illustrates a spatial matrix for use in space carving.

[0015] Fig. 6 illustrates a ray trace used to identify unoccupied space.

[0016] Fig. 7 is a flow chart of a process for displaying data based on a spatial matrix.

DETAILED DESCRIPTION

[0017] The following description relates to use of space carving techniques to improve processing of three-dimensional data acquired from a three-dimensional scanner. While the description emphasizes continuous scanning and dental applications, it will be appreciated that the inventive concepts disclosed herein are not limited to the specific embodiments disclosed. For example, the space carving techniques described herein may be used to improve any three-dimensional acquisition or processing in which the capture of three-dimensional data occurs over a period of time such as structured light projection, x-ray computed tomography, optical coherence tomography, interferometry, and the like. The techniques described herein may similarly be employed in any three-dimensional processing environment where accuracy or time of computation can benefit from the exclusion of outlier data. Similarly, while the following description emphasis use of space carving to avoid processing known outliers, the approach may be readily generalized by, for example, by identifying multiple objects in a scan volume and excluding objects that are not rigidly

associated with a scan subject. All such variations that would be apparent to one of ordinary skill in the art are intended to fall within the scope of this disclosure.

[0018] In the following description, the term "image" generally refers to a two-dimensional set of pixels forming a two-dimensional view of a subject within an image plane. The term "image set" generally refers to a set of related two dimensional images that might be resolved into three-dimensional data. The term "point cloud" generally refers to a three-dimensional set of points forming a three-dimensional view of the subject, such as might be reconstructed from a number of two-dimensional views. In a three-dimensional image capture system, a number of such point clouds may also be registered and combined into an aggregate point cloud constructed from images captured by, for example, a moving camera. Thus it will be understood that pixels generally refer to two-dimensional data and points generally refer to three-dimensional data, unless another meaning is specifically indicated or otherwise clear from the context.

[0019] The terms "three-dimensional surface representation", "digital surface representation", "three-dimensional surface map", and the like, as used herein, are intended to refer to any three-dimensional surface map of an object, such as a point cloud of surface data, a set of two-dimensional polygons, a particle system, or any other renderable primitives or other data representing all or some of the surface of an object, as might be obtained through the capture and/or processing of three-dimensional scan data, unless a different meaning is explicitly provided or otherwise clear from the context.

[0020] A "three-dimensional representation" may include any of the three-dimensional surface representations described above, as well as volumetric, vector, and/or other representations, unless a different meaning is explicitly provided or otherwise clear from the context.

[0021] In general, the terms "render" or "rendering" refer to a two-dimensional visualization of a three-dimensional object, such as for display on a monitor. However, it will be understood that stereoscopic, three-dimensional, and other rendering technologies exist, and may be usefully employed with the systems and methods disclosed herein to render objects in three dimensions. As such, rendering should be interpreted broadly unless a narrower meaning is explicitly provided or otherwise clear from the context.

[0022] The term "dental object", as used herein, is intended to refer broadly to subject matter specific to dentistry. This may include intraoral structures such as dentition, and more typically human dentition, such as individual teeth, quadrants, full arches, pairs of arches which may be separate or in various types of occlusion, soft tissue, and the like, as well bones and any other supporting or surrounding structures. As used herein, the term "intraoral structures" refers to both natural structures within a mouth as described above and artificial structures such as any of the dental objects described below that might be present in

the mouth. Dental objects may include "restorations", which may be generally understood to include components that restore the structure or function of existing dentition, such as crowns, bridges, veneers, inlays, onlays, amalgams, composites, and various substructures such as copings and the like, as well as temporary restorations for use while a permanent restoration is being fabricated. Dental objects may also include a "prosthesis" that replaces dentition with removable or permanent structures, such as dentures, partial dentures, implants, retained dentures, and the like. Dental objects may also include "appliances" used to correct, align, or otherwise temporarily or permanently adjust dentition, such as removable orthodontic appliances, surgical stents, bruxism appliances, snore guards, indirect bracket placement appliances, and the like. Dental objects may also include "hardware" affixed to dentition for an extended period, such as implant fixtures, implant abutments, orthodontic brackets, and other orthodontic components. Dental objects may also include "interim components" of dental manufacture which may not be intraoral structures as described above, such as dental models (full and/or partial), wax-ups, investment molds, and the like, as well as trays, bases, dies, and other components employed in the fabrication of restorations, prostheses, and the like. Dental objects may be categorized in a number of ways. For example, dental objects may be categorized as natural dental objects such as the teeth, bone, and other intraoral structures described above and artificial dental objects such as the restorations, prostheses, appliances, hardware, and interim components of dental manufacture as described above. Similarly, dental objects may be categorized intraoral dental objects (which may be natural or artificial) and extraoral dental objects (which are generally but not exclusively artificial).

[0023] Terms such as "digital dental model", "digital dental impression" and the like, are intended to refer to three-dimensional representations of dental objects that may be used in various aspects of acquisition, analysis, prescription, and manufacture, unless a different meaning is otherwise provided or clear from the context. Terms such as "dental model" or "dental impression" are intended to refer to a physical model, such as a cast, printed, or otherwise fabricated physical instance of a dental object. Unless specified or otherwise clear from the context, the term "model", when used alone, may refer to either or both of a physical model and a digital model.

[0024] Fig. 1 shows an image capture system. In general, the system 100 may include a scanner 102 that captures images of a subject 104 within an image plane 106, and forwards the images to a computer 108, which may include a display 110 and one or more user input devices such as a mouse 112 or a keyboard 114.

[0025] The scanner 102 may include any camera or camera system suitable for capturing images from which a three-dimensional point cloud may be recovered. For example, the scanner 102 may employ a multi-aperture system as disclosed, for example, in U.S. Pat. Pub. No. 20040155975 to Hart et al. While Hart discloses one multi-aperture

system, it will be appreciated that any multi-aperture system suitable for reconstructing a three-dimensional point cloud from a number of two-dimensional images may similarly be employed, including systems with moving apertures, fixed apertures, and/or electro-mechanically shuttered apertures. In one multi-aperture embodiment, the scanner 102 may include a plurality of apertures including a center aperture positioned along a center optical axis of a lens and any associated imaging hardware. The scanner 102 may also, or instead, include a stereoscopic, triscopic or other multi-camera or other configuration in which a number of cameras or optical paths are maintained in fixed or moving relation to one another to obtain two-dimensional images of an object from a number of slightly different perspectives. The scanner 102 may include suitable processing for deriving a three-dimensional point cloud from an image set or a number of image sets, or each two-dimensional image set may be transmitted to an external processor such as contained in the computer 108 described below. In other embodiments, the scanner 102 may employ structured light, laser scanning, direct ranging (for example, time of flight in a known direction), or any other technology suitable for acquiring three-dimensional data, or two-dimensional data that can be resolved into three-dimensional data.

[0026] In one embodiment, the scanner 102 is a handheld, freely positionable probe having at least one user input device, such as a button, lever, dial, thumb wheel, switch, or the like, for user control of the image capture system 100 such as starting and stopping scans. In an embodiment, the scanner 102 may be shaped and sized for dental scanning. More particularly, the scanner may be shaped and sized for intraoral scanning and data capture, such as by insertion into a mouth of an imaging subject and passing the imaging plane 106 over one or more intraoral structures at a suitable distance to acquire surface data from teeth, gums, and so forth. The scanner 102 may, through such a continuous acquisition process, capture a point cloud of surface data having sufficient spatial resolution and accuracy to prepare dental objects such as prosthetics, hardware, appliances, and the like therefrom, either directly or through a variety of intermediate processing steps. In other embodiments, surface data may be acquired from a dental model such as a dental prosthetic, to ensure proper fitting using a previous scan of corresponding dentition, such as a tooth surface prepared for the prosthetic.

[0027] Although not shown in Fig. 1, it will be appreciated that a number of supplemental lighting systems may be usefully employed during image capture. For example, environmental illumination may be enhanced with one or more spotlights illuminating the subject 104 to speed image acquisition and improve depth of field (or spatial resolution depth). The scanner 102 may also, or instead, include a strobe, flash, or other light source to supplement illumination of the subject 104 during image acquisition. In other structured light systems, the illumination may be in the form of an array of laser beams that form a pattern on

a surface, which pattern may be employed to recover three-dimensional data from the surface. Other systems employ a single laser beam along with directional information to gather point-by-point direction and range information. All such imaging systems may be usefully employed to acquire three-dimensional data as described herein.

[0028] The subject 104 may be any object, collection of objects, portion of an object, or other subject matter. While illustrated in Fig. 1 as a simple geometric form, the subject 104 may include much more complex surfaces, and any number of separate elements. For example, in a dental imaging application, the subject 104 may include a tooth, a quadrant of teeth, or a full collection of teeth including two opposing arches from which a virtual dental impression is desired. The subject 104 may also, or instead, include a dental prosthesis such as an inlay, a crown, or any other dental prosthesis, implant, or the like. The subject 104 may include a dental model, such as a plaster cast, wax-up, impression, or negative impression of a tooth, teeth, soft tissue, or some combination of these. An optical or textured imaging agent may optionally be applied to surfaces of the subject 104 to improve capture of three dimensional points. In other embodiments, the subject 104 may be a human head, or a portion thereof, from which a three-dimensional model may be acquired for custom fitting of a hearing aid, eyeglasses, goggles, or the like. In other embodiments, the subject 104 may be a physical model of an object for use in digital animation, such as a miniature, physical model for use in a three-dimensional digital animation process. From the preceding examples, it will be apparent that a system using the techniques described herein may be suitably adapted to a wide range of applications for relatively short range, high resolution three-dimensional image acquisition. However, one skilled in the art will appreciate that suitable adaptations to the image capture system 100 may be made for a variety of other three-dimensional imaging applications based upon multi-aperture or multi-camera systems, as well as other three-dimensional imaging systems and technologies, and all such variations are intended to fall within the scope of this disclosure.

[0029] The image plane 106 may include a two-dimensional field of view of the scanner 102. It will be appreciated that the term "image plane" as used in this paragraph, refers to a plane in the imaging environment rather than a plane within an optical sensor (such as film or sensors) where an image is captured. Though illustrated as a rectangle the image plane 106 may, for example, form a square, a circle, or any other geometry provided by the scanner 102. In general, the scanner 102 will have a depth of field or range of depth resolution that, together with the field of view 106, specifies a measurement volume of the scanner 102. The depth of field may vary with environmental conditions such as lighting (ambient or artificial), the texture or optical properties of the imaging subject, and so forth. It will further be understood that the term "field of view", as used herein may refer to a two-dimensional field such as an internal plane within the optics of an imaging system, an external plane such

as a field in an imaging environment, or a region in a display, or may refer to a three-dimensional region such as a current measurement volume in an imaging environment. Thus, "field of view" as used herein should be interpreted in the broadest sense possible, unless a more specific meaning is explicitly provided, or otherwise clear from the context.

[0030] The computer 108 may be, for example, a personal computer or other processing device. In one embodiment, the computer 108 includes a personal computer with a dual 2.8GHz Opteron central processing unit, 2 gigabytes of random access memory, a TYAN Thunder K8WE motherboard, and a 250 gigabyte, 10,000 rpm hard drive. This system may be operated to capture approximately 1,500 points per image set in real time using the techniques described herein, and store an aggregated point cloud of over one million points. As used herein, the term "real time" means generally with no observable latency between processing and display. In a video-based scanning system, real time more specifically refers to processing within the time between frames of video data, which may vary according to specific video technologies, but may generally be considered to fall between about ten frames per second and about thirty frames per second for many of the applications described herein. More generally, processing capabilities of the computer 108 may vary according to the size of the subject 104, the speed of image acquisition, and the desired spatial resolution of three-dimensional points. The computer 108 may also include peripheral devices such as a keyboard 114, display 110, and mouse 112 for user interaction with the camera system 100. The display 110 may be a touch screen display capable of receiving user input through direct, physical interaction with the display 110.

[0031] Communications between the computer 108 and the scanner 102 may use any suitable communications link including, for example, a wired connection or a wireless connection based upon, for example, IEEE 802.11 (also known as wireless Ethernet), Bluetooth, or any other suitable wireless standard using, for example, a radio frequency, infrared, ultrasound or other wireless communication medium. In medical imaging or other sensitive applications, wireless image transmission from the scanner 102 to the computer 108 may be secured. The computer 108 may generate control signals to the scanner 102 which, in addition to image acquisition commands, may include conventional camera controls such as focus or zoom.

[0032] In an example of general operation of a three-dimensional image capture system 100, the scanner 102 may acquire two-dimensional image sets at a video rate while the scanner 102 is passed over a surface of the subject. The two-dimensional image sets may be forwarded to the computer 108 for derivation of three-dimensional point clouds. The three-dimensional data for each newly acquired two-dimensional image set may be derived and fitted or "stitched" to existing three-dimensional data using a number of different techniques. One useful example of such a technique is described in commonly-owned U.S. App. No.

11/270,135, filed on November 9, 200. However, it will be appreciated that this example is not limiting, and that the principles described herein may be applied to a wide range of three-dimensional image capture systems. It will also be understood that terms such as "video" or "video rate" imply a wide range of possible frame rates associated with such video. While most modern video formats employ a frame rate of 25 to 30 frames per second, early video employed frame rates as low as 8 frames per second, and movies of the early 1900's varied from 12 to 18 frames per second. In addition, it is common for specialized imaging equipment to employ a rate adapted to the computational demands of particular imaging and rendering techniques, and some video systems operate with frame rates anywhere from 4 frames per second (for computationally extensive imaging systems) to 100 frames per second or higher (for high-speed video systems). As used herein, the terms video rate and frame rate should be interpreted broadly. Notwithstanding this broad meaning, it is noted that useful and visually pleasing three-dimensional imaging systems have been constructed according to the foregoing with frame rates of at least ten frames per second, frame rates of at least twenty frames per second, and frame rates between 25 and 30 frames per second.

[0033] It will be appreciated that the ability of certain systems, such as multiaperture camera systems, to derive three-dimensional data from two-dimensional video image sets may depend in part on an ability to establish correspondence of surface points between image pairs (or triplets, and so on). The process of establishing point correspondences may be improved by identifying, within the processing system, unique features of the surface upon which correspondence may be based. In certain aspects, distinguishing features of teeth at varying levels of detail may be employed to enhance this process. However, this process depends on an ability to locate such distinguishable features. The process of establishing point correspondences may also, or instead, be enhanced by the addition of optically detectable features thereto, which may be as simple as artificial black dots distributed over a white or relatively light surface. In a dental context, this may be achieved with a spray, powder, mouth rinse, or the like that distributes optically detectable matter across the dentition or other dental object to be scanned. By randomly distributing such small, distinguishable dots across the surface, the likelihood of locating distinguishable features in a particular image set may be significantly improved, thus improving the speed and accuracy of the overall three-dimensional data acquisition process.

[0034] From time to time in continuous or incremental data acquisition systems, the fitting or stitch between two frames may fail for reasons described in greater detail below. In such situations, a user may be notified through visual feedback that a recover mode has been entered. In the recover mode, the system 100 may seek to reacquire the previous scan by test fitting new scan data to previously acquired data, and providing visual feedback to a user to assist in navigating back to a scan location on the subject where the re-acquisition is being

attempted. In a related landing mode, a user may attempt to initiate a new scan registered or connected to an existing three-dimensional model. Similar visual feedback tools may be provided to guide a user to an appropriate scan location, and notify a user when the scan has been reacquired. These techniques are described in greater detail in commonly-owned U.S. App. No. 11/383,623, filed on May 16, 2006. Other suitable techniques may be employed for navigation, controlling scan quality, analyzing scanned subject matter, and manipulating scanned models, various embodiments of which are described in greater detail below.

[0035] The display 110 may include any display suitable for video or other rate rendering at a level of detail corresponding to the acquired data or a rendered version of the acquired data. Suitable displays include cathode ray tube displays, liquid crystal displays, light emitting diode displays, plasma displays, and the like. In some embodiments, the display may include a touch screen interface using, for example capacitive, resistive, or surface acoustic wave (also referred to as dispersive signal) touch screen technologies, or any other suitable technology for sensing physical interaction with the display 110. In addition, where three-dimensional visualization is desired, the display 110 may include a three-dimensional display using a wide variety of techniques including stereo pair imaging, holographic imaging, and multiplanar or volumetric imaging, each with a number of rendering modalities that may be usefully employed with the systems described herein.

[0036] Fig. 2 depicts a view of a user interface for an image capture system. The user interface 200 may include a window 202 rendered on a monitor such as the display 110 of Fig. 1. Within the window 202, a video image may be displayed including a measurement volume of a scanner, such as the image plane 106 of the scanner 102 of Fig. 1. Within the field of view or measurement volume, a video or other image of a subject such as the subject 104 of Fig. 1 may be displayed. However, as depicted in Fig. 2, no image acquisition steps have been initiated, so the window 202 remains blank except for various controls which will be described below.

[0037] Scanning controls may include, for example, a scan control 204, a pause control 206, a stop control 208, a clear control 210, a save control 212, and a retrieve control 214. The scan control 204 may initiate a three-dimensional scan. The pause control 206 may temporarily discontinue a scan in a manner that permits subsequent reacquisition of a continuous scanning process. The paused scan may exhibit a number of visual properties. For example, the video image may be frozen, or the video image may continue to display current video information while a point cloud or other scan data remains frozen, or the screen may go entirely blank, or some combination of these, all according to user preferences or a particular implementation. In general, a paused scan may remain active so that a user may resume the scan. By contrast, if a user activates the stop control 208, the scan may be terminated, such that a user would have to retrieve the scan, such as using the retrieve control 214 in order to

continue adding data thereto. The save control 212 may store a scan and any related data for subsequent use. These controls may operate as buttons that a user activates to perform the indicated function, such as through a mouse click or, where the display 110 is a touchscreen, by direct physical interaction with the display 110. It will be appreciated that activation of the control may create a pop-up window, or provide drop down lists, radio buttons, text input fields, and any other controls suitable for parameterizing the particular selection. Thus for example, where a user activates the save control 212, a text box may appear for a user to enter a filename, directory or path information, and the like for saving any related data. Numerous techniques for organizing user interfaces and providing controls within a user interface are known in the art, and may be suitably adapted to the interface 200 described herein.

[0038] A number of navigation controls may be provided, such as a zoom out control 216, a zoom in control 218, a zoom indicator 220, a rotate control 222, a pan control 224, and a reset control 226. These controls may be used to view an acquired three-dimensional representation after a scan has been completed or, where a pause/resume feature is provided, during a scan. The reset control 226 may, for example, restore a view of a three-dimensional representation to a global coordinate system, or to a most recent view from which data was acquired during a scan.

[0039] A number of range finding visualizations may also be included that provide visual cues related to one or more scanning parameters of an image capture system. These visualizations may be rendered in real time, for example, at the video rate of the image capture system, to provide real time user feedback and guidance with respect to proper orientation and positioning of a scanner during a scan. The user feedback may improve the quality and speed of data acquisition, particularly during continuous scanning operations that acquire a full three-dimensional representation of a subject as a sequence of fitted three-dimensional surface samples. These visual cues may be particularly useful in continuous three-dimensional data acquisition systems based upon camera motion estimation or similar techniques. In such techniques, sequential frames of data are registered to one another using various processing techniques such as those described in commonly owned U.S. App. No. 11/270,135, filed on November 9, 2005. This works well provided three-dimensional data can be successfully resolved from each sequential frame of image data, and there is sufficiently small displacement of the scanner that the data from sequential frames overlaps in three-dimensional space. However, when this "stitching" of sequential frames is lost, such as due to an operator moving outside the proper scanning distance, it can be very difficult to recover the continuous acquisition. Visualization tools that guide a user toward maintaining proper scanning distance advantageously promote a continuous, uninterrupted acquisition of three-dimensional data for an entire surface of interest.

[0040] For example, within a window 230 that shows a current video image from the image plane 106 of the scanner 102 (which is blank in Fig. 2, as the system has not started a scan), a volume 232 of space, such as the box depicted in Fig. 2, for which quality scan data can be captured may be depicted in perspective. This volume 232 rendered within the imaging space may assist a user in positioning subject matter within the video image appropriately for data acquisition. In addition, sliders 234 may be animated along z-axis edges of the volume 232 to indicate a distance of points of three-dimensional data actually being acquired. This may be based on, for example, a mean distance of some or all of the points, a distance of a central point, a range of distances for all or some of the points, or a distance of a point at each respective corner of the volume 232, such that the sliders 234 may move independently from one another during a scan. Distance calculations may be based on a current frame of image data, that is, the most recently acquired data set, or an average of a predetermined number of immediately prior data sets, or upon all three-dimensional points of the three-dimensional surface representation falling within the volume 432 without regard to when they were acquired.

[0041] As another example, a dynamic object 236 such as a sphere or bullseye may be rendered in the center of the window 230. The dynamic object 236 may also, or instead, be positioned at another location within the window; however positioning the dynamic object 236 within the center of the window 230 advantageously permits a user to receive visual feedback from the dynamic object 236 without looking away from current video of the subject being scanned.

[0042] A number of useful animations may be provided by the dynamic object 236 to give user feedback to an operator of the image capture system 100. In one implementation, the dynamic object 236 may be an animated bullseye that is color-coded to provide distance information. The bullseye may, for example be rendered as concentric rings of different colors, such as red, white, and blue, with the central color filling the entire bullseye when a subject is properly distanced from the scanner. When the scanner moves too far from the subject, a red ring may form around the white circle filling a greater portion of the bullseye as the scanner moves further from a subject until the entire bullseye is completely red. Conversely, when the scanner moves too close to a subject, a blue circle may appear within the center of the white circle and grow in size as the scanner moves farther from the subject until the entire circle is blue. In this manner, a user may receive continuous feedback with respect to scan distance - a growing blue central circle as the scanner moves too close, and an engulfing red ring when as the scanner moves too far away - so that the scanner may maintain a proper distance from the subject for continuous acquisition of three-dimensional data in a three-dimensional representation of the subject. One useful model for rendering such a dynamic bullseye employs three co-axial cones of different colors, where the bullseye renders

a planar cross-section of the three co-axial cones perpendicular to the common axis, and at a point along the common axis selected according to relative range from the subject.

[0043] In another example of animation, three concentric rings may be continuously displayed within the bullseye, with the radius of each ring independently controlled in proportion to the number of points that are too close, properly distanced, and too far. In another possible animation, the center ring (a circle) may move within the bullseye with an offset corresponding to an x-y displacement in the field of view or measurement volume of a region of the surface having the greatest density of points at a target, or desirable, scanning distance. Of course, it will be appreciated that the selection of colors for such animations is somewhat arbitrary, although significant contrast in hue or intensity may assist a user in recognizing deviations from an optimal scan distance.

[0044] Other visual cues and/or metaphors may also, or instead, be employed, such as a visualization of a plane passing through a sphere, active distance bars, animated text, or other visualizations, any of which may provide animated, visual feedback based on, for example, mean distance, center distance, or some other metric that can be derived from scanner output. More generally, visual cues may provide feedback concerning any scanning parameter such as depth of optimal data acquisition, width of field of view, rate of travel or yaw of the scanner 102, density of data acquisition, and so forth, as well as various combinations of these. These visual cues may provide graduated feedback to assist a user in maintaining proper scan distance, and to inform a user when a scan has been lost.

[0045] Fig. 3 depicts a view of a user interface for an image capture system. This abstracted drawing shows a window 302 of the user interface 300, which may be, for example, the window 230 of Fig. 2, without the visual cues described therein. The window 302 may include a video image from a point of view of a scanner such as the image plane 106 of the scanner 102 described above with reference to Fig. 1. Within the window 302, the video image may include a subject 304. As depicted in Fig. 3 (and not by way of limitation), the subject 304 is a slender cylinder extended from a near end 306 relatively close to the scanner to a distant end 308 relatively far from the scanner. During a continuous surface scan of the subject 304, three-dimensional surface data may have been acquired, as indicated generally by x's, o's, and encircled +s. Within the window 302, the three-dimensional surface scan may be rendered from the point of view of the scanner, along with shading or other visual effects to indicate shape and surface contours. The rendered three-dimensional surface scan may be superimposed in a registered fashion directly over the video image (or conversely, the video image may be superimposed on the rendered three-dimensional surface). This superposition alone provides significant user information, such as what surface regions of the subject 304 have been scanned. In addition, the rendered three-dimensional surface scan may be color-coded or otherwise rendered to provide color information

concerning, for example, what region is currently being scanned in the continuous data acquisition process, what regions are too close to acquire scan data from, what regions are at a proper distance for acquisition of surface data, and what regions are too far for surface data. For example, if points on or near the near end 306 of the subject 304 are too close to acquire scan data - these points are indicated in Fig. 3 as x's - they may be rendered in a first color. Points at an optimal scanning distance - indicated in Fig. 3 as o's - may be rendered in a second color. Points too distance for acquisition of three-dimensional data - indicated in Fig. 3 as encircled +s - may be rendered in a third color. Of course, this distance information may not be directly relevant because the rendered points have already been acquired in three-dimensional space. However, this color coding of the surface of the subject 304, as rendered through the acquired three-dimensional digital surface representation, may provide useful information to a user concerning the distance of the subject 304, particularly with respect to regions of the subject 304 that have not yet been scanned.

[0046] It will be appreciated that, while only a dozen or so points have been drawn in Fig. 3, a practical image capture system for use in dentistry and similar applications may require spatial resolution on the order of 100 microns or less for sufficient detail to fabricate properly fitting dental objects. As such, the actual point cloud acquired by the image capture system for a subject such as a dental arch may contain thousands, tens of thousands, hundreds of thousands, or millions of individual three-dimensional points, or more. While the small number of points illustrated in Fig. 3 is intended to assist in explaining the nature of a point cloud distribution and various rendering techniques applicable thereto with reference to the specific points shown (the x's, o's, and encircled x's), the larger number of points available in a typical scan can provide significantly improved visualization of surface contours and the like. It should also be appreciated that the points used to render the digital surface representation for display may include a subset of points in a full point cloud of acquired three-dimensional data, with the density of points selected according to any suitable design parameters including processing/rendering speed, need for contour visualization, and the like. It will also be understood that the data in the three-dimensional scan may be internally represented as points, particle systems, vectors, or any other suitable representation. Thus, while the data may be rendered as a point cloud of any desired density, this may or may not correspond to the internal representation of scan data. Further, the rendering may employ techniques other than point rendering, such as a polygonal mesh or the like, with suitable adaptations to the techniques described above for visualizing range, scan quality, and the like.

[0047] It will be appreciated that the capability of capturing highly detailed models of dental objects, and in particular, the capability of capturing highly detailed digital surface representations of dentition directly from an intraoral scan, enables an array of subsequent

processing steps that may be useful to dentists, dental laboratory technicians, oral surgeons, and the like. A number of such applications are now described in greater detail.

[0048] The embodiments described in reference to Fig. 2 and Fig. 3 emphasize the use of an interface that displays a subject from a point of view of the scanner. However it will be understood that alternative models may be used, such as an interface that renders acquired data from a fixed point of view within a global coordinate system. In an approach employing a fixed point of view, the generally visualization strategy may change, such as by providing continuous feedback as to the position of the scanner relative to the subject. However, the visual cues described above may generally be adapted to such an environment, or other environments, in a number of ways as will be readily appreciated by one of skill in the art.

[0049] In general, a system as described herein may have a number of operating modes, such as a file management mode, a model editing mode, a model evaluation and/or analysis mode, a scanning mode, and so forth. Two such modes are described with respect to Figs. 4 and 5 below, which show a scanning mode and an evaluation mode respectively.

[0050] Fig. 4 depicts a view of a user interface for an image capture system during an acquisition of three-dimensional data. The user interface 400 may include a window 402 including range-finding visual cues 404, 406, all as generally described above. Within the window 402, a video image may be displayed, such as a video image from a current point of view of a scanner, such as the scanner 102 described above. As depicted, the video image may include a plurality of teeth 410 and other intraoral structures visible during an intraoral scan. It will be noted that three-dimensional points acquired from the surface, that is, the current digital surface representation, may be rendered within the user interface 400, and more particularly, may be rendered from the point of view of the scanner and superimposed on the current video image. Although not depicted, it will be understood that in other embodiments, the current digital surface representation may be rendered from a fixed point of view.

[0051] In addition to permitting visual enhancements such as contour shading and feature emphasis, the rendering may provide specific feedback to a user concerning the current scan. For example, regions too close for capture of scan data may include previously acquired points, which may be rendered in the window 402 with a style or color that indicates their relative proximity to the scanner. Conversely, regions of the intraoral structures too far for capture may also, or instead, include previously acquired points, which may be rendered in the window 402 with a style or a color that indicates their relative distance from the scanner. As new surface data is acquired and added to the digital surface representation, the new point data may concurrently, or in real time or near real time, be added to the rendered view of the digital surface representation. In this manner, a user may receive immediate visual feedback, such as the density of rendered points or relative fineness/coarseness of a polygonal

mesh, with respect to whether data is being successfully acquired from surfaces visible within the window 402. This information may indicate gaps in surface data so that a user can back up and rescan surfaces of the subject for which data has not been captured, or for which inadequate or defective data has been captured. This feedback may in part flow directly from the process of rendering an increasing number of points within the window as new surface data is acquired. The visual feedback may also, or instead, be supplemented by rendering points with a density in the window 402 specifically selected to communicate to a user whether adequate data has been acquired from within the current view. While specific feedback examples are noted above, it will be understood that more generally, numerous and various uses of brightness, texture, shading, color, and/or rendered point cloud density, or the like may be employed to provide visual feedback to a user concerning scan quality, detail, and the like.

[0052] The visual metaphor may be one of spray painting the video image with a shaded surface map as points are acquired. The point cloud of the digital surface representation (or other representation) may be rendered as a growing constellation of points that forms over the video subject matter as data is acquired. Regions for which a target point density has been achieved may, for example appear as continuous surfaces, while regions with inadequate surface data may be rendered as discrete points having visible gaps therebetween, which gaps may be varied in size according to, for example, the density of point data in the underlying digital surface representation. As another example, points may be rendered as uniformly spaced surface points, which may be color coded according to density of point data in the underlying digital surface representation.

[0053] In certain embodiments, the acquired digital model may be compared to a statistical, spatial, or other model of expected shapes relevant to dentistry (or other objects, for non-dental applications), using known machine vision and other techniques. This may include relatively subtle variations such as unexpected tooth contours, thicknesses, or the like, as well as gross deviations that are likely a result of user or equipment malfunction or loss of scan data. Where deviations from expectations are detected, these may be visually identified within the window 402 through use of color, shading, and other cues and annotations described generally above. Thus, algorithmically unexpected scan results may be immediately flagged during a scan for any suitable human intervention (which may, of course, be none where the unexpected feature is known by the operator to actually be present).

[0054] Having discussed various aspects of a three-dimensional scanning system, the description now turns to use of space carving to improve processing and display of three-dimensional data.

[0055] Fig. 5 illustrates a spatial matrix for use in space carving. In general, the spatial matrix 500 may include a number of cells 502, each storing information related to a

voxel in a scan volume. In one aspect, each cell 502 may store a binary flag that indicates whether the corresponding voxel is permitted or forbidden for processing. This approach advantageously provides a compact memory representation of carved space, however it will be readily appreciated that other representations of this information may also or instead be employed, and that additional information may be included in the spatial matrix such as any information that might be usefully stored on a voxel-by-voxel basis for the volume in which an object is being scanned. It will also be appreciated that, while the spatial matrix 500 is depicted as a three-dimensional structure that maps to the volume of a scan space, no such physical structure is required.

[0056] The spatial matrix 500 may include any memory or combination of memories capable of storing and retrieving information according to voxels within the scan space, and all such variations that would be apparent to one of ordinary skill in the art are intended to fall within the scope of this invention. The spatial matrix 500 may define a mesh of voxels that together form the scan volume or scan space in which data is processed as generally described below. In this respect, it will be readily appreciated that while the spatial matrix 500 depicted in Fig. 5 corresponds to a cubic volume, any shape or size of volume may be suitably employed according to the shape and/or size of an object that is being scanned, a processing mesh used for three-dimensional reconstruction, or any other factors. Thus in one aspect, the mesh of the scan space is subdivided into voxels having a substantially cubic shape. The substantially cubic shape may measure about 250 microns on each edge (that is, a 250 x 250 x 250 micron cube for each voxel) or any other suitable size according to desired resolution, processing capabilities, and so forth. In one aspect, the spatial matrix 500 may include a binary flag for each one of the plurality of voxels that indicates whether processing is permitted (for example, unmodified) or forbidden (for example, modified) for a volume of the scan space.

[0057] Fig. 6 illustrates a ray trace used to identify unoccupied space. During a scan such as any of the scans described above, a scanner 602 such as any of the scanners described above may be passed over an object 604 within a scan space 606 to acquire three-dimensional data. While depicted two-dimensionally, it will be understood that the scan space 606 would generally be a three-dimensional volume. Given a position of the scanner 602 and the object 604, one or more rays - straight lines passing through the scan space 606 - may be determined such as a first ray 608 that intersects a surface of the object 604 and a second ray 610 that does not intersect a surface of the object 604. With the scan space 606 divided into a volumetric mesh according to the spatial matrix described above, all of the voxels that each ray 608, 610 passes through can be determined, and more particularly, each unoccupied one of the voxels in the mesh can be identified. Each unoccupied one of the voxels may be flagged in the spatial matrix as prohibited using, for example, a binary flag or any other

suitable identifier. In this manner, voxels that are known to be unoccupied at some time during the scan can be marked for modified processing and differentially processed during a scan, all as generally contemplated below.

[0058] It will be appreciated that numerous variations are possible. For example, a margin around the surface of the object may be provided in which voxels cannot be flagged for differential processing. This may be based on distance from the surface, or on a number of surrounding voxels that are marked for differential processing, or on the actual number of points of three-dimensional data acquired within a voxel of the mesh, and so forth, as well as combinations of the foregoing. In another aspect, a threshold may be provided for a minimum number of rays passing through a voxel before it can be marked for modified processing. Space carving is generally known in the art as a technique for identifying unoccupied volume, and any corresponding techniques or tools may be adapted to identify 'prohibited' voxels as contemplated herein. For example, commercially available software tools such as Voxel Space (Novalogic) and/or 3D-DDA support ray tracing through voxel spaces and may be used with space carving as described herein. As such, algorithms and software tools for space carving are not discussed here in detail, with emphasis being on use of space carving techniques to support differential processing of three-dimensional data.

[0059] Fig. 7 is a flow chart of a process for displaying data based on a spatial matrix. As generally described below, a spatial matrix such as the matrix described above with reference to Fig. 5 may be used to store information about what type of processing is permitted or forbidden for data within voxels of the scan space. While the 'forbidden' voxels may be generally understood as voxels that are unoccupied, it will be appreciated that this is not universally true and that voxels in which points are detected may be forbidden (such as where a surface temporarily moves into a scan space) and voxels that are empty may be permitted (such as where a voxel is immediately adjacent to an occupied voxel. Thus while terms such as occupied or unoccupied are used in this description, these terms should not be understood as a direct proxy for whether data points are or can be obtained from a voxel, or whether a voxel is permitted (that is, receiving unmodified processing) or forbidden (that is, receiving modified processing).

[0060] As shown in step 702, the process 700 may begin with storing a spatial matrix in a memory, such as the spatial matrix described above that includes information for a plurality of voxels in a mesh of a scan space.

[0061] As shown in step 704, three-dimensional data may be obtained from an object within a scan space using, for example, any of the scanners described above.

[0062] As shown in step 706, the process 700 may include identifying at least one of the plurality of voxels in the scan space that is unoccupied. This may be accomplished, for example, using any suitable ray tracing software or algorithm. A variety of commercially

available software tools (for example 3D-DDA) and general algorithms (for example, Bresenham's line algorithm) are known in the art for traversing voxels in a space and identifying what voxels contain a ray, any of which may be usefully adapted to identifying unoccupied voxels in a scan space as contemplated herein. In a ray tracing embodiment, unoccupied space may, for example, include voxels behind or beyond a known surface of an object, or voxels between a scanner and the surface, as well as combinations of these. In another aspect, other information may also or instead be used to determine whether a voxel should be forbidden or permitted. For example, for a voxel to be forbidden, the process 700 may provide a threshold for a minimum number of adjacent voxels that are already identified as forbidden. In another aspect, the number of rays passing through a voxel may be counted and used, for example, as a minimum threshold for identifying a voxel as forbidden. For occluded surfaces of the scanned object, the process 700 may provide an offset or step away from the border of the occlusion in a field of view. More generally, any suitable techniques for characterizing a voxel as containing or not containing the surface of interest may be suitably employed to identify prohibited space as contemplated herein.

[0063] In one aspect, voxels in a spatial margin of one or more voxels adjacent to a surface of an object being scanned may be prevented from being flagged as prohibited. That is, in order to ensure accuracy of the model, immediately adjacent data may be included regardless of whether an associated voxel is believed to be unoccupied. The spatial margin may, for example, be a single layer of voxels, or a number or depth of voxels as determined, for example, with reference to a standard deviation of z-axis measurements of a scanner. Thus for example, a voxel may be treated as 'permitted' regardless of whether it is occupied by three-dimensional data points if the voxel is within a distance from the surface of a scan subject that is less than one standard deviation, two standard deviations, or some other multiple of the standard deviation of z-axis measurements of the scanner. By controlling this metric, a scanning process may include more or less marginal data that is adjacent to but not on an inferred surface of the object.

[0064] As shown in step 708, the process 700 may include storing an indication for modified processing of the one of the plurality of voxels in the spatial matrix 710. After completing this step for one or more of the plurality of voxels, the spatial matrix identifies a prohibited volume that includes one or more voxels within the scan space. It will be understood that identifying the prohibited volume may be a cumulative process that is repeated as each new frame of three-dimensional data is repeated for a scan such as the sequential scans described above. Thus for example, each frame of data may provide different information on surfaces of the object that are occluded, that have changed, or that have disappeared, and this information may be generally used to update the spatial matrix in any suitable way. In general, it is contemplated that every voxel of the matrix is a permitted voxel

until a reliable inference can be made that the voxel should be prohibited. However, this is not strictly required, and variations to this initial condition may be made without departing from the scope of this disclosure.

[0065] As noted above, a voxel in the prohibited volume - that is, a voxel that receives modified processing - is not necessarily a voxel that is unoccupied. For example, if a new frame of data provides a first instance of a point, surface, or object that is not in a voxel in previous frames of data, then the voxel is occupied even though nominally 'prohibited'. Conversely, an unoccupied voxel may be nominally 'permitted,' such as a margin of voxels around a surface of an object, or a voxel for which sufficient data has not yet been acquired to conclude that the voxel should receive modified processing (that is, that the voxel is 'prohibited'). The prohibited volume may generally include more than one of the voxels in the mesh or spatial matrix.

[0066] The process 700 may then return to step 704 where additional three-dimensional data is obtained.

[0067] Concurrently with or subsequent to the identification of a prohibited volume, the process 700 may engage in a three-dimensional scanning process to obtain a three-dimensional surface representation or other digital model of a scan subject.

[0068] As shown in step 712, the process 700 may include obtaining three-dimensional data. This may be the same data acquired in step 704, or different data, or some combination of these.

[0069] As shown in step 714, one or more corresponding voxels may be identified in the spatial matrix 710. In this step, the location may be used to retrieve a processing indicator such as a 'permitted' or 'forbidden' flag for voxels from the spatial matrix 710. This information may in turn be used to apply differential processing as described below.

[0070] As shown in step 716, the process 700 may include processing a portion of the three-dimensional data that is not in the prohibited volume - or alternatively stated, three-dimensional data that is in the permitted volume of the scan space ---according to an unmodified or normal processing. This may include any processing associated with the acquisition of three-dimensional data such as derivation of a camera path for a scanner, feature-based or other derivation of individual three-dimensional data points from frames of video or image data, registration of three-dimensional surfaces and so forth. In general, it is contemplated that any three-dimensional process that does not use space carving or the like may be performed in an 'unmodified' processing step as that term is used herein, including without limitation acquisition, display, and refinement (for example, optimization, error minimization, etc.) of a three-dimensional surface representation based on, for example, a sequence of frames of image data or the like from a three-dimensional scanner.

[0071] As shown in step 718, the process 700 may include processing a portion of the three-dimensional data that is in the prohibited volume according to the modified processing. Modified processing may include any processing suitable for data in the 'prohibited' volume.

[0072] Modified processing may, for example, include selective use of three-dimensional data points in a three-dimensional reconstruction according to whether they are in prohibited or permitted volumes of the scan space. For example, a reconstruction process may treat data within the prohibited volume as outliers that are excluded from processing. Or data in the prohibited volume may be de-weighted or otherwise de-emphasized in the reconstruction process. This data exclusion or de-weighting may be performed in a real time reconstruction process while three-dimensional data is being displayed, or in a post-processing refinement step, or some combination of these. Thus in one aspect, modified processing includes omitting any points in the prohibited volume from a high-accuracy refinement of the three-dimensional data.

[0073] In another aspect, modified processing may include controlling how data in the prohibited volume is displayed. For example, data within the prohibited volume may be excluded from display, or may be displayed temporarily using a brief decay time such as 0.5 seconds or any other short interval.

[0074] In another aspect, modified processing may include controlling how data in the prohibited volume is used in a surface mesh of the three-dimensional data. For example, points in the prohibited volume may be excluded from a surface mesh of the scanned object created from the three-dimensional (point) data using a marching cubes grid or other surface mesh algorithm. In another aspect, where a processing grid for the surface mesh is identical (or substantially identical) to the mesh of the spatial matrix, voxels from the prohibited volume may be excluded entirely from the surface mesh. Surface mesh generation is a known technique for representing a three-dimensional shape as a collection of vertices, edges and faces that form polygons (for example, triangles, quadrilaterals). In one aspect, the processing mesh for generating such a surface from the three-dimensional data may be co-extensive and equally dimensioned with the mesh used for the spatial matrix, although this is not strictly required. Thus in one aspect the mesh of the scan space used for the spatial matrix may divide the scan space into a spatial grid that is substantially identical to a second spatial grid used to create a surface mesh from the three-dimensional data. In another aspect, the meshes may provide different processing resolutions and/or be unaligned spatially.

[0075] After modified and/or unmodified processing has been performed on three-dimensional data, the process 700 may return to step 712 where additional three-dimensional data is acquired. This process 700 may continue until a scan is manually or automatically stopped, or otherwise terminated.

[0076] As such there is generally disclosed herein methods and systems for differential processing of data in a three-dimensional data acquisition process according to where the data occurs in a scan space. It will be appreciated that, while the process 700 of Fig. 7 is representative, numerous variations may be made without departing from the scope of the invention. For example space carving and data processing (for example, of steps 716, 718) may be performed independently, or within a single repeating sequential process, or some combination of these. In addition, identifying the prohibited volume, or portions thereof, may be performed before, during, or after the data processing of steps 716 and 718, or some combination of these. Still more generally, any order and combination of steps that might be recognized as useful for identifying forbidden/permitted voxels in a scan space on one hand, and acquiring data for a three-dimensional reconstruction on the other, may be adapted to use with the methods and systems described herein without departing from the scope of this disclosure.

[0077] It will be appreciated that the processes and methods disclosed above may be realized in hardware, software, or any combination of these suitable for the three-dimensional imaging and modeling techniques described herein. It will also be appreciated that the user interfaces, user interface controls, and methods of using same, as well as the visualizations, digital model processing and analysis, and rendering as described herein may similarly be expressed as methods or processes embodied in hardware, software, and various combinations thereof. Thus in one aspect there is disclosed herein a computer program product comprising computer executable code stored in a transitory or non-transitory medium that, when executing on one or more computers, performs any one or more of the steps described above.

[0078] This also includes realization in one or more microprocessors, microcontrollers, embedded microcontrollers, programmable digital signal processors or other programmable devices, along with internal and/or external memory. The hardware may also, or instead, include one or more application specific integrated circuits, programmable gate arrays, programmable array logic components, or any other device or devices that may be configured to process electronic signals. It will further be appreciated that a realization may include computer executable code created using a structured programming language such as C, an object oriented programming language such as C++, or any other high-level or low-level programming language (including assembly languages, hardware description languages, and database programming languages and technologies) that may be stored, compiled or interpreted to run on one of the above devices, as well as heterogeneous combinations of processors, processor architectures, or combinations of different hardware and software. At the same time, processing may be distributed across devices such as a camera and/or computer in a number of ways or all of the functionality may be integrated into a dedicated,

standalone image capture device. All such permutations and combinations are intended to fall within the scope of the present disclosure.

[0079] It will also be appreciated that means for performing the steps associated with the processes described above may include any suitable components of the image capture system 100 described above with reference to Fig. 1, along with any software and/or hardware suitable for controlling operation of same. The user interfaces described herein may, for example, be rendered within the display 110 of the image capture system 100 of Fig. 1. All such realizations and means for performing the processes disclosed herein are intended to fall within the scope of this disclosure.

[0080] While the invention has been disclosed in connection with certain preferred embodiments, other embodiments will be recognized by those of ordinary skill in the art, and all such variations, modifications, and substitutions are intended to fall within the scope of this disclosure. Thus, the invention is to be understood with reference to the following claims, which are to be interpreted in the broadest sense allowable by law.

CLAIMS:

What is claimed is:

1. A method comprising:
storing a spatial matrix in a memory, the spatial matrix including information for a plurality of voxels in a mesh of a scan space;
obtaining three-dimensional data from an object within the scan space using a scanner;
identifying a one of the plurality of voxels in the mesh that is unoccupied;
storing an indication in the spatial matrix for a modified processing of data from the one of the plurality of voxels, thereby identifying a prohibited volume within the scan space; and
processing a portion of the three-dimensional data that is not in the prohibited volume according to an unmodified processing and processing a second portion of the three-dimensional data that is in the prohibited volume according to the modified processing.
2. The method of claim 1 wherein identifying the one of the plurality of voxels includes identifying a plurality of points on a ray between the scanner and the object that are unoccupied.
3. The method of claim 1 further comprising providing a spatial margin of one or more voxels adjacent to a surface of the object for which processing cannot be prohibited.
4. The method of claim 3 wherein the spatial margin is a multiple of a standard deviation of a z-axis measurement for the scanner.
5. The method of claim 1 wherein the modified processing includes detecting a point in the prohibited volume and displaying the point with a decay time.
6. The method of claim 1 wherein the modified processing includes omitting any points in the prohibited volume from a surface mesh of the object created with the three-dimensional data.
7. The method of claim 6 wherein the mesh divides the scan space into a spatial grid substantially identical to a second spatial grid used to create the surface mesh.

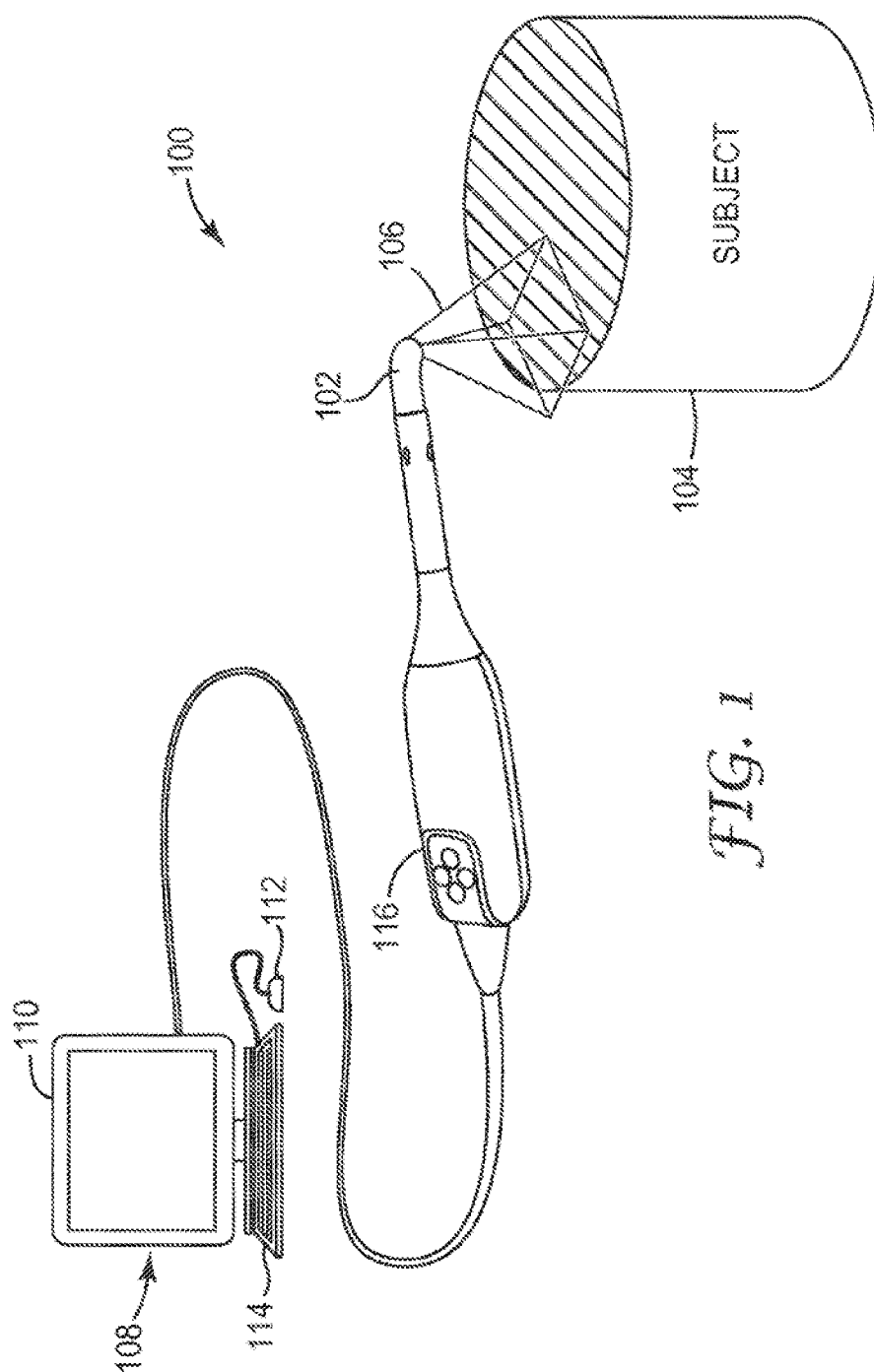
8. The method of claim 1 wherein the modified processing includes omitting any points in the prohibited volume from a high-accuracy refinement of the three-dimensional data.
9. The method of claim 1 wherein the mesh of the scan space is subdivided into voxels having a substantially cubic shape.
10. The method of claim 9 wherein the substantially cubic shape measures about 250 microns on each edge.
11. The method of claim 1 wherein the prohibited volume includes more than one of the plurality of voxels.
12. The method of claim 1 wherein the spatial matrix includes a binary flag for each one of the plurality of voxels that indicates whether processing is permitted or forbidden for a corresponding volume of the scan space.
13. A computer program product comprising computer executable code embodied on a non-transitory computer readable medium that, when executing on one or more computing devices, performs the steps of:
 - storing a spatial matrix in a memory, the spatial matrix storing information for a plurality of voxels in a mesh of a scan space;
 - obtaining three-dimensional data from an object within the scan space using a scanner;
 - identifying one of the plurality of voxels in the mesh of the scan space that is unoccupied;
 - storing an indication in the spatial matrix for a modified processing of data from the one of the plurality of voxels that contains the point, thereby identifying a prohibited volume within the scan space; and
 - processing a portion of the three-dimensional data in the prohibited volume according to the modified processing and processing a second portion of the three-dimensional data that is not in the prohibited volume according to an unmodified processing.
14. The computer program product of claim 13 wherein identifying the one of the plurality of voxels includes identifying a plurality of points on a ray between the scanner and the object that are unoccupied.

15. The computer program product of claim 13 further comprising code for providing a spatial margin of one or more voxels adjacent to a surface of the object for which processing cannot be prohibited.
16. The computer program product of claim 15 wherein the spatial margin is a multiple of a standard deviation of a z-axis measurement for the scanner.
17. The computer program product of claim 13 wherein the modified processing includes detecting a point in the prohibited volume and displaying the point with a decay time.
18. The computer program product of claim 13 wherein the modified processing includes omitting any points in the prohibited volume from a surface mesh of the object created with the three-dimensional data.
19. The computer program product of claim 18 wherein the mesh divides the scan space into a spatial grid substantially identical to a second spatial grid used to create the surface mesh.
20. The computer program product of claim 13 wherein the modified processing includes omitting any points in the prohibited volume from a high-accuracy refinement of the three-dimensional data.
21. The computer program product of claim 13 wherein the mesh of the scan space is subdivided into voxels having a substantially cubic shape.
22. The computer program product of claim 21 wherein the substantially cubic shape measures about 250 microns on each edge.
23. The computer program product of claim 13 wherein the prohibited volume includes more than one of the plurality of voxels.
24. The computer program product of claim 13 wherein the spatial matrix includes a binary flag for each one of the plurality of voxels that indicates whether processing is permitted or forbidden for a corresponding volume of the scan space.

25. A system comprising:
a scanner configured to obtain three-dimensional data from an object within a scan space;
a memory configured to store a spatial matrix that includes information for a plurality of voxels in a mesh of a scan space; and
a processor configured to identify a point in the scan space that is unoccupied, to store an indication in the spatial matrix for a modified processing of data from a one of the plurality of voxels that contains the point, thereby identifying a prohibited volume within the scan space, to process a portion of the three-dimensional data that is not in the prohibited volume according to an unmodified processing, and to process a second portion of the three-dimensional data that is in the prohibited volume according to the modified processing.

26. A system comprising:
storing means for storing a spatial matrix that includes information for a plurality of voxels in a mesh of a scan space;
scanning means for obtaining three-dimensional data from an object within the scan space; and
processing means for identifying a point in the scan space that is unoccupied, storing an indication in storing means for a modified processing of data from a one of the plurality of voxels that contains the point, thereby identifying a prohibited volume within the scan space, processing a portion of the three-dimensional data that is not in the prohibited volume according to an unmodified processing and processing a second portion of the three-dimensional data that is in the prohibited volume according to the modified processing.

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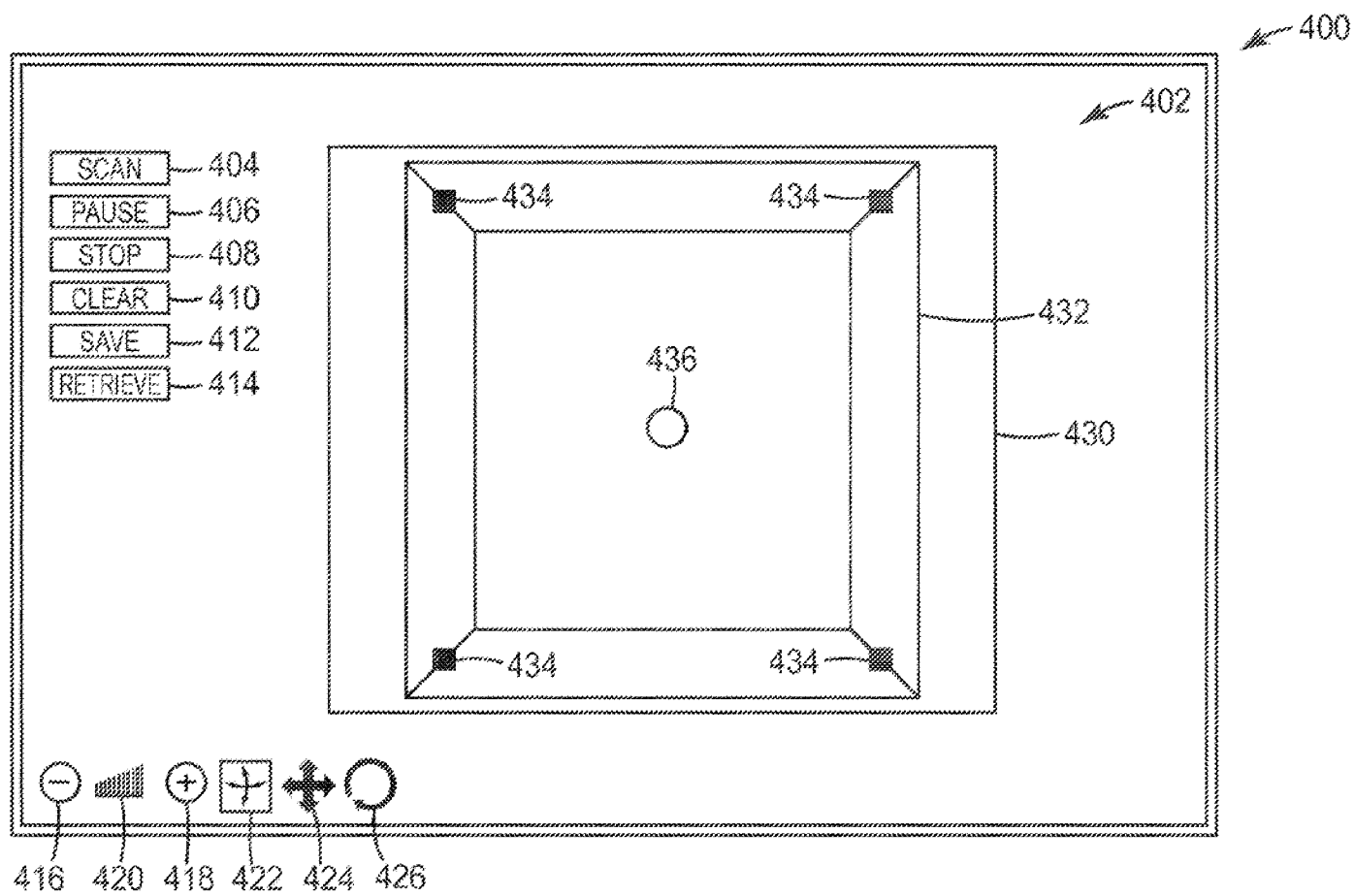


FIG. 2

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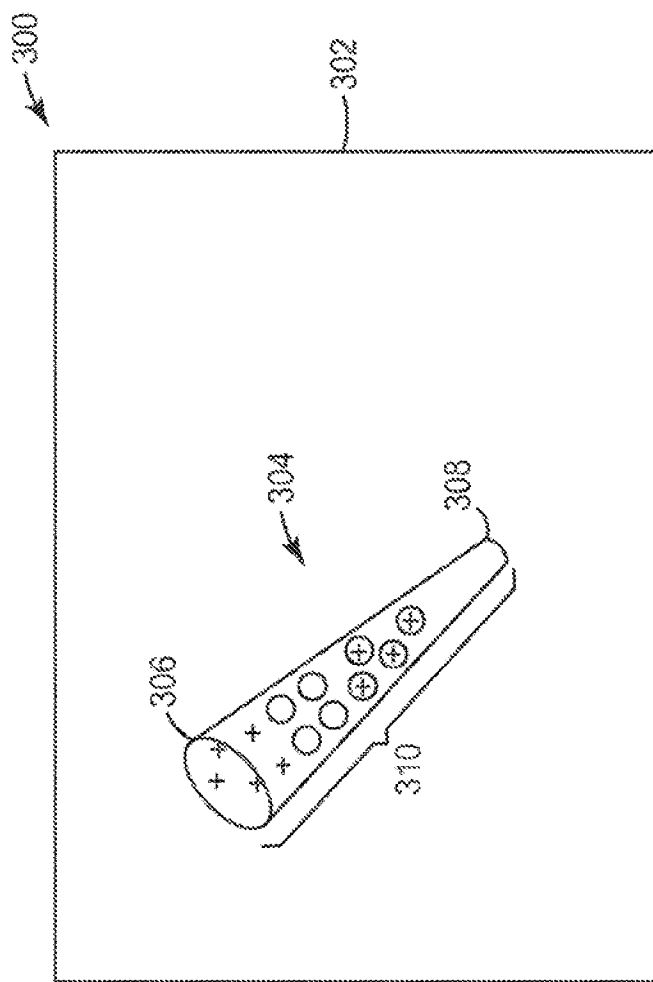


FIG. 3

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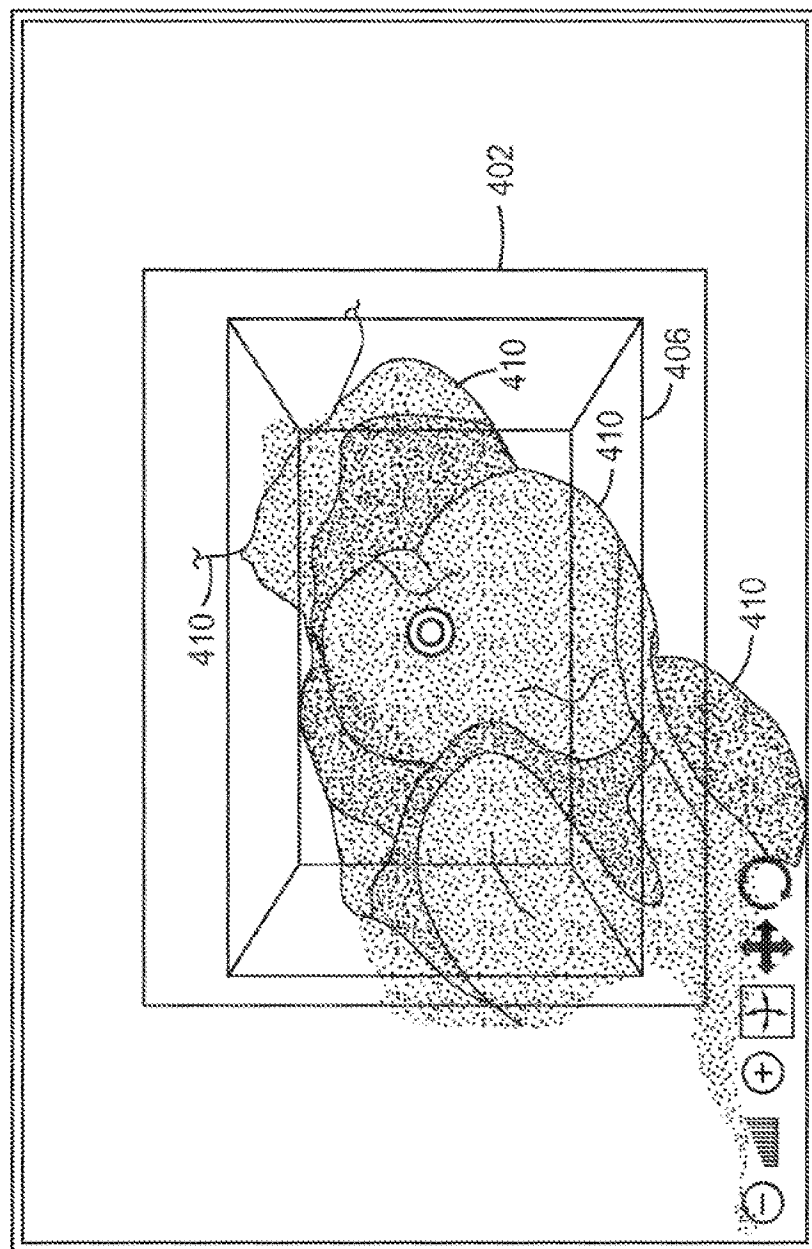
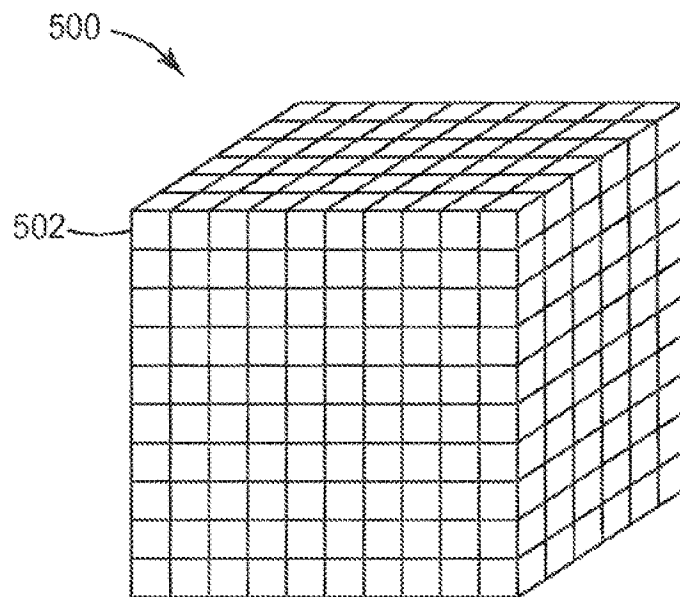
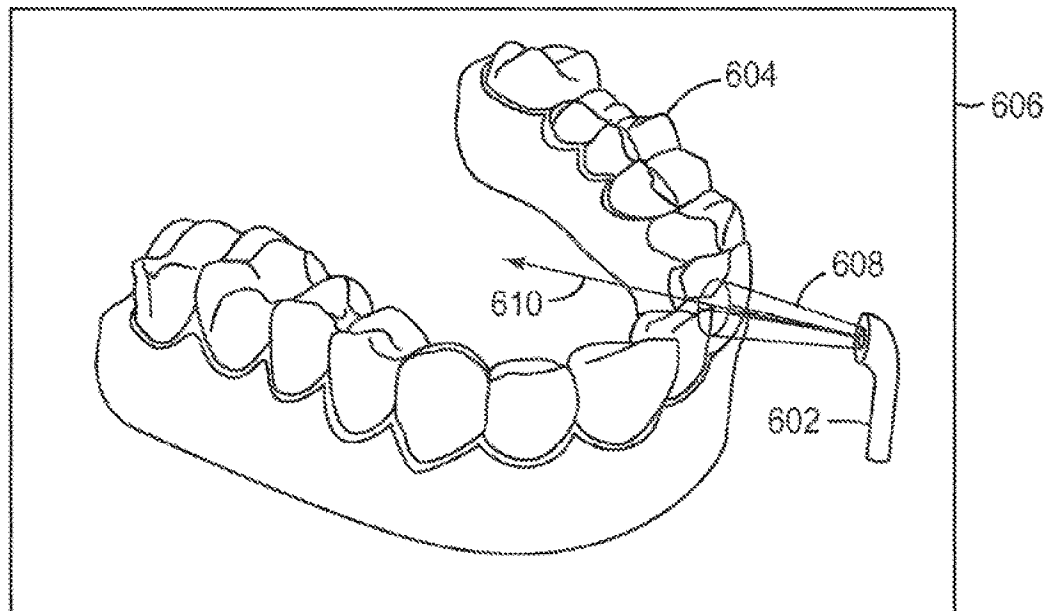


FIG. 4

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*FIG. 5**FIG. 6*

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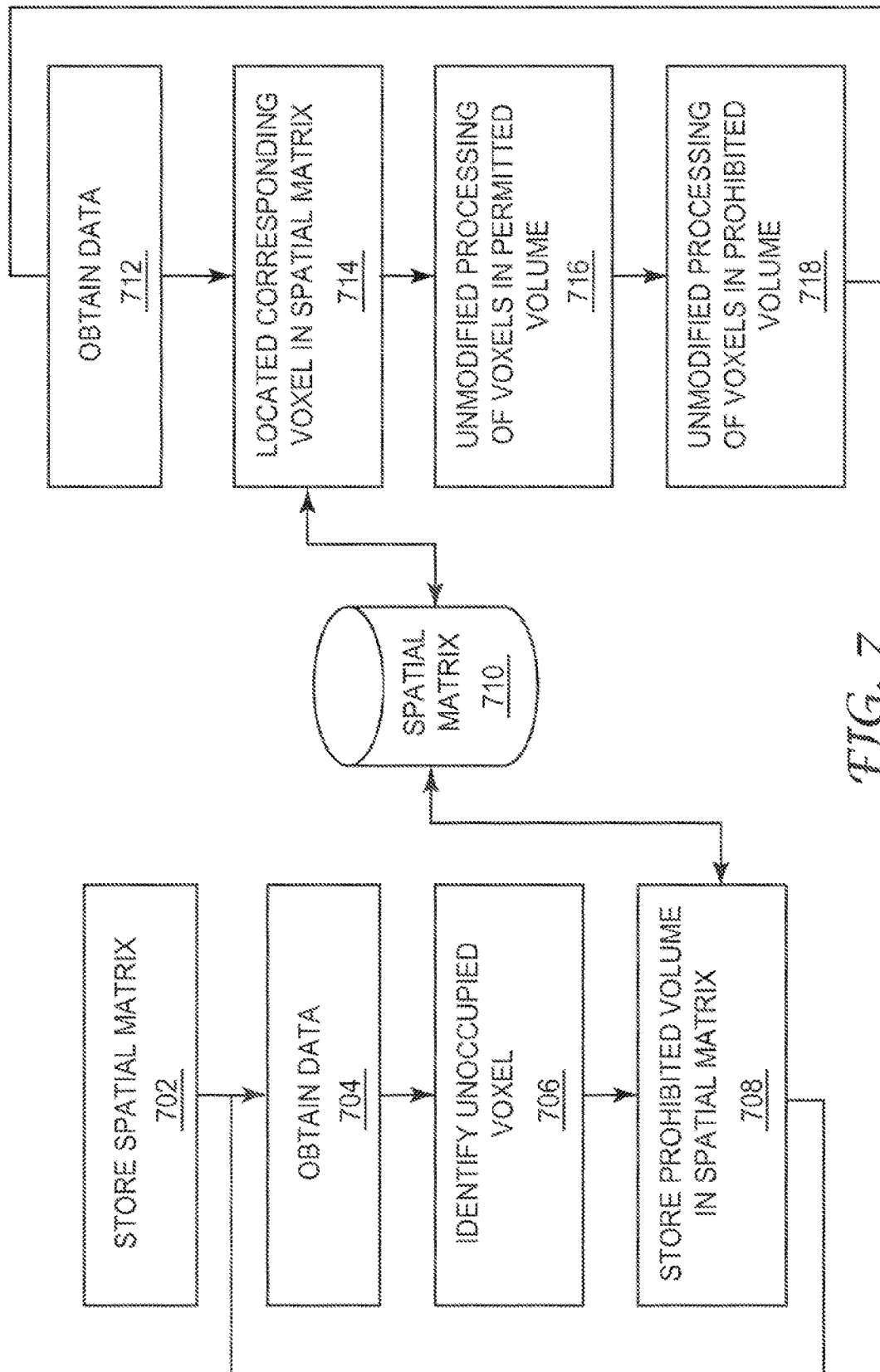


FIG. 7

PATENT COOPERATION TREATY

PCT

OCT 15 2012

INTERNATIONAL SEARCH REPORT

REFERRED TO _____

(PCT Article 18 and Rules 43 and 44)

Applicant's or agent's file reference 67245WO003	FOR FURTHER ACTION see Form PCT/ISA/220 as well as, where applicable, item 5 below.	
International application No. PCT/US2012/025554	International filing date (day/month/year) 17 FEBRUARY 2012 (17.02.2012)	(Earliest) Priority Date (day/month/year) 22 FEBRUARY 2011 (22.02.2011)
Applicant 3M INNOVATIVE PROPERTIES COMPANY et al		

This International search report has been prepared by this International Searching Authority and is transmitted to the applicant according to Article 18. A copy is being transmitted to the International Bureau.

This international search report consists of a total of 3 sheets.

☐ It is also accompanied by a copy of each prior art document cited in this report.

1. **Basis of the report**

a. With regard to the **language**, the international search was carried out on the basis of:

☒ the international application in the language in which it was filed

☐ a translation of the international application into _____, which is the language of a translation furnished for the purposes of international search (Rules 12.3(a) and 23.1(b))

b. ☐ This international search report has been established taking into account the **rectification of an obvious mistake** authorized by or notified to this Authority under Rule 91 (Rule 43.6bis(a)).

c. ☐ With regard to any **nucleotide and/or amino acid sequence** disclosed in the international application, see Box No. I.

2. ☐ **Certain claims were found unsearchable** (See Box No. II)

3. ☐ **Unity of invention is lacking** (See Box No. III)

4. With regard to the **title**,

☒ the text is approved as submitted by the applicant.

☐ the text has been established by this Authority to read as follows:

5. With regard to the **abstract**,

☒ the text is approved as submitted by the applicant.

☐ the text has been established, according to Rule 38.2, by this Authority as it appears in Box No. IV. The applicant may, within one month from the date of mailing of this international search report, submit comments to this Authority.

6. With regard to the **drawings**,

a. the figure of the **drawings** to be published with the abstract is Figure No. 7

☒ as suggested by the applicant.

☐ as selected by this Authority, because the applicant failed to suggest a figure.

☐ as selected by this Authority, because this figure better characterizes the invention.

b. ☐ none of the figure is to be published with the abstract.

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US2012/025554**A. CLASSIFICATION OF SUBJECT MATTER****G06T 17/00(2006.01)i, A61B 1/24(2006.01)i**

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

G06T 17/00; G06F 3/048; H04N 13/02; G06K 9/00; G06F 3/01

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Korean utility models and applications for utility models

Japanese utility models and applications for utility models

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

eKOMPASS(KIPO internal) & Keywords: 3D, register, camera, path

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X A	US 2010-0303341 A1 (Häl:USLER GERD) 02 December 2010 See abstract: paragraphs [0096], [0103]; claims 1, 2, 10; figure 1.	1-7, 12-18, 23, 24 8-11, 19-22
A	US 2007-0172101 A1 (ILYA A. KRIVESHKO et al.) 26 July 2007 See abstract: paragraphs [0022], [0036], [0038], [0049], [0050]; claims 1, 9; figures 2,3.	1-24
A	US 2010-0281370 A1 (ROHALY JANOS et al.) 04 November 2010 See abstract: paragraphs [0045], [0053], [0057], [0059], [0065]; figure 2.	1-24



Further documents are listed in the continuation of Box C.



See patent family annex.

* Special categories of cited documents:

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier application or patent but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search

26 SEPTEMBER 2012 (26.09.2012)

Date of mailing of the international search report

26 SEPTEMBER 2012 (26.09.2012)

Name and mailing address of the ISA/KR

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189 Cheongsa-ro, Seo-gu, Daejeon Metropolitan
City, 302-701, Republic of Korea

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Authorized officer

Moon, Nam Doo

Telephone No. 82-42-481-5751



INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No.

PCT/US2012/025554

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
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		WO 2009-006303 A3	08.01.2009

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Application Number:	14000442
International Application Number:	
Confirmation Number:	8005
Title of Invention:	HYBRID STITCHING
First Named Inventor/Applicant Name:	Ilya A. Kriveshko
Customer Number:	32692
Filer:	Lance L. Vietzke/Paula Bick
Filer Authorized By:	Lance L. Vietzke
Attorney Docket Number:	67245US004
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Filing Date:	20-AUG-2013
Time Stamp:	11:31:27
Application Type:	U.S. National Stage under 35 USC 371

Payment information:

Submitted with Payment	no
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File Listing:

Document Number	Document Description	File Name	File Size(Bytes)/ Message Digest	Multi Part /.zip	Pages (if appl.)
1	Transmittal Letter	IDS1_67245US004.PDF	77247 82913829c029e65ec8db7ab6377880b44466297b	no	2

Warnings:

Information:

2	Information Disclosure Statement (IDS) Form (SB08)	IDS1_1449_67245US004.PDF	96926	no	2
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Warnings:					
Information:					
6	Non Patent Literature	DORST_First_Order_Error_2005_pp221-229_.PDF	505696	no	9
			7450c5ef0c0794d98532dfd368902112e01f23a4		
Warnings:					
Information:					
7	Non Patent Literature	GOVINDU_Combining_Two-View_2001_pp218-225_.PDF	1453808	no	8
			2cd35a54d2f894c4ad8b1a9f601175e959919452		
Warnings:					
Information:					
8	Non Patent Literature	KRISHNAN_Global_registration_of_2005_11pages_.PDF	2027255	no	11
			ae64e4b9da3e97647066daa8279faf6e9d2d3f69		
Warnings:					
Information:					
9	Non Patent Literature	WILLIAMS_Simultaneous_Regis-tration_of_2001_117-142_.PDF	18360104	no	26
			c6b72427796371c98354332217685374fc73b369		
Warnings:					
Information:					
10	Other Reference-Patent/App/Search documents	ISA210INTLSEARCHRPT.PDF	139469	no	3
			07e4971ce88c8296e9ad9e65e44d9ce09501a0c6		

Warnings:	
Information:	
Total Files Size (in bytes):	43032822
This Acknowledgement Receipt evidences receipt on the noted date by the USPTO of the indicated documents, characterized by the applicant, and including page counts, where applicable. It serves as evidence of receipt similar to a Post Card, as described in MPEP 503. <u>New Applications Under 35 U.S.C. 111</u> If a new application is being filed and the application includes the necessary components for a filing date (see 37 CFR 1.53(b)-(d) and MPEP 506), a Filing Receipt (37 CFR 1.54) will be issued in due course and the date shown on this Acknowledgement Receipt will establish the filing date of the application. <u>National Stage of an International Application under 35 U.S.C. 371</u> If a timely submission to enter the national stage of an international application is compliant with the conditions of 35 U.S.C. 371 and other applicable requirements a Form PCT/DO/EO/903 indicating acceptance of the application as a national stage submission under 35 U.S.C. 371 will be issued in addition to the Filing Receipt, in due course. <u>New International Application Filed with the USPTO as a Receiving Office</u> If a new international application is being filed and the international application includes the necessary components for an international filing date (see PCT Article 11 and MPEP 1810), a Notification of the International Application Number and of the International Filing Date (Form PCT/RO/105) will be issued in due course, subject to prescriptions concerning national security, and the date shown on this Acknowledgement Receipt will establish the international filing date of the application.	

32692
Customer Number

Patent
Case No.: 67245US004

IN THE UNITED STATES PATENT AND TRADEMARK OFFICE

First Named Inventor: KRIVESHKO, ILYA A

Application No.: 14/000442

Confirmation No.: 8005

Filed: 17-FEB-2012

Title HYBRID STITCHING

INFORMATION DISCLOSURE STATEMENT

Mail Stop: Amendment
Commissioner for Patents
P.O. Box 1450
Alexandria, VA 22313-1450

CERTIFICATE OF MAILING OR TRANSMISSION [37 CFR § 1.8(a)]

I hereby certify that this correspondence is being:

- ☒ transmitted to United States Patent and Trademark Office on the date shown below via the Office electronic filing system.
- ☐ deposited with the United States Postal Service on the date shown below with sufficient postage as first class mail in an envelope addressed to: Commissioner for Patents, P.O. Box 1450, Alexandria, VA 22313-1450.
- ☐ transmitted by facsimile on the date shown below to the United States Patent and Trademark Office at 571-273-8300.

March 14, 2014

/Paula J. Bick/

Date

Signed by: Paula J. Bick

Dear Sir:

Pursuant to 37 CFR §§ 1.56, 1.97, and 1.98, enclosed is a completed Form PTO-1449, citing references submitted for consideration by the Examiner. It is respectfully requested that the Examiner initial and return the enclosed Form PTO-1449 to indicate that each reference has been considered.

This Information Disclosure Statement is being filed within three months of the filing date of the application, or within three months of entry into the national stage, or before the mailing of a first Office Action on the merits.

Fees

- ☒ It is believed that no fee is due; however, in the event a fee is required, please charge the fee to Deposit Account No. 13-3723.
- ☐ The fee required under 37 CFR § 1.17(p) will be paid at the time of EFS-Web submission. In the event fees are not or cannot be paid at the time of EFS-Web submission, please charge any fees under 37 CFR § 1.17 which may be required to Deposit Account No. 13-3723.
- ☐ Please charge the fee provided in 37 CFR § 1.17(p) to Deposit Account No. 13-3723.

Copies of Documents

Copies of any cited foreign patents, foreign publications, non-patent literature documents, and any pending U.S. applications filed before June 30, 2003, are enclosed. Copies of any pending U.S. applications filed after June 30, 2003 that can be accessed on the USPTO's IFW system are not enclosed as per USPTO Waiver dated September 21, 2004. Copies of any U.S. patents and published U.S. patent applications are not enclosed.

Respectfully submitted,

March 13, 2014

Date

By: _____/Lance Vietzke/

Lance L. Vietzke, Reg. No.: 36,708

Telephone No.: 651-737-2180

Office of Intellectual Property Counsel
3M Innovative Properties Company
Facsimile No.: 651-736-3833



UNITED STATES PATENT AND TRADEMARK OFFICE

UNITED STATES DEPARTMENT OF COMMERCE
United States Patent and Trademark Office
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P.O. Box 1450
Alexandria, Virginia 22313-1450
www.uspto.gov

APPLICATION NUMBER	FILING OR 371(C) DATE	FIRST NAMED APPLICANT	ATTY. DOCKET NO./TITLE
14/000,442	08/20/2013	Ilya A. Kriveshko	67245US004

CONFIRMATION NO. 8005

PUBLICATION NOTICE



OC000000065494693

32692
3M INNOVATIVE PROPERTIES COMPANY
PO BOX 33427
ST. PAUL, MN 55133-3427

Title:HYBRID STITCHING

Publication No.US-2013-0329020-A1

Publication Date:12/12/2013

NOTICE OF PUBLICATION OF APPLICATION

The above-identified application will be electronically published as a patent application publication pursuant to 37 CFR 1.211, et seq. The patent application publication number and publication date are set forth above.

The publication may be accessed through the USPTO's publically available Searchable Databases via the Internet at www.uspto.gov. The direct link to access the publication is currently <http://www.uspto.gov/patft/>.

The publication process established by the Office does not provide for mailing a copy of the publication to applicant. A copy of the publication may be obtained from the Office upon payment of the appropriate fee set forth in 37 CFR 1.19(a)(1). Orders for copies of patent application publications are handled by the USPTO's Office of Public Records. The Office of Public Records can be reached by telephone at (703) 308-9726 or (800) 972-6382, by facsimile at (703) 305-8759, by mail addressed to the United States Patent and Trademark Office, Office of Public Records, Alexandria, VA 22313-1450 or via the Internet.

In addition, information on the status of the application, including the mailing date of Office actions and the dates of receipt of correspondence filed in the Office, may also be accessed via the Internet through the Patent Electronic Business Center at www.uspto.gov using the public side of the Patent Application Information and Retrieval (PAIR) system. The direct link to access this status information is currently <http://pair.uspto.gov/>. Prior to publication, such status information is confidential and may only be obtained by applicant using the private side of PAIR.

Further assistance in electronically accessing the publication, or about PAIR, is available by calling the Patent Electronic Business Center at 1-866-217-9197.

Office of Data Management, Application Assistance Unit (571) 272-4000, or (571) 272-4200, or 1-888-786-0101



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UNITED STATES DEPARTMENT OF COMMERCE
United States Patent and Trademark Office
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Alexandria, Virginia 22313-1450
www.uspto.gov

U.S. APPLICATION NUMBER NO.	FIRST NAMED APPLICANT	ATTY. DOCKET NO.
14/000,442	Ilya A. Kriveshko	67245US004

32692
3M INNOVATIVE PROPERTIES COMPANY
PO BOX 33427
ST. PAUL, MN 55133-3427

INTERNATIONAL APPLICATION NO.	
PCT/US12/25554	
I.A. FILING DATE	PRIORITY DATE
02/17/2012	02/22/2011

CONFIRMATION NO. 8005
371 ACCEPTANCE LETTER



Date Mailed: 09/04/2013

NOTICE OF ACCEPTANCE OF APPLICATION UNDER 35 U.S.C 371 AND 37 CFR 1.495

The applicant is hereby advised that the United States Patent and Trademark Office in its capacity as a Designated / Elected Office (37 CFR 1.495), has determined that the above identified international application has met the requirements of 35 U.S.C. 371, and is ACCEPTED for national patentability examination in the United States Patent and Trademark Office.

The United States Application Number assigned to the application is shown above and the relevant dates are:

08/20/2013
DATE OF RECEIPT OF 35 U.S.C. 371(c)(1),
(c)(2) and (c)(4) REQUIREMENTS

08/22/2013
DATE OF COMPLETION OF ALL
35 U.S.C. 371 REQUIREMENTS

A Filing Receipt (PTO-103X) will be issued for the present application in due course. **THE DATE APPEARING ON THE FILING RECEIPT AS THE " FILING DATE" IS THE DATE ON WHICH THE LAST OF THE 35 U.S.C. 371 (c)(1), (c)(2) and (c)(4) REQUIREMENTS HAS BEEN RECEIVED IN THE OFFICE. THIS DATE IS SHOWN ABOVE.** *The filing date of the above identified application is the international filing date of the international application (Article 11(3) and 35 U.S.C. 363).* Once the Filing Receipt has been received, send all correspondence to the Group Art Unit designated thereon.

The following items have been received:

- Copy of the International Application filed on 08/20/2013
- Copy of the International Search Report filed on 08/20/2013
- Oath or Declaration filed on 08/20/2013
- U.S. Basic National Fees filed on 08/20/2013
- Priority Documents filed on 08/20/2013
- Authorization to Permit Access filed on 08/20/2013

Applicant is reminded that any communications to the United States Patent and Trademark Office must be mailed to the address given in the heading and include the U.S. application no. shown above (37 CFR 1.5)

KAREN M WILLIAMS

Telephone: (571) 272-9075

PATENT APPLICATION FEE DETERMINATION RECORD Substitute for Form PTO-875						Application or Docket Number 14/000,442			
APPLICATION AS FILED - PART I									
(Column 1)		(Column 2)		SMALL ENTITY		OTHER THAN SMALL ENTITY			
FOR	NUMBER FILED	NUMBER EXTRA	RATE(\$)	FEE(\$)		RATE(\$)	FEE(\$)		
BASIC FEE (37 CFR 1.16(a), (b), or (c))	N/A	N/A	N/A			N/A	280		
SEARCH FEE (37 CFR 1.16(k), (l), or (m))	N/A	N/A	N/A			N/A	480		
EXAMINATION FEE (37 CFR 1.16(o), (p), or (q))	N/A	N/A	N/A			N/A	720		
TOTAL CLAIMS (37 CFR 1.16(j))	24	minus 20 = *	4			x 80 =	320		
INDEPENDENT CLAIMS (37 CFR 1.16(h))	4	minus 3 = *	1			x 420 =	420		
APPLICATION SIZE FEE (37 CFR 1.16(s))			If the specification and drawings exceed 100 sheets of paper, the application size fee due is \$310 (\$155 for small entity) for each additional 50 sheets or fraction thereof. See 35 U.S.C. 41(a)(1)(G) and 37 CFR 1.16(s).			0.00			
MULTIPLE DEPENDENT CLAIM PRESENT (37 CFR 1.16(j))						0.00			
				TOTAL		TOTAL	2220		
* If the difference in column 1 is less than zero, enter "0" in column 2.									
APPLICATION AS AMENDED - PART II									
(Column 1)		(Column 2)		(Column 3)		SMALL ENTITY		OTHER THAN SMALL ENTITY	
AMENDMENT A		CLAIMS REMAINING AFTER AMENDMENT		HIGHEST NUMBER PREVIOUSLY PAID FOR	PRESENT EXTRA	RATE(\$)	ADDITIONAL FEE(\$)	RATE(\$)	ADDITIONAL FEE(\$)
	Total (37 CFR 1.16(i))	*	Minus	**	=	x =		x =	
	Independent (37 CFR 1.16(h))	*	Minus	***	=	x =		x =	
	Application Size Fee (37 CFR 1.16(s))								
	FIRST PRESENTATION OF MULTIPLE DEPENDENT CLAIM (37 CFR 1.16(j))								
						TOTAL ADD'L FEE		TOTAL ADD'L FEE	
AMENDMENT B		CLAIMS REMAINING AFTER AMENDMENT		HIGHEST NUMBER PREVIOUSLY PAID FOR	PRESENT EXTRA	RATE(\$)	ADDITIONAL FEE(\$)	RATE(\$)	ADDITIONAL FEE(\$)
	Total (37 CFR 1.16(i))	*	Minus	**	=	x =		x =	
	Independent (37 CFR 1.16(h))	*	Minus	***	=	x =		x =	
	Application Size Fee (37 CFR 1.16(s))								
	FIRST PRESENTATION OF MULTIPLE DEPENDENT CLAIM (37 CFR 1.16(j))								
						TOTAL ADD'L FEE		TOTAL ADD'L FEE	
* If the entry in column 1 is less than the entry in column 2, write "0" in column 3. ** If the "Highest Number Previously Paid For" IN THIS SPACE is less than 20, enter "20". *** If the "Highest Number Previously Paid For" IN THIS SPACE is less than 3, enter "3". The "Highest Number Previously Paid For" (Total or Independent) is the highest found in the appropriate box in column 1.									

MULTIPLE DEPENDENT CLAIM FEE CALCULATION SHEET Substitute for Form PTO-1360 (For use with Form PTO/SB/06)							Application Number 14000442		Filing Date					
							Applicant(s) Ilya Kriveshko							
							* May be used for additional claims or amendments							
CLAIMS	AS FILED		AFTER FIRST AMENDMENT		AFTER SECOND AMENDMENT				*		*		*	
	Indep	Depend	Indep	Depend	Indep	Depend			Indep	Depend	Indep	Depend	Indep	Depend
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Total Depend	20	↙	0	↙	0	↙								
Total Claims	24		0		0									
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APPLICATION NUMBER	FILING or 371(c) DATE	GRP ART UNIT	FIL FEE REC'D	ATTY. DOCKET NO	TOT CLAIMS	IND CLAIMS
14/000,442	08/20/2013		2220	67245US004	24	4

CONFIRMATION NO. 8005

32692
3M INNOVATIVE PROPERTIES COMPANY
PO BOX 33427
ST. PAUL, MN 55133-3427

FILING RECEIPT



Date Mailed: 09/04/2013

Receipt is acknowledged of this non-provisional patent application. The application will be taken up for examination in due course. Applicant will be notified as to the results of the examination. Any correspondence concerning the application must include the following identification information: the U.S. APPLICATION NUMBER, FILING DATE, NAME OF APPLICANT, and TITLE OF INVENTION. Fees transmitted by check or draft are subject to collection. Please verify the accuracy of the data presented on this receipt. **If an error is noted on this Filing Receipt, please submit a written request for a Filing Receipt Correction. Please provide a copy of this Filing Receipt with the changes noted thereon. If you received a "Notice to File Missing Parts" for this application, please submit any corrections to this Filing Receipt with your reply to the Notice. When the USPTO processes the reply to the Notice, the USPTO will generate another Filing Receipt incorporating the requested corrections**

Inventor(s)

Ilya A. Kriveshko, Littleton, MA;
Benjamin Frantzdale, Shrewsbury, MA;

Applicant(s)

Ilya A. Kriveshko, Littleton, MA;
Benjamin Frantzdale, Shrewsbury, MA;

Assignment For Published Patent Application

3M INNOVATIVE PROPERTIES COMPANY, St. Paul, MN

Power of Attorney: The patent practitioners associated with Customer Number 32692

Domestic Priority data as claimed by applicant

This application is a 371 of PCT/US12/25554 02/17/2012
which claims benefit of 61/445,464 02/22/2011

Foreign Applications for which priority is claimed (You may be eligible to benefit from the **Patent Prosecution Highway** program at the USPTO. Please see <http://www.uspto.gov> for more information.) - None.

Foreign application information must be provided in an Application Data Sheet in order to constitute a claim to foreign priority. See 37 CFR 1.55 and 1.76.

Permission to Access - A proper **Authorization to Permit Access to Application by Participating Offices** (PTO/SB/39 or its equivalent) has been received by the USPTO.

If Required, Foreign Filing License Granted: 08/29/2013

The country code and number of your priority application, to be used for filing abroad under the Paris Convention, is **US 14/000,442**

Projected Publication Date: 12/12/2013

Non-Publication Request: No

Early Publication Request: No

Title

HYBRID STITCHING

Preliminary Class

Statement under 37 CFR 1.55 or 1.78 for AIA (First Inventor to File) Transition Applications: No

PROTECTING YOUR INVENTION OUTSIDE THE UNITED STATES

Since the rights granted by a U.S. patent extend only throughout the territory of the United States and have no effect in a foreign country, an inventor who wishes patent protection in another country must apply for a patent in a specific country or in regional patent offices. Applicants may wish to consider the filing of an international application under the Patent Cooperation Treaty (PCT). An international (PCT) application generally has the same effect as a regular national patent application in each PCT-member country. The PCT process **simplifies** the filing of patent applications on the same invention in member countries, but **does not result** in a grant of "an international patent" and does not eliminate the need of applicants to file additional documents and fees in countries where patent protection is desired.

Almost every country has its own patent law, and a person desiring a patent in a particular country must make an application for patent in that country in accordance with its particular laws. Since the laws of many countries differ in various respects from the patent law of the United States, applicants are advised to seek guidance from specific foreign countries to ensure that patent rights are not lost prematurely.

Applicants also are advised that in the case of inventions made in the United States, the Director of the USPTO must issue a license before applicants can apply for a patent in a foreign country. The filing of a U.S. patent application serves as a request for a foreign filing license. The application's filing receipt contains further information and guidance as to the status of applicant's license for foreign filing.

Applicants may wish to consult the USPTO booklet, "General Information Concerning Patents" (specifically, the section entitled "Treaties and Foreign Patents") for more information on timeframes and deadlines for filing foreign patent applications. The guide is available either by contacting the USPTO Contact Center at 800-786-9199, or it can be viewed on the USPTO website at <http://www.uspto.gov/web/offices/pac/doc/general/index.html>.

For information on preventing theft of your intellectual property (patents, trademarks and copyrights), you may wish to consult the U.S. Government website, <http://www.stopfakes.gov>. Part of a Department of Commerce initiative, this website includes self-help "toolkits" giving innovators guidance on how to protect intellectual property in specific countries such as China, Korea and Mexico. For questions regarding patent enforcement issues, applicants may call the U.S. Government hotline at 1-866-999-HALT (1-866-999-4258).

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Title 35, United States Code, Section 184
Title 37, Code of Federal Regulations, 5.11 & 5.15

GRANTED

The applicant has been granted a license under 35 U.S.C. 184, if the phrase "IF REQUIRED, FOREIGN FILING LICENSE GRANTED" followed by a date appears on this form. Such licenses are issued in all applications where the conditions for issuance of a license have been met, regardless of whether or not a license may be required as set forth in 37 CFR 5.15. The scope and limitations of this license are set forth in 37 CFR 5.15(a) unless an earlier license has been issued under 37 CFR 5.15(b). The license is subject to revocation upon written notification. The date indicated is the effective date of the license, unless an earlier license of similar scope has been granted under 37 CFR 5.13 or 5.14.

This license is to be retained by the licensee and may be used at any time on or after the effective date thereof unless it is revoked. This license is automatically transferred to any related applications(s) filed under 37 CFR 1.53(d). This license is not retroactive.

The grant of a license does not in any way lessen the responsibility of a licensee for the security of the subject matter as imposed by any Government contract or the provisions of existing laws relating to espionage and the national security or the export of technical data. Licensees should apprise themselves of current regulations especially with respect to certain countries, of other agencies, particularly the Office of Defense Trade Controls, Department of State (with respect to Arms, Munitions and Implements of War (22 CFR 121-128)); the Bureau of Industry and Security, Department of Commerce (15 CFR parts 730-774); the Office of Foreign Assets Control, Department of Treasury (31 CFR Parts 500+) and the Department of Energy.

NOT GRANTED

No license under 35 U.S.C. 184 has been granted at this time, if the phrase "IF REQUIRED, FOREIGN FILING LICENSE GRANTED" DOES NOT appear on this form. Applicant may still petition for a license under 37 CFR 5.12, if a license is desired before the expiration of 6 months from the filing date of the application. If 6 months has lapsed from the filing date of this application and the licensee has not received any indication of a secrecy order under 35 U.S.C. 181, the licensee may foreign file the application pursuant to 37 CFR 5.15(b).

SelectUSA

The United States represents the largest, most dynamic marketplace in the world and is an unparalleled location for business investment, innovation, and commercialization of new technologies. The U.S. offers tremendous resources and advantages for those who invest and manufacture goods here. Through SelectUSA, our nation works to promote and facilitate business investment. SelectUSA provides information assistance to the international investor community; serves as an ombudsman for existing and potential investors; advocates on behalf of U.S. cities, states, and regions competing for global investment; and counsels U.S. economic development organizations on investment attraction best practices. To learn more about why the United States is the best country in the world to develop technology, manufacture products, deliver services, and grow your business, visit <http://www.SelectUSA.gov> or call +1-202-482-6800.

FORM PTO-1390 (REV 09-2007)		U.S. DEPARTMENT OF COMMERCE PATENT AND TRADEMARK OFFICE		DATE: August 20, 2013	
TRANSMITTAL LETTER TO THE UNITED STATES DESIGNATED/ELECTED OFFICE (DO/EO/US) CONCERNING A FILING UNDER 35 USC § 371				ATTORNEY DOCKET NUMBER 67245US004	
				U.S. APPLICATION NO. (if known, see 37 CFR § 1.5)	
INTERNATIONAL APPLICATION NO. PCT/US2012/025554		INTERNATIONAL FILING DATE February 17, 2012		PRIORITY DATE CLAIMED February 22, 2011	
TITLE OF INVENTION Hybrid Stitching					
APPLICANT(S) FOR DO/EO/US Ilya Kriveshko, Benjamin Frantzdale					
Applicant herewith submits to the United States Designated/Elected Office (DO/EO/US) the following items and other information:					
1. ☒ This is a FIRST submission of items concerning a filing under 35 USC § 371. 2. ☐ This is a SECOND or SUBSEQUENT submission of items concerning a filing under 35 USC § 371. 3. ☐ This is an express request to begin national examination procedures (35 USC § 371(f)). The submission must include items (5), (6), (9) and (21) indicated below. 4. ☐ The US has been elected (Article 31). 5. ☒ A copy of the International Application as filed (35 USC § 371(c)(2)). a. ☐ is attached hereto (required only if not communicated by the International Bureau). b. ☐ has been communicated by the International Bureau. c. ☒ is not required, as the application was filed in the United States Receiving Office (RO/US) 6. ☐ An English language translation of the International Application as filed (35 USC § 371(c)(2)). a. ☐ is attached hereto b. ☐ has been previously submitted under 35 USC § 154(d)(4) 7. ☒ Amendments to the claims of the International Application under PCT Article 19 (35 USC § 371(c)(3)) a. ☐ are attached hereto (required only if not communicated by the International Bureau). b. ☐ have been communicated by the International Bureau c. ☐ have not been made; however, the time limit for making such amendments has NOT expired d. ☒ have not been made and will not be made. 8. ☐ An English language translation of the amendments to the claims under PCT Article 19 (35 USC § 371(c)(3)). 9. ☒ An oath or declaration of the inventor(s) (35 USC § 371 (c)(4)). 10. ☐ An English language translation of the annexes to the International Preliminary Examination Report under PCT Article 36 (35 USC §§ 371(c)(5)). Items 11 to 20 below concern document(s) or information included: 11. ☐ An Information Disclosure Statement under 37 CFR §§ 1.97 and 1.98 12. ☒ An executed Assignment to 3M Innovative Properties Company will follow. 13. ☐ A Preliminary Amendment. 14. ☒ An Application Data Sheet under 37 CFR § 1.76. 15. ☐ A substitute specification. 16. ☐ A power of attorney and/or change of address letter. 17. ☐ A computer-readable form of the sequence listing in accordance with PCT Rule 13ter.2 and 37 CFR §§ 1.821 – 1.825. 18. ☐ A second copy of the published international application under 35 USC § 154(d)(4). 19. ☐ A second copy of the English language translation of the international application under 35 USC § 154(d)(4). 20. ☐ Other items or information:					

U.S. APPLN. NO. (if known, see 37 CFR § 1.5):		INTERNATIONAL APPN. NO.: PCT/US2012/025554	ATTORNEY'S DOCKET NO.: 67245US004
The following fees will be paid via EFS-Web at the time of filing:			Calculations
21. ☒ Basic national fee (37 CFR 1.492(a)).....\$280			280
22. ☒ Examination fee (37 CFR 1.492(c))			
If the written opinion prepared by ISA/US or the international preliminary examination report prepared by IPEA/US indicates all claims satisfy provisions of PCT Article 33(1)-(4).....\$0			
All other situations.....\$720			720
23. ☒ Search fee (37 CFR 1.492(b)(1))			
If the written opinion prepared by ISA/US or the international preliminary examination report prepared by IPEA/US indicates all claims satisfy provisions of PCT Article 33(1)-(4).....0			
Search fee (37 CFR 1.492(b)(2)) has been paid on the international application to the USPTO as an International Searching Authority.....\$120			
International Search Report prepared by an ISA other than the US and provided to the Office or previously communicated to the US by the IB.....\$480			480
All other situations.....\$600			
TOTAL OF 21, 22 and 23 =			\$1,480.00
☐ Additional fee for specification and drawings filed in paper over 100 sheets (excluding sequence or computer program listing filed in an electronic medium). The fee is \$400 for each additional 50 sheets of paper or fraction thereof.			
Fee Calc	Number Filed	Minus 100	Divide by 50
Application Size Fee	43	100	50
			0
			\$400.00
Surcharge of \$140.00 for furnishing the oath or declaration later than 30 months from the earliest claimed priority date (37 CFR § 1.492(e)).			\$0.00
CLAIMS	NUMBER FILED	EXTRA	RATE
Total claims	24	- 20 =	4
Independent claims	4	- 3 =	1
Add'l fee for one or more multiple dependent claims			\$780.00
Total Amount Due			\$2,220.00
☐ Applicant claims small entity status. See 37 CFR § 1.27. The fees indicated above are reduced by 1/2.			\$0.00
SUBTOTAL =			\$2,220.00
Processing fee of \$140.00 for furnishing the English translation later than 30 months from the earliest priority date (37 CFR § 1.492(f)).			\$0.00
TOTAL NATIONAL FEE =			\$2,220.00
Fee for recording the enclosed assignment (37 CFR § 1.21(h)). The assignment must be accompanied by an appropriate cover sheet (37 CFR §§ 3.28, 3.31). \$40.00 per property			\$0.00
TOTAL FEES ENCLOSED =			\$2,220.00
			Amount to be refunded:
			Amount to be charged
			\$2,220.00
a.	☒	The fee for filing this application will be made at the time of submission via EFS-Web. In the event fees are not or cannot be paid at the time of EFS-Web submission, please charge to Deposit Account No. 13-3723 any fees under 37 CFR §§ 1.16 and 1.17, which may be required to file and during the entire pendency of this application. This authorization includes the fee for any necessary extension of time under 37 CFR § 1.136(a). To the extent any such extension should become necessary, it is hereby requested. Please credit any overpayment to the same deposit account.	
b.	☐	Please charge to Deposit Account No. 13-3723 any fees under 37 CFR §§ 1.16 and 1.17, which may be required to file and during the entire pendency of this application. This authorization includes the fee for any necessary extension of time under 37 CFR § 1.136(a). To the extent any such extension should become necessary, it is hereby requested. Please credit any overpayment to the same deposit account.	
NOTE: Where an appropriate time limit under 37 CFR § 1.495 has not been met, a petition to revive (37 CFR § 1.137(a) or (b)) must be filed and granted to restore the application to pending status.			
Signature			
/Lance Vietzke/			
Name: Lance L. Vietzke		Registration Number: 36,708	
Address: Office of Intellectual Property Counsel 3M Innovative Properties Company		P.O. Box 33427 St. Paul, Minnesota 55133-3427	

☒ Customer Number for

Correspondence Address:

32692

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**TRANSMITTAL LETTER TO THE UNITED STATES
DESIGNATED/ELECTED OFFICE (DO/EO/US)
CONCERNING A FILING UNDER 35 USC § 371**

DATE:

August 20, 2013

ATTORNEY DOCKET NUMBER

67245US004

U.S. APPLICATION NO.

(if known, see 37 CFR § 1.5)

INTERNATIONAL APPLICATION NO.
PCT/US2012/025554INTERNATIONAL FILING DATE
February 17, 2012PRIORITY DATE CLAIMED
February 22, 2011

TITLE OF INVENTION

Hybrid Stitching

APPLICANT(S) FOR DO/EO/US

Ilya Kriveshko, Benjamin Frantzdale

Applicant herewith submits to the United States Designated/Elected Office (DO/EO/US) the following items and other information:

1. ☒ This is a **FIRST** submission of items concerning a filing under 35 USC § 371.
2. ☐ This is a **SECOND** or **SUBSEQUENT** submission of items concerning a filing under 35 USC § 371.
3. ☐ This is an express request to begin national examination procedures (35 USC § 371(f)). The submission must include items (5), (6), (9) and (21) indicated below.
4. ☐ The US has been elected (Article 31).
5. ☒ A copy of the International Application as filed (35 USC § 371(c)(2)).
 - a. ☐ is attached hereto (required only if not communicated by the International Bureau).
 - b. ☐ has been communicated by the International Bureau.
 - c. ☒ is not required, as the application was filed in the United States Receiving Office (RO/US)
6. ☐ An English language translation of the International Application as filed (35 USC § 371(c)(2)).
 - a. ☐ is attached hereto
 - b. ☐ has been previously submitted under 35 USC § 154(d)(4)
7. ☒ Amendments to the claims of the International Application under PCT Article 19 (35 USC § 371(c)(3))
 - a. ☐ are attached hereto (required only if not communicated by the International Bureau).
 - b. ☐ have been communicated by the International Bureau
 - c. ☐ have not been made; however, the time limit for making such amendments has NOT expired
 - d. ☒ have not been made and will not be made.
8. ☐ An English language translation of the amendments to the claims under PCT Article 19 (35 USC § 371(c)(3)).
9. ☒ An oath or declaration of the inventor(s) (35 USC § 371 (c)(4)).
10. ☐ An English language translation of the annexes to the International Preliminary Examination Report under PCT Article 36 (35 USC §§ 371(c)(5)).

Items 11 to 20 below concern document(s) or information included:

11. ☐ An Information Disclosure Statement under 37 CFR §§ 1.97 and 1.98
12. ☒ An executed Assignment to 3M Innovative Properties Company will follow.
13. ☐ A Preliminary Amendment.
14. ☒ An Application Data Sheet under 37 CFR § 1.76.
15. ☐ A substitute specification.
16. ☐ A power of attorney and/or change of address letter.
17. ☐ A computer-readable form of the sequence listing in accordance with PCT Rule 13~~ter~~.2 and 37 CFR §§ 1.821 – 1.825.
18. ☐ A second copy of the published international application under 35 USC § 154(d)(4).
19. ☐ A second copy of the English language translation of the international application under 35 USC § 154(d)(4).
20. ☐ Other items or information:

U.S. APPLN. NO. (if known, see 37 CFR § 1.5):		INTERNATIONAL APPN. NO.: PCT/US2012/025554	ATTORNEY'S DOCKET NO.: 67245US004
The following fees will be paid via EFS-Web at the time of filing:			Calculations
21. ☒ Basic national fee (37 CFR 1.492(a)).....\$280			280
22. ☒ Examination fee (37 CFR 1.492(c))			
If the written opinion prepared by ISA/US or the international preliminary examination report prepared by IPEA/US indicates all claims satisfy provisions of PCT Article 33(1)-(4).....\$0			
All other situations.....\$720			720
23. ☒ Search fee (37 CFR 1.492(b)(1))			
If the written opinion prepared by ISA/US or the international preliminary examination report prepared by IPEA/US indicates all claims satisfy provisions of PCT Article 33(1)-(4).....0			
Search fee (37 CFR 1.492(b)(2)) has been paid on the international application to the USPTO as an International Searching Authority.....\$120			
International Search Report prepared by an ISA other than the US and provided to the Office or previously communicated to the US by the IB.....\$480			480
All other situations.....\$600			
TOTAL OF 21, 22 and 23 =			\$1,480.00
☐ Additional fee for specification and drawings filed in paper over 100 sheets (excluding sequence or computer program listing filed in an electronic medium). The fee is \$400 for each additional 50 sheets of paper or fraction thereof.			
Fee Calc	Number Filed	Minus 100	Divide by 50
Application Size Fee	43	100	50
			0
			\$400.00
Surcharge of \$140.00 for furnishing the oath or declaration later than 30 months from the earliest claimed priority date (37 CFR § 1.492(e)).			\$0.00
CLAIMS	NUMBER FILED	EXTRA	RATE
Total claims	24	- 20 =	4
Independent claims	4	- 3 =	1
Add'l fee for one or more multiple dependent claims			\$780.00
Total Amount Due			\$2,220.00
☐ Applicant claims small entity status. See 37 CFR § 1.27. The fees indicated above are reduced by 1/2.			\$0.00
SUBTOTAL =			\$2,220.00
Processing fee of \$140.00 for furnishing the English translation later than 30 months from the earliest priority date (37 CFR § 1.492(f)).			\$0.00
TOTAL NATIONAL FEE =			\$2,220.00
Fee for recording the enclosed assignment (37 CFR § 1.21(h)). The assignment must be accompanied by an appropriate cover sheet (37 CFR §§ 3.28, 3.31). \$40.00 per property			\$0.00
TOTAL FEES ENCLOSED =			\$2,220.00
			Amount to be refunded:
			Amount to be charged
			\$2,220.00
a.	☒	The fee for filing this application will be made at the time of submission via EFS-Web. In the event fees are not or cannot be paid at the time of EFS-Web submission, please charge to Deposit Account No. 13-3723 any fees under 37 CFR §§ 1.16 and 1.17, which may be required to file and during the entire pendency of this application. This authorization includes the fee for any necessary extension of time under 37 CFR § 1.136(a). To the extent any such extension should become necessary, it is hereby requested. Please credit any overpayment to the same deposit account.	
b.	☐	Please charge to Deposit Account No. 13-3723 any fees under 37 CFR §§ 1.16 and 1.17, which may be required to file and during the entire pendency of this application. This authorization includes the fee for any necessary extension of time under 37 CFR § 1.136(a). To the extent any such extension should become necessary, it is hereby requested. Please credit any overpayment to the same deposit account.	
NOTE: Where an appropriate time limit under 37 CFR § 1.495 has not been met, a petition to revive (37 CFR § 1.137(a) or (b)) must be filed and granted to restore the application to pending status.			
Signature			
/Lance Vietzke/			
Name: Lance L. Vietzke		Registration Number: 36,708	
Address: Office of Intellectual Property Counsel 3M Innovative Properties Company		P.O. Box 33427 St. Paul, Minnesota 55133-3427	

☒ Customer Number for

Correspondence Address:

32692

-162-

Under the Paperwork Reduction Act of 1995, no persons are required to respond to a collection of information unless it contains a valid OMB control number.

Application Data Sheet 37 CFR 1.76		Attorney Docket Number	67245US004
		Application Number	
Title of Invention	HYBRID STITCHING		
The application data sheet is part of the provisional or nonprovisional application for which it is being submitted. The following form contains the bibliographic data arranged in a format specified by the United States Patent and Trademark Office as outlined in 37 CFR 1.76. This document may be completed electronically and submitted to the Office in electronic format using the Electronic Filing System (EFS) or the document may be printed and included in a paper filed application.			

Secrecy Order 37 CFR 5.2

☐ Portions or all of the application associated with this Application Data Sheet may fall under a Secrecy Order pursuant to 37 CFR 5.2 (Paper filers only. Applications that fall under Secrecy Order may not be filed electronically.)
--

Inventor Information:

Inventor 1					Remove	
Legal Name						
Prefix	Given Name	Middle Name	Family Name	Suffix		
	ILYA	A.	KRIVESHKO			
Residence Information (Select One) ☒ US Residency ☐ Non US Residency ☐ Active US Military Service						
City	LITTLETON	State/Province	MA	Country of Residence ⁱ	US	

Mailing Address of Inventor:

Address 1	P.O. Box 33427					
Address 2						
City	St. Paul	State/Province	MN			
Postal Code	55133-3427	Country ⁱ	US			

Inventor 2					Remove	
Legal Name						
Prefix	Given Name	Middle Name	Family Name	Suffix		
	BENJAMIN		FRANTZDALE			
Residence Information (Select One) ☒ US Residency ☐ Non US Residency ☐ Active US Military Service						
City	SHREWSBURY	State/Province	MA	Country of Residence ⁱ	US	

Mailing Address of Inventor:

Address 1	P.O. BOX 33427					
Address 2						
City	SAINT PAUL	State/Province	MN			
Postal Code	55133-3427	Country ⁱ	US			

All Inventors Must Be Listed - Additional Inventor Information blocks may be generated within this form by selecting the Add button.

Add

Correspondence Information:

Enter either Customer Number or complete the Correspondence Information section below.
For further information see 37 CFR 1.33(a).

Application Data Sheet 37 CFR 1.76		Attorney Docket Number	67245US004
		Application Number	
Title of Invention	HYBRID STITCHING		

☐ An Address is being provided for the correspondence information of this application.

Customer Number	32692		
Email Address		Add Email	Remove Email

Application Information:

Title of the Invention	HYBRID STITCHING		
Attorney Docket Number	67245US004	Small Entity Status Claimed	☐
Application Type	Nonprovisional		
Subject Matter	Utility		
Total Number of Drawing Sheets (if any)		Suggested Figure for Publication (if any)	

Publication Information:

☐ Request Early Publication (Fee required at time of Request 37 CFR 1.219)

☐ **Request Not to Publish.** I hereby request that the attached application not be published under 35 U.S.C. 122(b) and certify that the invention disclosed in the attached application **has not and will not** be the subject of an application filed in another country, or under a multilateral international agreement, that requires publication at eighteen months after filing.

Representative Information:

Representative information should be provided for all practitioners having a power of attorney in the application. Providing this information in the Application Data Sheet does not constitute a power of attorney in the application (see 37 CFR 1.32). Either enter Customer Number or complete the Representative Name section below. If both sections are completed the customer Number will be used for the Representative Information during processing.

Please Select One:	☒ Customer Number	☐ US Patent Practitioner	☐ Limited Recognition (37 CFR 11.9)
Customer Number	32692		

Domestic Benefit/National Stage Information:

This section allows for the applicant to either claim benefit under 35 U.S.C. 119(e), 120, 121, or 365(c) or indicate National Stage entry from a PCT application. Providing this information in the application data sheet constitutes the specific reference required by 35 U.S.C. 119(e) or 120, and 37 CFR 1.78.

Prior Application Status	Pending	Remove	
Application Number	Continuity Type	Prior Application Number	Filing Date (YYYY-MM-DD)
	a 371 of international	PCT/US2012/025554	2012-02-17
Prior Application Status	Expired	Remove	

Application Data Sheet 37 CFR 1.76		Attorney Docket Number	67245US004
		Application Number	
Title of Invention	HYBRID STITCHING		
Application Number	Continuity Type	Prior Application Number	Filing Date (YYYY-MM-DD)
PCT/US2012/025554	non provisional of	61/445464	2011-02-22
Additional Domestic Benefit/National Stage Data may be generated within this form by selecting the Add button.			Add

Foreign Priority Information:

This section allows for the applicant to claim priority to a foreign application. Providing this information in the application data sheet constitutes the claim for priority as required by 35 U.S.C. 119(b) and 37 CFR 1.55(d). When priority is claimed to a foreign application that is eligible for retrieval under the priority document exchange program (PDX) the information will be used by the Office to automatically attempt retrieval pursuant to 37 CFR 1.55(h)(1) and (2). Under the PDX program, applicant bears the ultimate responsibility for ensuring that a copy of the foreign application is received by the Office from the participating foreign intellectual property office, or a certified copy of the foreign priority application is filed, within the time period specified in 37 CFR 1.55(g)(1).

			Remove
Application Number	Country ⁱ	Filing Date (YYYY-MM-DD)	Access Code ^j (if applicable)
Additional Foreign Priority Data may be generated within this form by selecting the Add button.			Add

Statement under 37 CFR 1.55 or 1.78 for AIA (First Inventor to File) Transition Applications

☐ This application (1) claims priority to or the benefit of an application filed before March 16, 2013 and (2) also contains, or contained at any time, a claim to a claimed invention that has an effective filing date on or after March 16, 2013.

Authorization to Permit Access:

☒ Authorization to Permit Access to the Instant Application by the Participating Offices

Application Data Sheet 37 CFR 1.76		Attorney Docket Number	67245US004
		Application Number	
Title of Invention	HYBRID STITCHING		

If checked, the undersigned hereby grants the USPTO authority to provide the European Patent Office (EPO), the Japan Patent Office (JPO), the Korean Intellectual Property Office (KIPO), the World Intellectual Property Office (WIPO), and any other intellectual property offices in which a foreign application claiming priority to the instant patent application is filed access to the instant patent application. See 37 CFR 1.14(c) and (h). This box should not be checked if the applicant does not wish the EPO, JPO, KIPO, WIPO, or other intellectual property office in which a foreign application claiming priority to the instant patent application is filed to have access to the instant patent application.

In accordance with 37 CFR 1.14(h)(3), access will be provided to a copy of the instant patent application with respect to: 1) the instant patent application-as-filed; 2) any foreign application to which the instant patent application claims priority under 35 U.S.C. 119(a)-(d) if a copy of the foreign application that satisfies the certified copy requirement of 37 CFR 1.55 has been filed in the instant patent application; and 3) any U.S. application-as-filed from which benefit is sought in the instant patent application.

In accordance with 37 CFR 1.14(c), access may be provided to information concerning the date of filing this Authorization.

Applicant Information:

Providing assignment information in this section does not substitute for compliance with any requirement of part 3 of Title 37 of CFR to have an assignment recorded by the Office.			
Applicant 1			Remove
If the applicant is the inventor (or the remaining joint inventor or inventors under 37 CFR 1.45), this section should not be completed. The information to be provided in this section is the name and address of the legal representative who is the applicant under 37 CFR 1.43; or the name and address of the assignee, person to whom the inventor is under an obligation to assign the invention, or person who otherwise shows sufficient proprietary interest in the matter who is the applicant under 37 CFR 1.46. If the applicant is an applicant under 37 CFR 1.46 (assignee, person to whom the inventor is obligated to assign, or person who otherwise shows sufficient proprietary interest) together with one or more joint inventors, then the joint inventor or inventors who are also the applicant should be identified in this section.			
Clear			
☒ Assignee	☐ Legal Representative under 35 U.S.C. 117	☐ Joint Inventor	
☐ Person to whom the inventor is obligated to assign.		☐ Person who shows sufficient proprietary interest	
If applicant is the legal representative, indicate the authority to file the patent application, the inventor is:			
Name of the Deceased or Legally Incapacitated Inventor :			
If the Applicant is an Organization check here. ☒			
Organization Name	3M INNOVATIVE PROPERTIES COMPANY		
Mailing Address Information:			
Address 1	P.O. BOX 33427		
Address 2			
City	St. Paul	State/Province	MN
Country ⁱ	US	Postal Code	55133-3427
Phone Number		Fax Number	

Application Data Sheet 37 CFR 1.76		Attorney Docket Number	67245US004
		Application Number	
Title of Invention	HYBRID STITCHING		
Email Address			
Additional Applicant Data may be generated within this form by selecting the Add button.			Add

Non-Applicant Assignee Information:

Providing assignment information in this section does not substitute for compliance with any requirement of part 3 of Title 37 of CFR to have an assignment recorded by the Office.

Assignee 1				
Complete this section only if non-applicant assignee information is desired to be included on the patent application publication in accordance with 37 CFR 1.215(b). Do not include in this section an applicant under 37 CFR 1.46 (assignee, person to whom the inventor is obligated to assign, or person who otherwise shows sufficient proprietary interest), as the patent application publication will include the name of the applicant(s).				
				Remove
If the Assignee is an Organization check here. ☐				
Prefix	Given Name	Middle Name	Family Name	Suffix
Mailing Address Information:				
Address 1				
Address 2				
City		State/Province		
Country i		Postal Code		
Phone Number		Fax Number		
Email Address				
Additional Assignee Data may be generated within this form by selecting the Add button.				Add

Signature:

NOTE: This form must be signed in accordance with 37 CFR 1.33. See 37 CFR 1.4 for signature requirements and certifications				
Signature	/Lance Vietzke/		Date (YYYY-MM-DD)	2013-08-20
First Name	LANCE	Last Name	VIETZKE	Registration Number
				36708
Additional Signature may be generated within this form by selecting the Add button.				Add

Application Data Sheet 37 CFR 1.76		Attorney Docket Number	67245US004
		Application Number	
Title of Invention	HYBRID STITCHING		

This collection of information is required by 37 CFR 1.76. The information is required to obtain or retain a benefit by the public which is to file (and by the USPTO to process) an application. Confidentiality is governed by 35 U.S.C. 122 and 37 CFR 1.14. This collection is estimated to take 23 minutes to complete, including gathering, preparing, and submitting the completed application data sheet form to the USPTO. Time will vary depending upon the individual case. Any comments on the amount of time you require to complete this form and/or suggestions for reducing this burden, should be sent to the Chief Information Officer, U.S. Patent and Trademark Office, U.S. Department of Commerce, P.O. Box 1450, Alexandria, VA 22313-1450. DO NOT SEND FEES OR COMPLETED FORMS TO THIS ADDRESS. **SEND TO: Commissioner for Patents, P.O. Box 1450, Alexandria, VA 22313-1450.**

Privacy Act Statement

The Privacy Act of 1974 (P.L. 93-579) requires that you be given certain information in connection with your submission of the attached form related to a patent application or patent. Accordingly, pursuant to the requirements of the Act, please be advised that: (1) the general authority for the collection of this information is 35 U.S.C. 2(b)(2); (2) furnishing of the information solicited is voluntary; and (3) the principal purpose for which the information is used by the U.S. Patent and Trademark Office is to process and/or examine your submission related to a patent application or patent. If you do not furnish the requested information, the U.S. Patent and Trademark Office may not be able to process and/or examine your submission, which may result in termination of proceedings or abandonment of the application or expiration of the patent.

The information provided by you in this form will be subject to the following routine uses:

1. The information on this form will be treated confidentially to the extent allowed under the Freedom of Information Act (5 U.S.C. 552) and the Privacy Act (5 U.S.C. 552a). Records from this system of records may be disclosed to the Department of Justice to determine whether the Freedom of Information Act requires disclosure of these records.
2. A record from this system of records may be disclosed, as a routine use, in the course of presenting evidence to a court, magistrate, or administrative tribunal, including disclosures to opposing counsel in the course of settlement negotiations.
3. A record in this system of records may be disclosed, as a routine use, to a Member of Congress submitting a request involving an individual, to whom the record pertains, when the individual has requested assistance from the Member with respect to the subject matter of the record.
4. A record in this system of records may be disclosed, as a routine use, to a contractor of the Agency having need for the information in order to perform a contract. Recipients of information shall be required to comply with the requirements of the Privacy Act of 1974, as amended, pursuant to 5 U.S.C. 552a(m).
5. A record related to an International Application filed under the Patent Cooperation Treaty in this system of records may be disclosed, as a routine use, to the International Bureau of the World Intellectual Property Organization, pursuant to the Patent Cooperation Treaty.
6. A record in this system of records may be disclosed, as a routine use, to another federal agency for purposes of National Security review (35 U.S.C. 181) and for review pursuant to the Atomic Energy Act (42 U.S.C. 218(c)).
7. A record from this system of records may be disclosed, as a routine use, to the Administrator, General Services, or his/her designee, during an inspection of records conducted by GSA as part of that agency's responsibility to recommend improvements in records management practices and programs, under authority of 44 U.S.C. 2904 and 2906. Such disclosure shall be made in accordance with the GSA regulations governing inspection of records for this purpose, and any other relevant (i.e., GSA or Commerce) directive. Such disclosure shall not be used to make determinations about individuals.
8. A record from this system of records may be disclosed, as a routine use, to the public after either publication of the application pursuant to 35 U.S.C. 122(b) or issuance of a patent pursuant to 35 U.S.C. 151. Further, a record may be disclosed, subject to the limitations of 37 CFR 1.14, as a routine use, to the public if the record was filed in an application which became abandoned or in which the proceedings were terminated and which application is referenced by either a published application, an application open to public inspections or an issued patent.
9. A record from this system of records may be disclosed, as a routine use, to a Federal, State, or local law enforcement agency, if the USPTO becomes aware of a violation or potential violation of law or regulation.

DECLARATION AND POWER OF ATTORNEY, FOR UTILITY OR DESIGN PATENT APPLICATION (37 CFR § 1.63)	Case No:	67245US004
	First Named Inventor:	Ilya A. Kriveshko
	COMPLETE IF KNOWN	
	Application No.:	
	Filing Date:	
☒ Declaration Submitted with Initial Filing ☐ Declaration Submitted after Initial Filing (surcharge 37 CFR § 1.16(e) required)	Confirmation No.:	

As a below named inventor, I hereby declare that my residence, mailing address, and citizenship are as stated below next to my name, and that I believe I am an original, first, and sole inventor (if only one name is listed below) or an original, first, and joint inventor (if plural names are listed below) of the subject matter which is claimed and for which a patent is sought on the invention entitled:

HYBRID STITCHING

The specification of which

☐ is attached hereto;

☐ was filed on _____
as United States Application No. _____

☒ is identified as PCT International Application No. _____
filed on **February 17, 2012**

PCT/US2012/025554

and was amended on _____ (if applicable).

I hereby state that I have reviewed and understand the contents of the above-identified specification, including the claims, as amended by any amendment specifically referred to above.

I acknowledge the duty to disclose all information known to me to be material to patentability as defined in 37 CFR § 1.56, including for continuation-in-part applications, material information which became available between the filing date of the prior application and the national or PCT international filing date of the continuation-in-part application.

I hereby claim foreign priority benefits under 35 USC §§ 119(a)-(d) or (f), or 365(b) of any foreign application(s) for patent, inventor's or plant breeder's rights certificate(s), or 365(a) of any PCT international application which designated at least one country other than the United States of America, listed below and have also identified below, by checking the box, any foreign application for patent, inventor's or plant breeder's rights certificate(s), or any PCT international application having a filing date before that of the application on which priority is claimed.

Prior Foreign Application No.	Country	Foreign Filing Date (MM/DD/YYYY)	Priority NOT Claimed	Certified Copy Attached	
				YES	NO
			☐	☐	☐
			☐	☐	☐
			☐	☐	☐

I hereby appoint Practitioners at Customer Number 32692 as my attorneys and/or agents with full powers (including the powers of appointment, substitution, and revocation) to prosecute this application and any division, continuation, continuation-in-part, reexamination, or reissue thereof, and to transact all business in the U.S. Patent and Trademark Office connected therewith.

**Customer Number for
Practitioner of Record: 32692**

I also appoint the following Practitioners as my attorneys and/or agents with full powers (including the powers of appointment, substitution, and revocation) to prosecute this application and any division, continuation, continuation-in-part, reexamination, or reissue thereof, and to transact all business in the U.S. Patent and Trademark Office connected therewith: None

The mailing address and the telephone number of the above-identified attorneys and/or agents are that of Customer No. **32692**.

Inquiries regarding this application can be made to:

Attention: Lance L. Vietzke
Office of Intellectual Property Counsel
3M Innovative Properties Company
Telephone No.: 651-737-2180

I hereby declare that all statements made herein of my own knowledge are true and that all statements made on information and belief are believed to be true; and further that these statements were made with the knowledge that willful false statements and the like so made are punishable by fine or imprisonment, or both, under 18 USC § 1001 and that such willful false statements may jeopardize the validity of the application or any patent issued thereon.

NAME OF SOLE OR FIRST INVENTOR:		☐ A petition has been filed for this unsigned inventor.
Given Name (first and middle (if any)): Ilya A.		Family Name or Surname: Kriveshko
Inventor's Signature: 		Date: 06/21/2013
Residence: Littleton, Massachusetts	Country: USA	Citizenship: United States of America
Mailing Address: P.O. Box 33427, St. Paul, Minnesota 55133-3427, USA		

NAME OF JOINT INVENTOR, IF ANY:		☐ A petition has been filed for this unsigned inventor.
Given Name (first and middle (if any)): Benjamin		Family Name or Surname: Frantzdale
Inventor's Signature:		Date:
Residence: Shrewsbury, Massachusetts	Country: USA	Citizenship: United States of America
Mailing Address: P.O. Box 33427, St. Paul, Minnesota 55133-3427, USA		

DECLARATION AND POWER OF ATTORNEY, FOR UTILITY OR DESIGN PATENT APPLICATION (37 CFR § 1.63)		Case No.:	67245US004
		First Named Inventor:	Ilya A. Kriveshko
		COMPLETE IF KNOWN	
		Application No.:	
☒ Declaration Submitted with Initial Filing ☐ Declaration Submitted after Initial Filing (surcharge 37 CFR § 1.16(e) required)		Filing Date:	
		Confirmation No.:	

As a below named inventor, I hereby declare that my residence, mailing address, and citizenship are as stated below next to my name, and that I believe I am an original, first, and sole inventor (if only one name is listed below) or an original, first, and joint inventor (if plural names are listed below) of the subject matter which is claimed and for which a patent is sought on the invention entitled:

HYBRID STITCHING

The specification of which

☐ is attached hereto;

☐ was filed on

as United States Application No.

☒ is identified as PCT International Application No.

filed on

February 17, 2012

PCT/US2012/025554

and was amended on

(if applicable).

I hereby state that I have reviewed and understand the contents of the above-identified specification, including the claims, as amended by any amendment specifically referred to above.

I acknowledge the duty to disclose all information known to me to be material to patentability as defined in 37 CFR § 1.56, including for continuation-in-part applications, material information which became available between the filing date of the prior application and the national or PCT international filing date of the continuation-in-part application.

I hereby claim foreign priority benefits under 35 USC §§ 119(a)-(d) or (f), or 365(b) of any foreign application(s) for patent, inventor's or plant breeder's rights certificate(s), or 365(a) of any PCT international application which designated at least one country other than the United States of America, listed below and have also identified below, by checking the box, any foreign application for patent, inventor's or plant breeder's rights certificate(s), or any PCT international application having a filing date before that of the application on which priority is claimed.

Prior Foreign Application No.	Country	Foreign Filing Date (MM/DD/YYYY)	Priority NOT Claimed	Certified Copy Attached	
				YES	NO
			☐	☐	☐
			☐	☐	☐
			☐	☐	☐

I hereby appoint Practitioners at Customer Number 32692 as my attorneys and/or agents with full powers (including the powers of appointment, substitution, and revocation) to prosecute this application and any division, continuation, continuation-in-part, reexamination, or reissue thereof, and to transact all business in the U.S. Patent and Trademark Office connected therewith.

**Customer Number for
Practitioner of Record:**

32692

I also appoint the following Practitioners as my attorneys and/or agents with full powers (including the powers of appointment, substitution, and revocation) to prosecute this application and any division, continuation, continuation-in-part, reexamination, or reissue thereof, and to transact all business in the U.S. Patent and Trademark Office connected therewith: None

The mailing address and the telephone number of the above-identified attorneys and/or agents are that of Customer No. **32692**.

Inquiries regarding this application can be made to:

Attention: Lance L. Vietzke
Office of Intellectual Property Counsel
3M Innovative Properties Company
Telephone No.: 651-737-2180

I hereby declare that all statements made herein of my own knowledge are true and that all statements made on information and belief are believed to be true; and further that these statements were made with the knowledge that willful false statements and the like so made are punishable by fine or imprisonment, or both, under 18 USC § 1001 and that such willful false statements may jeopardize the validity of the application or any patent issued thereon.

NAME OF SOLE OR FIRST INVENTOR:		☐ A petition has been filed for this unsigned inventor.
Given Name (first and middle (if any)): Ilya A.		Family Name or Surname: Kriveshko
Inventor's Signature:		Date:
Residence: Littleton, Massachusetts		Country: USA
		Citizenship: United States of America
Mailing Address: P.O. Box 33427, St. Paul, Minnesota 55133-3427, USA		

NAME OF JOINT INVENTOR, IF ANY:		☐ A petition has been filed for this unsigned inventor.
Given Name (first and middle (if any)): Benjamin		Family Name or Surname: Frantzdale
Inventor's Signature: 		Date: 13 Aug 2003
Residence: Shrewsbury, Massachusetts		Country: USA
		Citizenship: United States of America
Mailing Address: P.O. Box 33427, St. Paul, Minnesota 55133-3427, USA		

Electronic Patent Application Fee Transmittal				
Application Number:				
Filing Date:				
Title of Invention:		HYBRID STITCHING		
First Named Inventor/Applicant Name:		ILYA KRIVESHKO		
Filer:		Robert V. Heiti/ANGELA ZONTELLI		
Attorney Docket Number:		67245US004		
Filed as Large Entity				
U.S. National Stage under 35 USC 371 Filing Fees				
Description	Fee Code	Quantity	Amount	Sub-Total in USD(\$)
Basic Filing:				
National Stage Fee	1631	1	280	280
Natl Stage Search Fee - Report provided	1642	1	480	480
National Stage Exam - all other cases	1633	1	720	720
Pages:				
Claims:				
Claims in excess of 20	1615	4	80	320
Independent claims in excess of 3	1614	1	420	420
Miscellaneous-Filing:				

Description	Fee Code	Quantity	Amount	Sub-Total in USD(\$)
Petition:				
Patent-Appeals-and-Interference:				
Post-Allowance-and-Post-Issuance:				
Extension-of-Time:				
Miscellaneous:				
Total in USD (\$)				2220

Electronic Acknowledgement Receipt

EFS ID:	16631359
Application Number:	14000442
International Application Number:	PCT/US12/25554
Confirmation Number:	8005
Title of Invention:	HYBRID STITCHING
First Named Inventor/Applicant Name:	ILYA KRIVESHKO
Customer Number:	32692
Filer:	Robert V. Heiti/ANGELA ZONTELLI
Filer Authorized By:	Robert V. Heiti
Attorney Docket Number:	67245US004
Receipt Date:	20-AUG-2013
Filing Date:	
Time Stamp:	12:02:02
Application Type:	U.S. National Stage under 35 USC 371

Payment information:

Submitted with Payment	yes
Payment Type	Deposit Account
Payment was successfully received in RAM	\$2220
RAM confirmation Number	9355
Deposit Account	133723
Authorized User	

The Director of the USPTO is hereby authorized to charge indicated fees and credit any overpayment as follows:

Charge any Additional Fees required under 37 C.F.R. 1.492 (National application filing, search, and examination fees)

Charge any Additional Fees required under 37 C.F.R. Section 1.176 (Patent application and reexamination processing fees)

Charge any Additional Fees required under 37 C.F.R. Section 1.19 (Document supply fees)

Charge any Additional Fees required under 37 C.F.R. Section 1.20 (Post Issuance fees)

Charge any Additional Fees required under 37 C.F.R. Section 1.21 (Miscellaneous fees and charges)

File Listing:

Document Number	Document Description	File Name	File Size(Bytes)/ Message Digest	Multi Part /.zip	Pages (if appl.)
1	Transmittal of New Application	Transmittal_67245US004.PDF	109888	no	2
			5353a770989949d6d006bb99117b6fbbc34f75af		

Warnings:

Information:

2	Application Data Sheet	ADS_67245US004.PDF	1503473	no	7
			2345bae90ec4163b1a4c0a3d05a427f16e27fe5a		

Warnings:

Information:

3	Oath or Declaration filed	DeclarationSigned_67245US004.PDF	986599	no	4
			9cb2b45e4a3c06a5477e250a73f707263a2b8e70		

Warnings:

Information:

4	Fee Worksheet (SB06)	fee-info.pdf	38021	no	2
			6f77b1b2e51e7b98b1b4e3f8380a2d87ad25928a		

Warnings:

Information:

Total Files Size (in bytes):	2637981
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This Acknowledgement Receipt evidences receipt on the noted date by the USPTO of the indicated documents, characterized by the applicant, and including page counts, where applicable. It serves as evidence of receipt similar to a Post Card, as described in MPEP 503.

New Applications Under 35 U.S.C. 111

If a new application is being filed and the application includes the necessary components for a filing date (see 37 CFR 1.53(b)-(d) and MPEP 506), a Filing Receipt (37 CFR 1.54) will be issued in due course and the date shown on this Acknowledgement Receipt will establish the filing date of the application.

National Stage of an International Application under 35 U.S.C. 371

If a timely submission to enter the national stage of an international application is compliant with the conditions of 35 U.S.C. 371 and other applicable requirements a Form PCT/DO/EO/903 indicating acceptance of the application as a national stage submission under 35 U.S.C. 371 will be issued in addition to the Filing Receipt, in due course.

New International Application Filed with the USPTO as a Receiving Office

If a new international application is being filed and the international application includes the necessary components for an international filing date (see PCT Article 11 and MPEP 1810), a Notification of the International Application Number and of the International Filing Date (Form PCT/RO/105) will be issued in due course, subject to prescriptions concerning national security, and the date shown on this Acknowledgement Receipt will establish the international filing date of the application.

67245WO003

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PCT REQUEST

Original (for SUBMISSION)

0	For receiving Office use only	PCT/US12/25554
0-1	International Application No.	
0-2	International Filing Date	(17.02.12) 17 FEB 2012
0-3	Name of receiving Office and "PCT International Application"	PCT INTERNATIONAL APPLICATION RO/US
0-4	Form PCT/RO/101 PCT Request	
0-4-1	Prepared Using	PCT-SAFE [EASY mode] Version 3.51.053.229 MT/FOP 20120101/0.20.5.19
0-5	Petition The undersigned requests that the present international application be processed according to the Patent Cooperation Treaty	
0-6	Receiving Office (specified by the applicant)	United States Patent and Trademark Office (USPTO) (RO/US)
0-7	Applicant's or agent's file reference	67245WO003
I	Title of Invention	HYBRID STITCHING
II	Applicant	
II-1	This person is	Applicant only
II-2	Applicant for	All designated States except US
II-4	Name	3M INNOVATIVE PROPERTIES COMPANY
II-5	Address	3M Center Post Office Box 33427 Saint Paul, Minnesota 55133-3427 United States of America
II-6	State of nationality	US
II-7	State of residence	US
II-8	Telephone No.	(651) 733-1500
II-9	Facsimile No.	(651) 736-7586
III-1	Applicant and/or inventor	
III-1-1	This person is	Applicant and inventor
III-1-2	Applicant for	US only
III-1-4	Name (LAST, First)	KRIVESHKO, Ilya A.,
III-1-5	Address	86 Foster Street Littleton, Massachusetts 01460 United States of America
III-1-6	State of nationality	US
III-1-7	State of residence	US

67245WO003

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PCT REQUEST

Original (for SUBMISSION)

III-2	Applicant and/or inventor	
III-2-1	This person is	Applicant and inventor
III-2-2	Applicant for	US only
III-2-4	Name (LAST, First)	FRANTZDALE, Benjamin
III-2-5	Address	21 Wormwood Street No. 420 Boston, Massachusetts 02421 United States of America
III-2-6	State of nationality	US
III-2-7	State of residence	US
IV-1	Agent or common representative; or address for correspondence The person identified below is hereby/ has been appointed to act on behalf of the applicant(s) before the competent International Authorities as:	Agent
IV-1-1	Name (LAST, First)	VIETZKE, Lance L.,
IV-1-2	Address	3M Center Office of Intellectual Property Counsel Post Office Box 33427 Saint Paul, Minnesota 55133-3427 United States of America
IV-1-3	Telephone No.	(651) 737-2180
IV-1-4	Facsimile No.	(651) 736-7586
IV-1-6	Agent's registration No.	36708
IV-2	Additional agent(s)	additional agent(s) with same address as first named agent
IV-2-1	Name(s)	RHODES, Kevin H., (42102); BLANK, Colene H., (41056); FLORCZAK, Yen Tong, (45163); HARTS, Dean M., (47634); LITTLE, Douglas B., (28439); MAKI, Eloise J., (33418); MILLER, William D., (37988); OLSON, Peter L., (35308); RINGSRED, Ted K., (35658); SKOLNICK, Steven E., (33789); SPRAGUE, Robert W., (30497)
V	DESIGNATIONS	
V-1	The filing of this request constitutes under Rule 4.9(a), the designation of all Contracting States bound by the PCT on the international filing date, for the grant of every kind of protection available and, where applicable, for the grant of both regional and national patents.	
VI-1	Priority claim of earlier national application	
VI-1-1	Filing date	22 February 2011 (22.02.2011)
VI-1-2	Number	61/445,464
VI-1-3	Country	US

67245WO003

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PCT REQUEST

Original (for SUBMISSION)

VI-2	Priority document request The receiving Office is requested to prepare and transmit to the International Bureau a certified copy of the earlier application(s) identified above as item(s):	VI - 1	
VI-3	Incorporation by reference : where an element of the international application referred to in Article 11(1)(iii)(d) or (e) or a part of the description, claims or drawings referred to in Rule 20.5(a) is not otherwise contained in this international application but is completely contained in an earlier application whose priority is claimed on the date on which one or more elements referred to in Article 11(1)(iii) were first received by the receiving Office, that element or part is, subject to confirmation under Rule 20.6, incorporated by reference in this international application for the purposes of Rule 20.6.		
VII-1	International Searching Authority Chosen	Korean Intellectual Property Office (ISA/KR)	
VIII	Declarations	Number of declarations	
VIII-1	Declaration as to the identity of the inventor	-	
VIII-2	Declaration as to the applicant's entitlement, as at the international filing date, to apply for and be granted a patent	-	
VIII-3	Declaration as to the applicant's entitlement, as at the international filing date, to claim the priority of the earlier application	-	
VIII-4	Declaration of inventorship (only for the purposes of the designation of the United States of America)	-	
VIII-5	Declaration as to non-prejudicial disclosures or exceptions to lack of novelty	-	
IX	Check list	Number of sheets	Electronic file(s) attached
IX-1	Request (including declaration sheets)	4	✓
IX-2	Description	29	-
IX-3	Claims	5	-
IX-4	Abstract	1	✓
IX-5	Drawings	9	-
IX-7	TOTAL	48	

67245WO003

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PCT REQUEST

Original (for SUBMISSION)

	Accompanying Items	Paper document(s) attached	Electronic file(s) attached
IX-8	Fee calculation sheet	✓	-
IX-18	PCT-SAFE physical media	-	✓
IX-19	Other	Record of Action taken by Directors of 3M Innovative Properties	
IX-19	Other	Transmittal Letter	
IX-20	Figure of the drawings which should accompany the abstract	7	
IX-21	Language of filing of the international application	English	
X-1	Signature of applicant, agent or common representative		
X-1-1	Name	3M INNOVATIVE PROPERTIES COMPANY	
X-1-2	Name of signatory	RINGSRED, Ted K.	
X-1-3	Capacity (if such capacity is not obvious from reading the request)	Assistant Chief Intellectual Property Counsel	

FOR RECEIVING OFFICE USE ONLY

10-1	Date of actual receipt of the purported international application	17 FEB 2012 (17.02.12)
10-2	Drawings:	
10-2-1	Received	
10-2-2	Not received	
10-3	Corrected date of actual receipt due to later but timely received papers or drawings completing the purported international application	
10-4	Date of timely receipt of the required corrections under PCT Article 11(2)	
10-5	International Searching Authority	ISA/KR
10-6	Transmittal of search copy delayed until search fee is paid	

FOR INTERNATIONAL BUREAU USE ONLY

11-1	Date of receipt of the record copy by the International Bureau	
------	--	--

450045

THE UNITED STATES OF AMERICA

TO ALL TO WHOM THESE PRESENTS SHALL COME:

UNITED STATES DEPARTMENT OF COMMERCE

United States Patent and Trademark Office

February 24, 2012

THIS IS TO CERTIFY THAT ANNEXED HERETO IS A TRUE COPY FROM THE RECORDS OF THE UNITED STATES PATENT AND TRADEMARK OFFICE OF THOSE PAPERS OF THE BELOW IDENTIFIED PATENT APPLICATION THAT MET THE REQUIREMENTS TO BE GRANTED A FILING DATE.

APPLICATION NUMBER: 61/445,464

FILING DATE: February 22, 2011

RELATED PCT APPLICATION NUMBER: PCT/US12/25554

THE COUNTRY CODE AND NUMBER OF YOUR PRIORITY APPLICATION, TO BE USED FOR FILING ABROAD UNDER THE PARIS CONVENTION, IS US61/445,464



Certified by

David J. Kappas

Under Secretary of Commerce
for Intellectual Property
and Director of the United States
Patent and Trademark Office

Application Data Sheet 37 CFR 1.76		Attorney Docket Number	67245US002
		Application Number	
Title of Invention	HYBRID STITCHING		
The application data sheet is part of the provisional or nonprovisional application for which it is being submitted. The following form contains the bibliographic data arranged in a format specified by the United States Patent and Trademark Office as outlined in 37 CFR 1.76. This document may be completed electronically and submitted to the Office in electronic format using the Electronic Filing System (EFS) or the document may be printed and included in a paper filed application.			

Secrecy Order 37 CFR 5.2

☐ Portions or all of the application associated with this Application Data Sheet may fall under a Secrecy Order pursuant to 37 CFR 5.2 (Paper filers only. Applications that fall under Secrecy Order may not be filed electronically.)

Applicant Information:

Applicant 1						Remove	
Applicant Authority		☒ Inventor		☐ Legal Representative under 35 U.S.C. 117		☐ Party of Interest under 35 U.S.C. 118	
Prefix	Given Name	Middle Name		Family Name		Suffix	
	Ilya	A.		Kriveshko			
Residence Information (Select One)		☒ US Residency		☐ Non US Residency		☐ Active US Military Service	
City	Littleton	State/Province	MA	Country of Residence i		US	
Citizenship under 37 CFR 1.41(b) i		US					
Mailing Address of Applicant:							
Address 1		86 Foster Street					
Address 2							
City	Littleton	State/Province		MA			
Postal Code	01460	Countryi		US			
Applicant 2						Remove	
Applicant Authority		☒ Inventor		☐ Legal Representative under 35 U.S.C. 117		☐ Party of Interest under 35 U.S.C. 118	
Prefix	Given Name	Middle Name		Family Name		Suffix	
	Benjamin			FrantzDale			
Residence Information (Select One)		☒ US Residency		☐ Non US Residency		☐ Active US Military Service	
City	Mansfield	State/Province	MA	Country of Residence i		US	
Citizenship under 37 CFR 1.41(b) i		US					
Mailing Address of Applicant:							
Address 1		115 Twin Oaks Village					
Address 2							
City	Mansfield	State/Province		MA			
Postal Code	02048	Countryi		US			
All Inventors Must Be Listed - Additional Inventor Information blocks may be generated within this form by selecting the Add button.						Add	

Correspondence Information:

Enter either Customer Number or complete the Correspondence Information section below.
For further information see 37 CFR 1.33(a).

Application Data Sheet 37 CFR 1.76		Attorney Docket Number	67245US002
		Application Number	
Title of Invention	HYBRID STITCHING		

☐ An Address is being provided for the correspondence information of this application.

Customer Number	43520		
Email Address	patents@strategic-patents.com	Add Email	Remove Email

Application Information:

Title of the Invention	HYBRID STITCHING		
Attorney Docket Number	67245US002	Small Entity Status Claimed	☐
Application Type	Provisional		
Subject Matter	Utility		
Suggested Class (if any)		Sub Class (if any)	
Suggested Technology Center (if any)			
Total Number of Drawing Sheets (if any)	11	Suggested Figure for Publication (if any)	

Publication Information:

☐ Request Early Publication (Fee required at time of Request 37 CFR 1.219)

☐ **Request Not to Publish.** I hereby request that the attached application not be published under 35 U.S.C. 122(b) and certify that the invention disclosed in the attached application **has not and will not** be the subject of an application filed in another country, or under a multilateral international agreement, that requires publication at eighteen months after filing.

Representative Information:

Representative information should be provided for all practitioners having a power of attorney in the application. Providing this information in the Application Data Sheet does not constitute a power of attorney in the application (see 37 CFR 1.32). Enter either Customer Number or complete the Representative Name section below. If both sections are completed the Customer Number will be used for the Representative Information during processing.

Please Select One:	☒ Customer Number	☐ US Patent Practitioner	☐ Limited Recognition (37 CFR 11.9)
Customer Number	43520		

Domestic Benefit/National Stage Information:

This section allows for the applicant to either claim benefit under 35 U.S.C. 119(e), 120, 121, or 365(c) or indicate National Stage entry from a PCT application. Providing this information in the application data sheet constitutes the specific reference required by 35 U.S.C. 119(e) or 120, and 37 CFR 1.78(a)(2) or CFR 1.78(a)(4), and need not otherwise be made part of the specification.

Prior Application Status		Remove	
Application Number	Continuity Type	Prior Application Number	Filing Date (YYYY-MM-DD)
Additional Domestic Benefit/National Stage Data may be generated within this form by selecting the Add button.			Add

Application Data Sheet 37 CFR 1.76		Attorney Docket Number	67245US002
		Application Number	
Title of Invention	HYBRID STITCHING		

Foreign Priority Information:

This section allows for the applicant to claim benefit of foreign priority and to identify any prior foreign application for which priority is not claimed. Providing this information in the application data sheet constitutes the claim for priority as required by 35 U.S.C. 119(b) and 37 CFR 1.55(a).

				Remove
Application Number	Country ⁱ	Parent Filing Date (YYYY-MM-DD)	Priority Claimed	
			☒ Yes ☐ No	
Additional Foreign Priority Data may be generated within this form by selecting the Add button.				Add

Assignee Information:

Providing this information in the application data sheet does not substitute for compliance with any requirement of part 3 of Title 37 of the CFR to have an assignment recorded in the Office.

Assignee ¹					Remove
If the Assignee is an Organization check here. ☐					
Prefix	Given Name	Middle Name	Family Name	Suffix	
Mailing Address Information:					
Address 1					
Address 2					
City		State/Province			
Country ⁱ		Postal Code			
Phone Number		Fax Number			
Email Address					
Additional Assignee Data may be generated within this form by selecting the Add button.					
Add					

Signature:

A signature of the applicant or representative is required in accordance with 37 CFR 1.33 and 10.18. Please see 37 CFR 1.4(d) for the form of the signature.

Signature	/John Nortrup/			Date (YYYY-MM-DD)	2011-02-22
First Name	John	Last Name	Nortrup	Registration Number	59063

Application Data Sheet 37 CFR 1.76		Attorney Docket Number	67245US002
		Application Number	
Title of Invention	HYBRID STITCHING		

This collection of information is required by 37 CFR 1.76. The information is required to obtain or retain a benefit by the public which is to file (and by the USPTO to process) an application. Confidentiality is governed by 35 U.S.C. 122 and 37 CFR 1.14. This collection is estimated to take 23 minutes to complete, including gathering, preparing, and submitting the completed application data sheet form to the USPTO. Time will vary depending upon the individual case. Any comments on the amount of time you require to complete this form and/or suggestions for reducing this burden, should be sent to the Chief Information Officer, U.S. Patent and Trademark Office, U.S. Department of Commerce, P.O. Box 1450, Alexandria, VA 22313-1450. DO NOT SEND FEES OR COMPLETED FORMS TO THIS ADDRESS. **SEND TO: Commissioner for Patents, P.O. Box 1450, Alexandria, VA 22313-1450.**

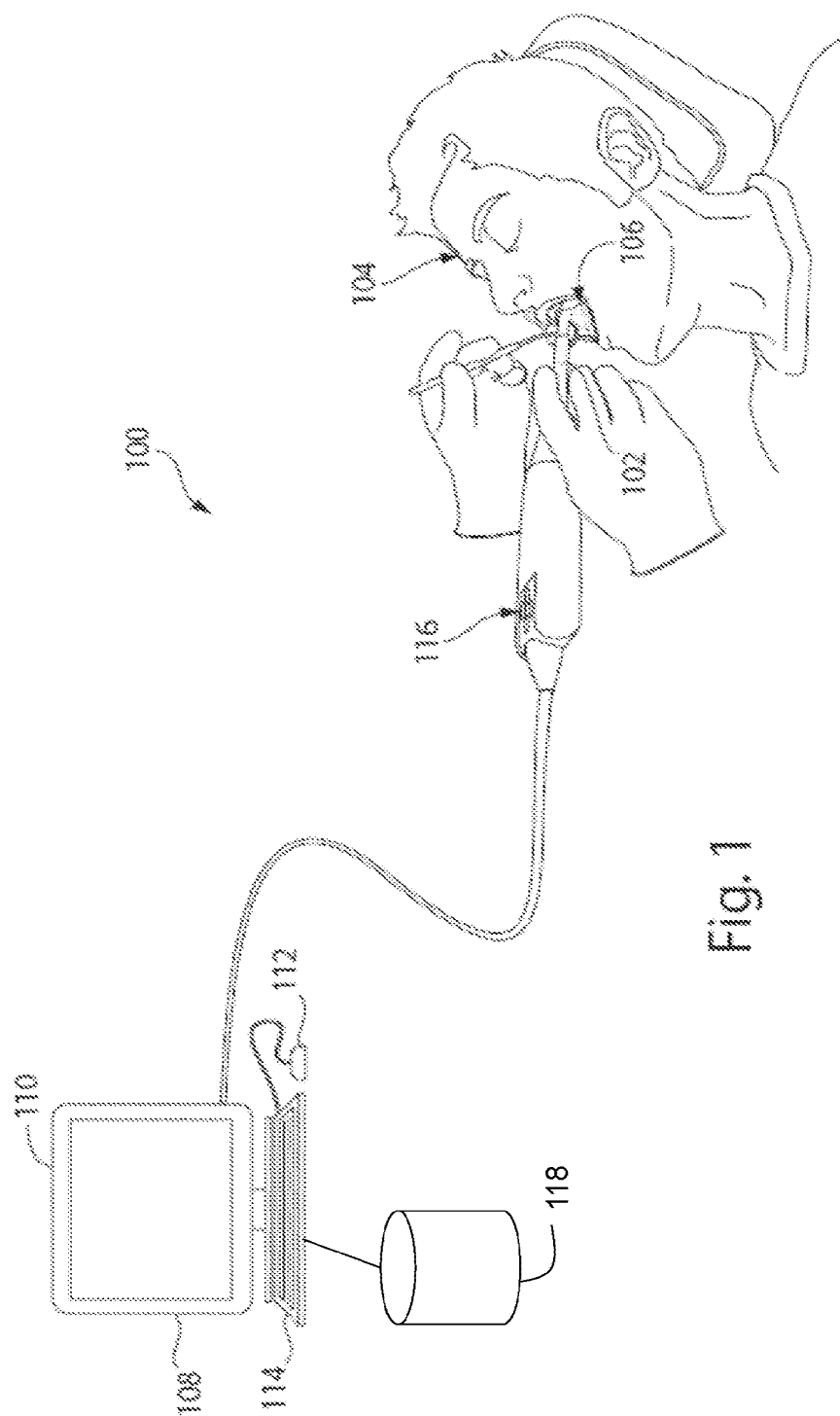


Fig. 1

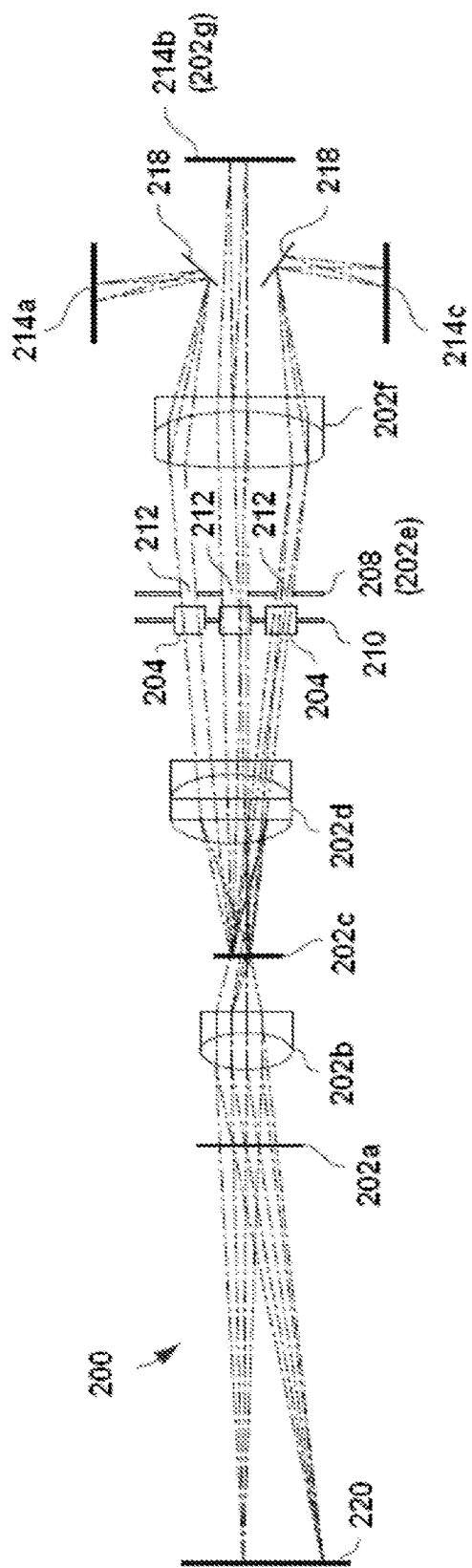


Fig. 2

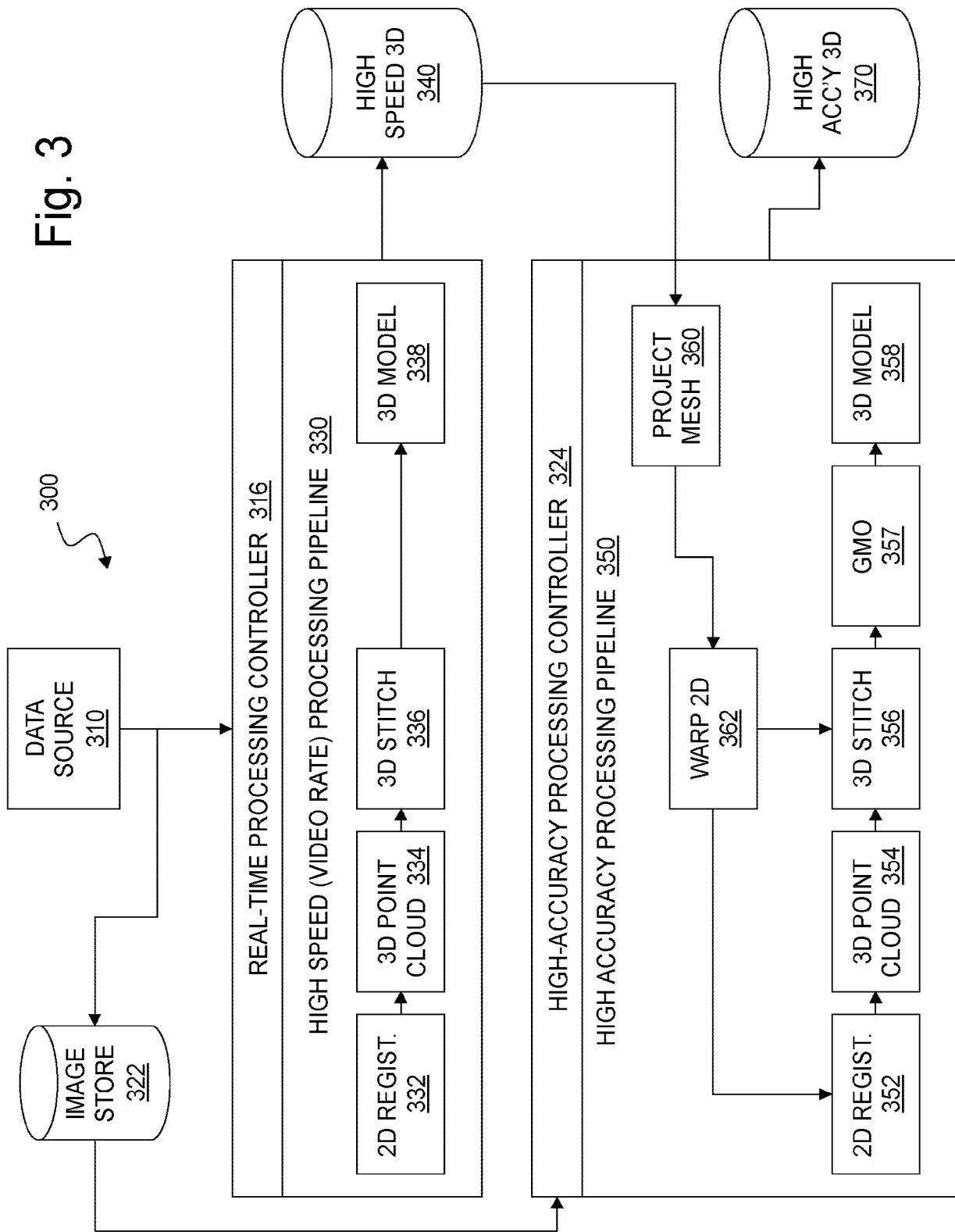


Fig. 3

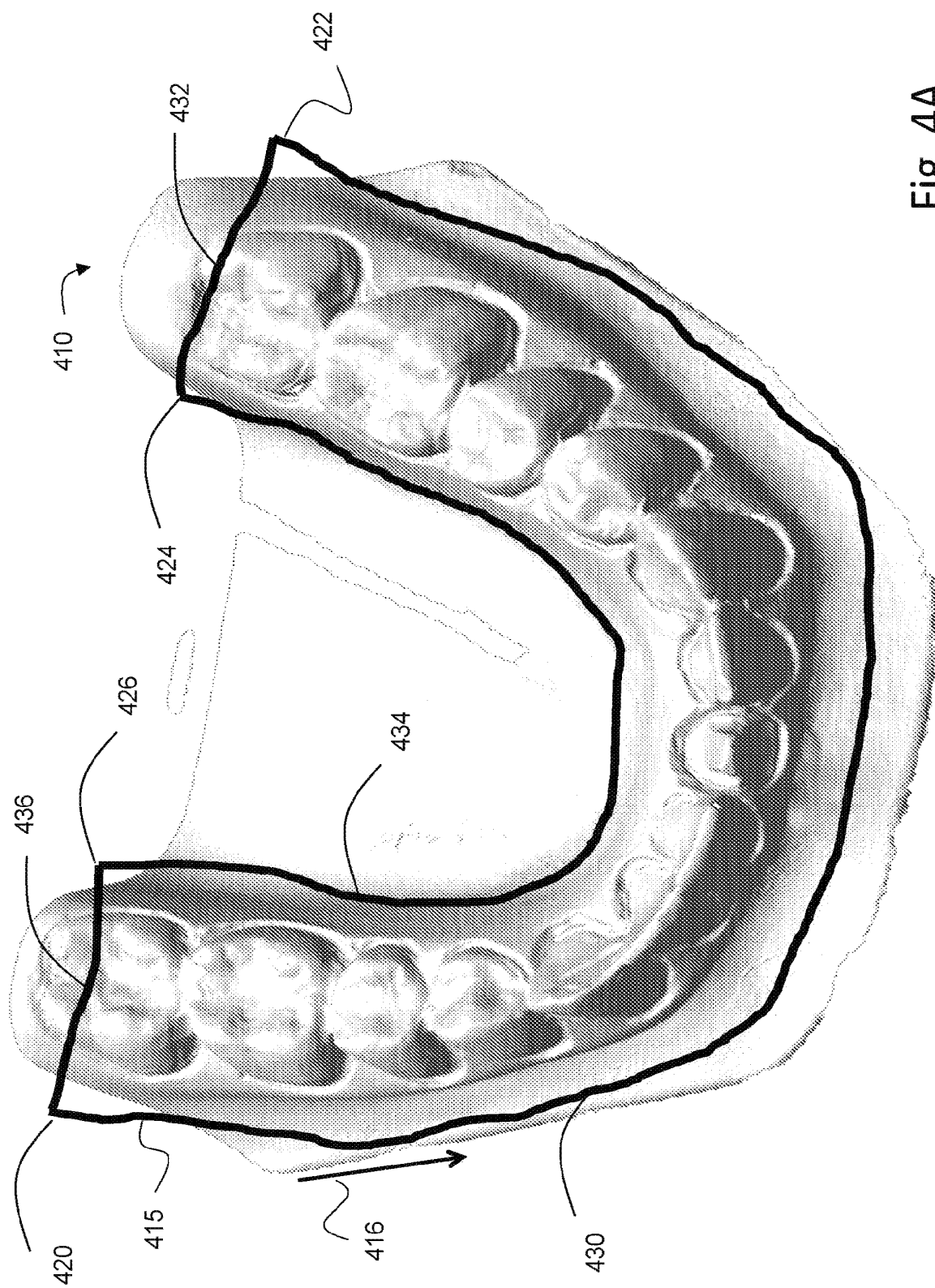


Fig. 4A

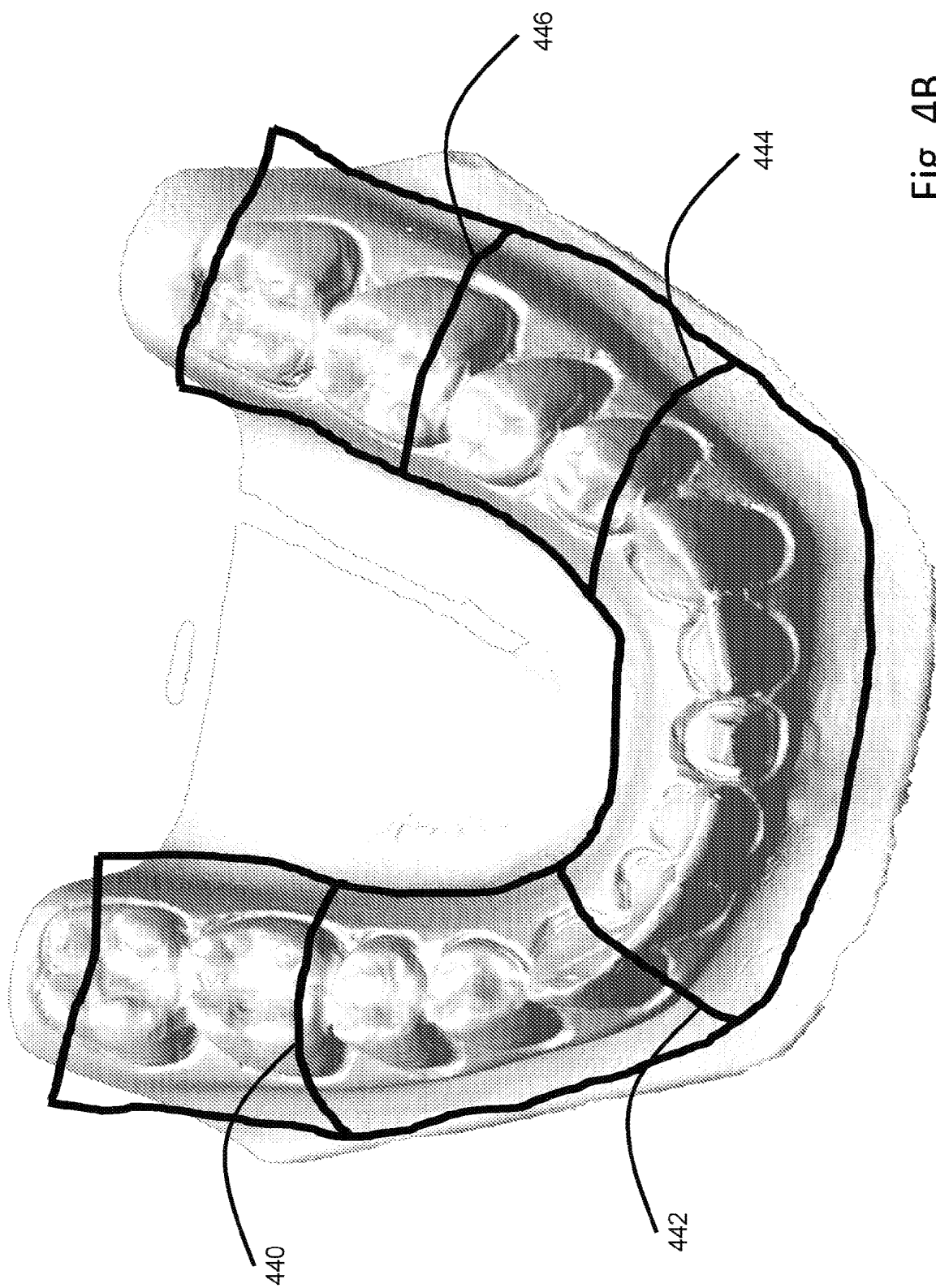


Fig. 4B

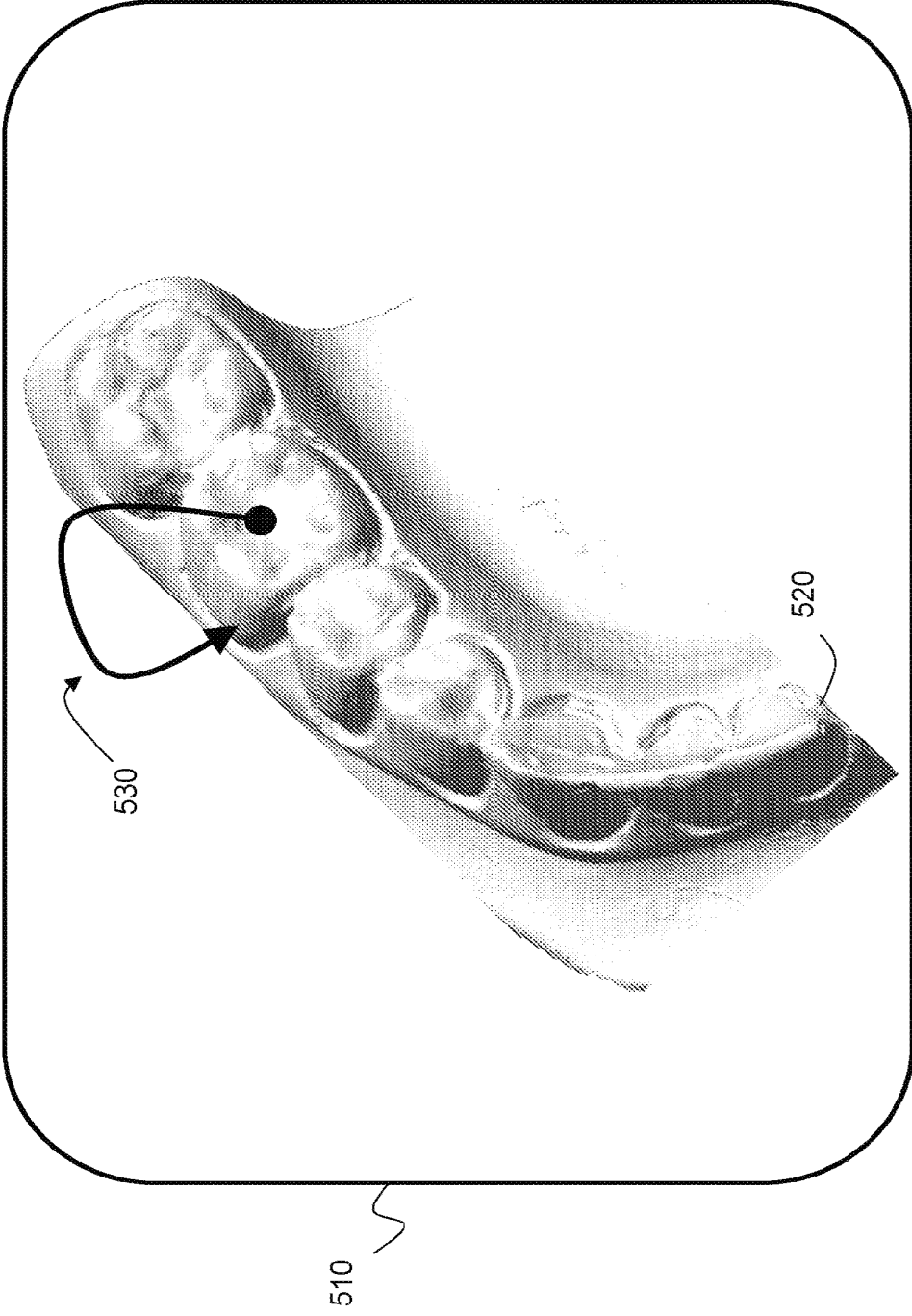


Fig. 5

Fig. 6A

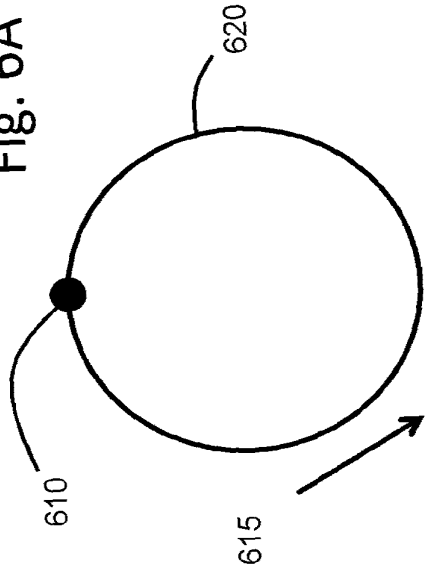
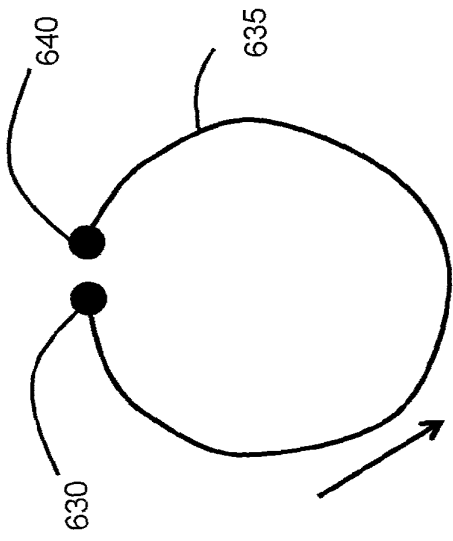


Fig. 6B



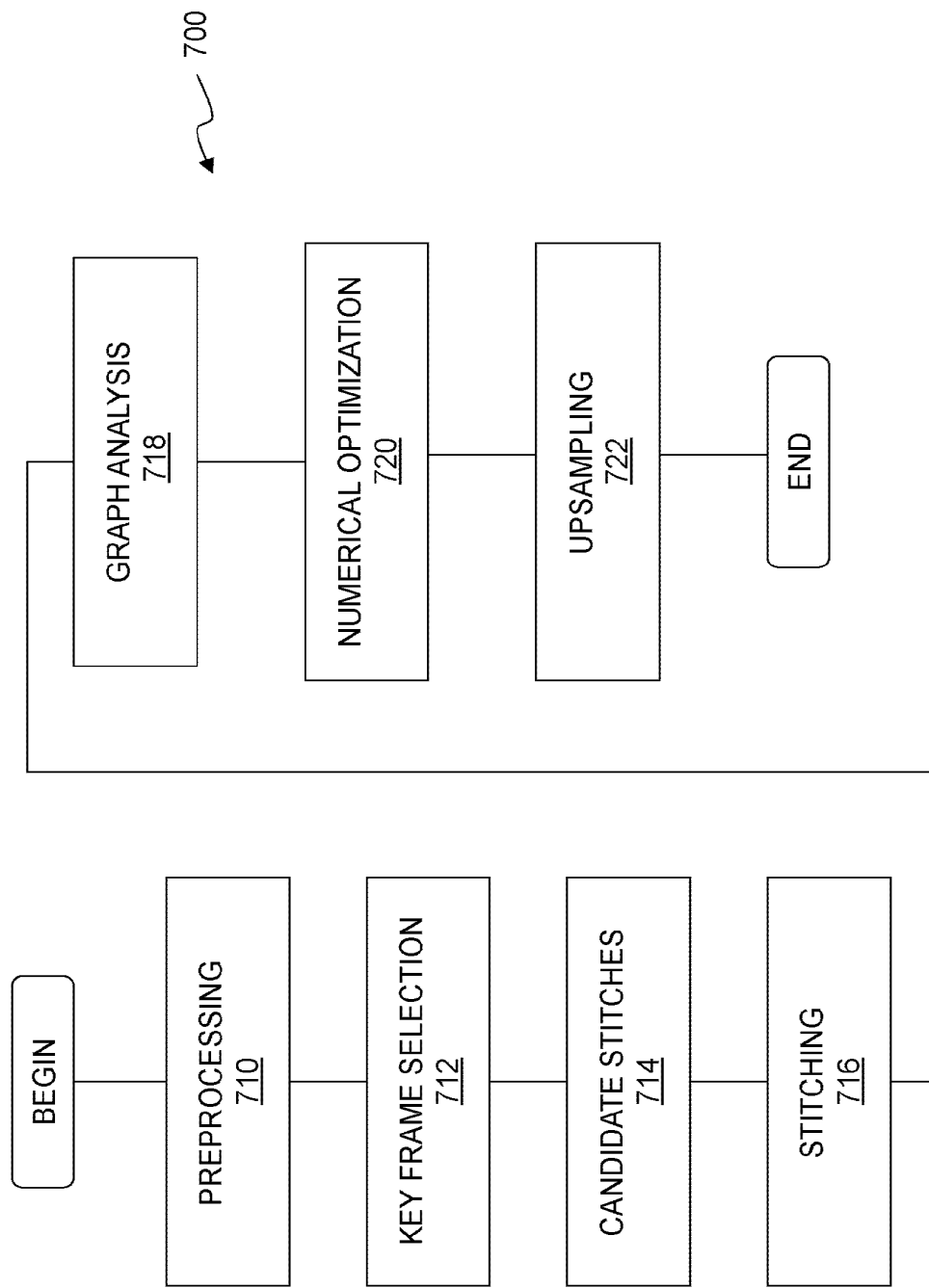


Fig. 7

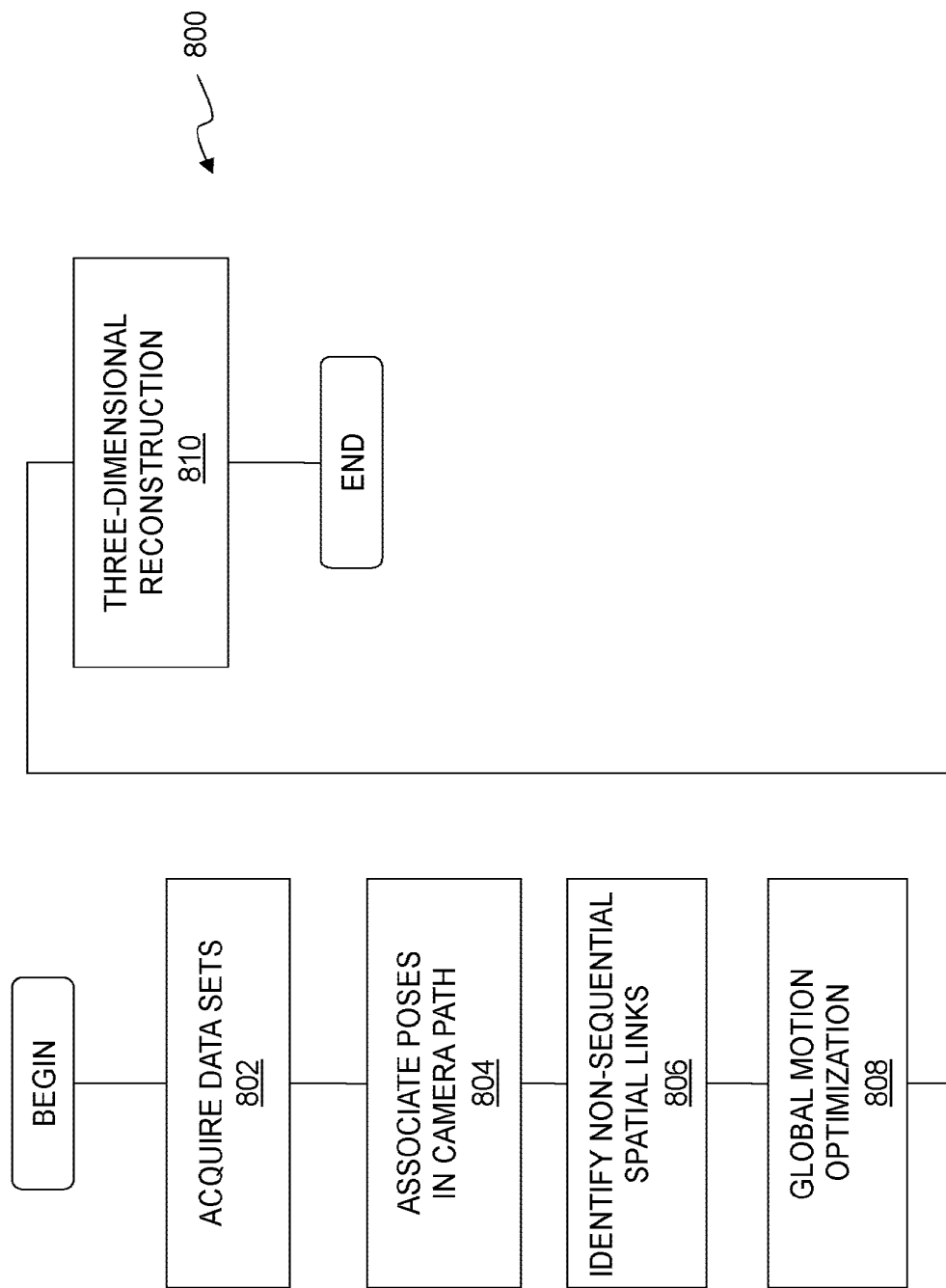


Fig. 8

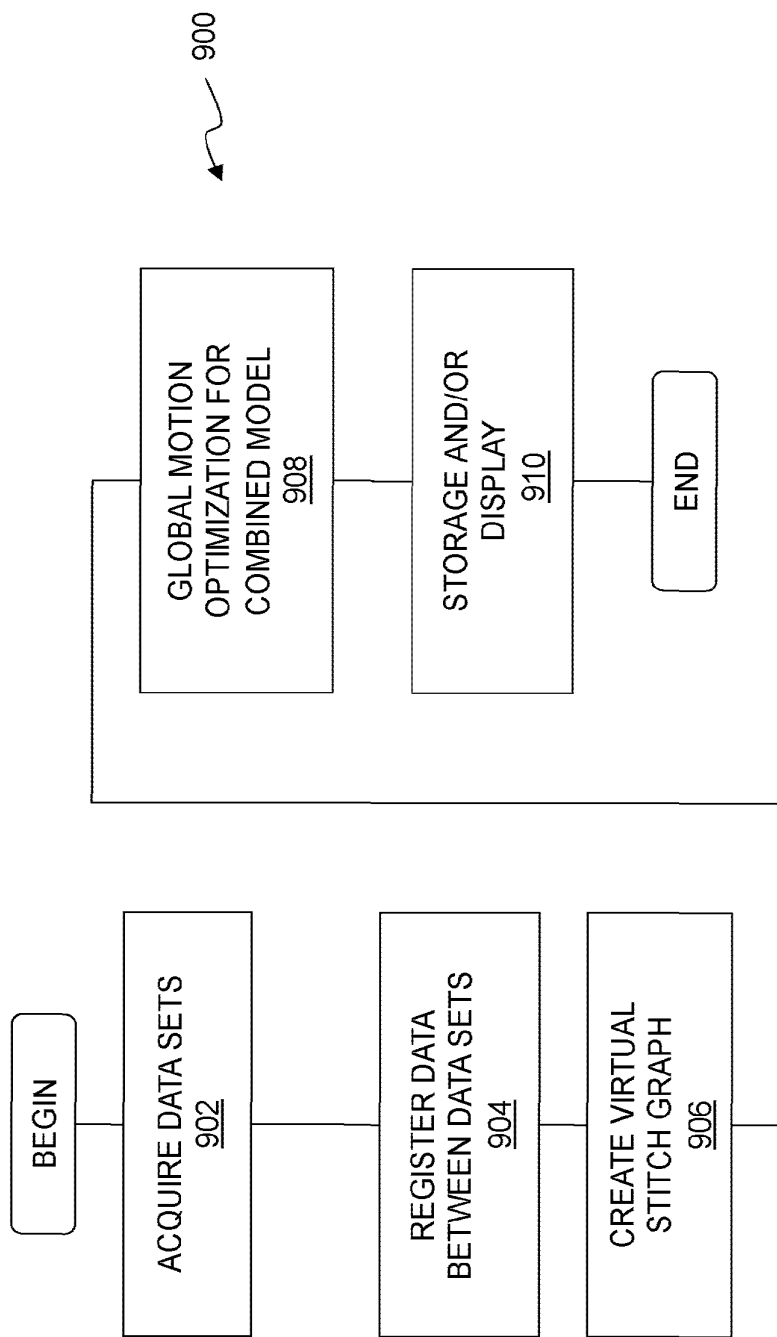


Fig. 9

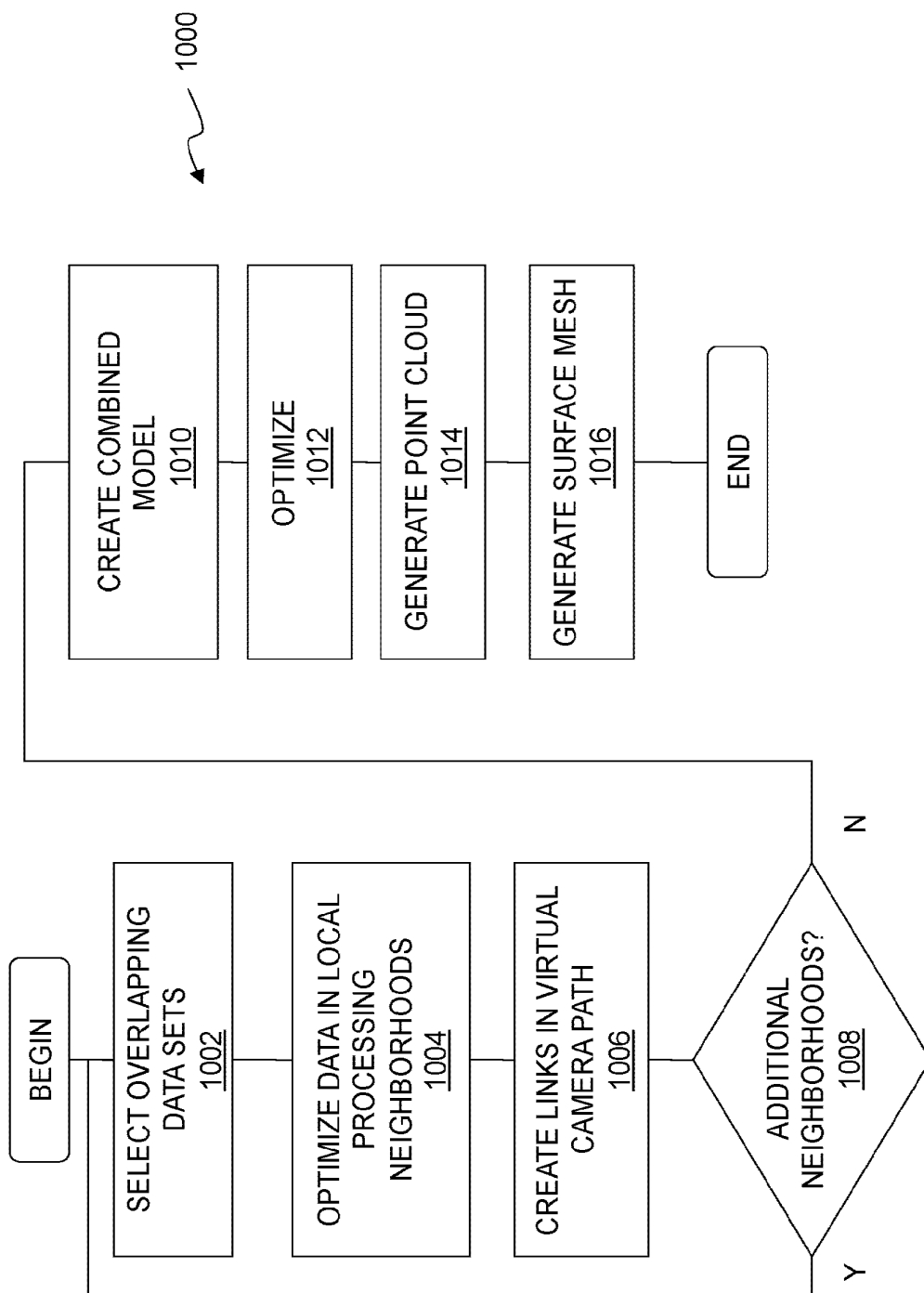


Fig. 10

HYBRID STITCHING

FIELD OF INVENTION

[0001] This invention relates generally to three-dimensional imaging and more specifically techniques for combining disparate scans of a common three-dimensional surface.

BACKGROUND

[0002] In one technique for three-dimensional image reconstruction, a number of images or image sets of an object are captured with a camera that travels in a path over the surface of the object. A three-dimensional model of the object can then be obtained from a description of the camera path and individual three-dimensional measurements captured along the camera path. In certain applications, data from a surface of an object is available in multiple, disparate data sets, such as where a scan is interrupted prior to completion or where additional scans are performed to augment an initial scan. The resulting multiple models can be registered to one another to obtain a combined model. While conventional registration techniques can minimize an error in alignment between two such resulting models, this approach does not afford an opportunity to refine the individual models in view of the combined data.

[0003] There remains a need for improved techniques to combine disparate three-dimensional data sets, particularly disparate data sets based upon a path of poses of a three-dimensional scanner.

SUMMARY

[0004] In a system or method where three-dimensional data is acquired as a sequence of frames of data along a camera path, disparate sequences are related to one another through a number of geometric stitches obtained by direct registration of three-dimensional data between frames in the disparate sequences. These geometric stitches are then used in addition to or in place of other camera path relationships to form a single virtual stitch graph for the combined model, upon which an integrated global path optimization can be performed.

BRIEF DESCRIPTION OF THE DRAWINGS

[0005] The invention and the following detailed description of certain embodiments thereof may be understood by reference to the following figures.

[0006] Fig. 1 shows a three-dimensional scanning system.

[0007] Fig. 2 shows a schematic diagram of an optical system for a three-dimensional scanner.

[0008] Fig. 3 shows a processing pipeline for obtaining three-dimensional data from a video scanner.

[0009] Fig. 4A and 4B illustrate camera paths for a three-dimensional scanner.

[0010] Fig. 5 shows a user interface image where additional data is requested by a software tool.

[0011] Fig. 6A and 6B illustrate accumulated error in camera paths.

[0012] Fig. 7 is a flow chart of a three-dimensional reconstruction process including global path optimization for improved accuracy.

[0013] Fig. 8 is a flow chart of a dental object reconstruction process using numerical optimization.

[0014] Fig. 9 is a flow chart of a hybrid stitching process for combining disparate three-dimensional scans of a common surface.

[0015] Fig. 10 is a flow chart of a process for creating of a virtual stitch graph.

DETAILED DESCRIPTION

[0016] In the following text, references to items in the singular should be understood to include items in the plural, and vice versa, unless explicitly stated otherwise or clear from the text. Grammatical conjunctions are intended to express any and all disjunctive and conjunctive combinations of conjoined clauses, sentences, words, and the like, unless otherwise stated or clear from the context.

[0017] In the systems and methods described herein, a number of techniques for global motion optimization are employed to improve accuracy of three-dimensional reconstructions based upon camera path.

[0018] The following description details specific scanning technologies and focuses on dental applications of three-dimensional imaging; however, it will be appreciated that variations, adaptations, and combinations of the methods and systems below will be apparent to one of ordinary skill in the art. For example, while an image-based system is described, non-image based scanning techniques such as infrared time-of-flight techniques or structured light techniques using patterned projections may similarly employ reconstruction based on camera path that may benefit from the improvements described herein. As another example, while digital dentistry is one useful application of the improved accuracy that results from the techniques described herein, global path optimization may also usefully be employed to refine three-dimensional animation models or three-dimensional scans for machine vision applications or for mapping applications. All such variations, adaptations, and combinations are intended to fall within the scope of this disclosure.

[0019] In the following description, the term “image” generally refers to a two-dimensional set of pixels forming a two-dimensional view of a subject within an image plane. The term “image set” generally refers to a set of related two-dimensional images that might be resolved into three-dimensional data. The term “point cloud” generally refers to a three-dimensional set of points forming a three-dimensional view of the subject reconstructed from a number of two-dimensional images. In a three-dimensional image capture system, a number of such point clouds may also be registered and combined into an aggregate point cloud constructed from images captured by a moving camera. Thus it will be understood that pixels generally refer to two-dimensional data and points generally refer to three-dimensional data, unless another meaning is specifically indicated or clear from the context.

[0020] The terms “three-dimensional model”, “three-dimensional surface representation”, “digital surface representation”, “three-dimensional surface map”, and the like, as used herein, are intended to refer to any three-dimensional surface map of an object, such as a point cloud of surface data, a set of two-dimensional polygons, or any other data representing all or some of the surface of an object, as might be obtained through the capture and/or processing of three-dimensional scan data, unless a different meaning is explicitly provided or otherwise clear from the context. A “three-dimensional

representation” may include any of the three-dimensional surface representations described above, as well as volumetric and other representations, unless a different meaning is explicitly provided or otherwise clear from the context.

[0021] In general, the terms “render” or “rendering” refer to a two-dimensional visualization of a three-dimensional object, such as for display on a monitor. However, it will be understood that a variety of three-dimensional rendering technologies exist, and may be usefully employed with the systems and methods disclosed herein. For example, the system and methods described herein may usefully employ a holographic display, an autostereoscopic display, an anaglyph display, a head-mounted stereo display, or any other two-dimensional and/or three-dimensional display. As such, rendering as described herein should be interpreted broadly unless a narrower meaning is explicitly provided or otherwise clear from the context.

[0022] The term “dental object”, as used herein, is intended to refer broadly to subject matter related to dentistry. This may include intraoral structures such as dentition, and more typically human dentition, such as individual teeth, quadrants, full arches, pairs of arches (which may be separate or in occlusion of various types), soft tissue, and the like, as well bones and any other supporting or surrounding structures. As used herein, the term “intraoral structures” refers to both natural structures within a mouth as described above and artificial structures such as any of the dental objects described below that might be present in the mouth. Dental objects may include “restorations”, which may be generally understood to include components that restore the structure or function of existing dentition, such as crowns, bridges, veneers, inlays, onlays, amalgams, composites, and various substructures such as copings and the like, as well as temporary restorations for use while a permanent restoration is being fabricated. Dental objects may also include a “prosthesis” that replaces dentition with removable or permanent structures, such as dentures, partial dentures, implants, retained dentures, and the like. Dental objects may also include “appliances” used to correct, align, or otherwise temporarily or permanently adjust dentition, such as removable orthodontic appliances, surgical stents, bruxism appliances, snore guards, indirect bracket placement appliances, and the like. Dental objects may also include “hardware” affixed to dentition for an extended period, such as implant fixtures, implant abutments, orthodontic brackets, and

other orthodontic components. Dental objects may also include “interim components” of dental manufacture such as dental models (full and/or partial), wax-ups, investment molds, and the like, as well as trays, bases, dies, and other components employed in the fabrication of restorations, prostheses, and the like. Dental objects may also be categorized as natural dental objects such as the teeth, bone, and other intraoral structures described above or as artificial dental objects such as the restorations, prostheses, appliances, hardware, and interim components of dental manufacture as described above.

[0023] Terms such as “digital dental model”, “digital dental impression” and the like, are intended to refer to three-dimensional representations of dental objects that may be used in various aspects of acquisition, analysis, prescription, and manufacture, unless a different meaning is otherwise provided or clear from the context. Terms such as “dental model” or “dental impression” are intended to refer to a physical model, such as a cast, printed, or otherwise fabricated physical instance of a dental object. Unless specified, the term “model”, when used alone, may refer to either or both of a physical model and a digital model.

[0024] It will further be understood that terms such as “tool” or “control”, when used to describe aspects of a user interface, are intended to refer generally to a variety of techniques that may be employed within a graphical user interface or other user interface to receive user input that stimulates or controls processing including without limitation drop-down lists, radio buttons, cursor and/or mouse actions (selections by point, selections by area, drag-and-drop operations, and so forth), check boxes, command lines, text input fields, messages and alerts, progress bars, and so forth. A tool or control may also include any physical hardware relating to the user input, such as a mouse, keyboard, display, keypad, track ball, and/or any other device that receives physical input from a user and converts the physical input into an input for use in a computerized system. Thus in the following description the terms “tool”, “control” and the like should be broadly construed unless a more specific meaning is otherwise provided or clear from the context.

[0025] Fig. 1 depicts a three-dimensional scanning system that may be used with the systems and methods described herein. In general, the system 100 may include a scanner 102 that captures images from a surface 106 of an object 104, such as a dental patient, and forwards the images to a computer 108, which may include a display 110 and

one or more user-input devices 112, 114 such as a mouse 112 or a keyboard 114. The scanner 102 may also include an integrated input or output device 116 such as a control input (e.g., button, touchpad, thumbwheel, etc.) or a display (e.g., LCD or LED display) to provide status information.

[0026] The scanner 102 may include any camera or camera system suitable for capturing images from which a three-dimensional point cloud or other three-dimensional data may be recovered. For example, the scanner 102 may employ a multi-aperture system as disclosed in U.S. Pat. No. 7,372,642 to Rohály et al., the entire content of which is incorporated herein by reference. While Rohály discloses one multi-aperture system, it will be appreciated that any multi-aperture system suitable for reconstructing a three-dimensional point cloud from a number of two-dimensional images may similarly be employed. In one multi-aperture embodiment, the scanner 102 may include a plurality of apertures including a center aperture positioned along a center optical axis of a lens that provides a center channel for the scanner 102, along with any associated imaging hardware. In such embodiments, the center channel may provide a conventional video image of the scanned subject matter, while a number of axially offset channels yield image sets containing disparity information that can be employed in three-dimensional reconstruction of a surface. In other embodiments, a separate video camera and/or channel may be provided to achieve the same result, i.e., a video of an object corresponding temporally to a three-dimensional scan of the object, preferably from the same perspective, or from a perspective having a fixed, known relationship to the perspective of the scanner 102. The scanner 102 may also, or instead, include a stereoscopic, triscopic or other multi-camera or other configuration in which a number of cameras or optical paths are maintained in fixed relation to one another to obtain two-dimensional images of an object from a number of different perspectives. The scanner 102 may include suitable processing for deriving a three-dimensional point cloud from an image set or a number of image sets, or each two-dimensional image set may be transmitted to an external processor such as contained in the computer 108 described below. In other embodiments, the scanner 102 may employ structured light, laser scanning, direct ranging, or any other technology suitable for acquiring three-dimensional data, or two-dimensional data that can be resolved into three-dimensional data. While the

techniques described below can usefully employ video data acquired by a video-based three-dimensional scanning system, it will be understood that any other three-dimensional scanning system may be supplemented with a video acquisition system that captures suitable video data contemporaneously with, or otherwise synchronized with, the acquisition of three-dimensional data.

[0027] In one embodiment, the scanner 102 is a handheld, freely-positionable probe having at least one user-input device 116, such as a button, lever, dial, thumb wheel, switch, or the like, for user control of the image capture system 100 such as starting and stopping scans. In an embodiment, the scanner 102 may be shaped and sized for dental scanning. More particularly, the scanner may be shaped and sized for intraoral scanning and data capture, such as by insertion into a mouth of an imaging subject and passing over an intraoral surface 106 at a suitable distance to acquire surface data from teeth, gums, and so forth. The scanner 102 may, through such a continuous data acquisition process, capture a point cloud of surface data having sufficient spatial resolution and accuracy to prepare dental objects such as prosthetics, hardware, appliances, and the like therefrom, either directly or through a variety of intermediate processing steps. In other embodiments, surface data may be acquired from a dental model such as a dental prosthetic, to ensure proper fitting using a previous scan of corresponding dentition, such as a tooth surface prepared for the prosthetic.

[0028] Although not shown in Fig. 1, it will be appreciated that a number of supplemental lighting systems may be usefully employed during image capture. For example, environmental illumination may be enhanced with one or more spotlights illuminating the object 104 to speed image acquisition and improve depth of field (or spatial resolution depth). The scanner 102 may also, or instead, include a strobe, flash, or other light source to supplement illumination of the object 104 during image acquisition.

[0029] The object 104 may be any object, collection of objects, portion of an object, or other subject matter. More particularly with respect to the dental techniques discussed herein, the object 104 may include human dentition captured intraorally from a dental patient's mouth. A scan may capture a three-dimensional representation of some or all of the dentition according to particular purpose of the scan. Thus the scan may capture a digital model of a tooth, a quadrant of teeth, or a full collection of teeth including two

opposing arches, as well as soft tissue or any other relevant intraoral structures. The scan may capture multiple representations, such as a tooth surface before and after preparation for a restoration. As will be noted below, this data may be employed for subsequent modeling such as designing a restoration or determining a margin line for same. During the scan, a center channel of the scanner 102 or a separate video system may capture video of the dentition from the point of view of the scanner 102. In other embodiments where, for example, a completed fabrication is being virtually test fitted to a surface preparation, the scan may include a dental prosthesis such as an inlay, a crown, or any other dental prosthesis, dental hardware, dental appliance, or the like. The object 104 may also, or instead, include a dental model, such as a plaster cast, wax-up, impression, or negative impression of a tooth, teeth, soft tissue, or some combination of these.

[0030] The computer 108 may include, for example, a personal computer or other processing device. In one embodiment, the computer 108 includes a personal computer with a dual 2.8GHz Opteron central processing unit, 2 gigabytes of random access memory, a TYAN Thunder K8WE motherboard, and a 250 gigabyte, 10,000 rpm hard drive. In one current embodiment, the system can be operated to capture more than five thousand points per image set in real time using the techniques described herein, and store an aggregated point cloud of several million points. Of course, this point cloud may further processed to accommodate subsequent data handling, such as by decimating the point cloud data or generating a corresponding mesh of surface data. As used herein, the term “real time” means generally with no observable latency between processing and display. In a video-based scanning system, real time more specifically refers to processing within the time between frames of video data, which may vary according to specific video technologies between about fifteen frames per second and about thirty frames per second. More generally, processing capabilities of the computer 108 may vary according to the size of the object 104, the speed of image acquisition, and the desired spatial resolution of three-dimensional points. The computer 108 may also include peripheral devices such as a keyboard 114, display 110, and mouse 112 for user interaction with the camera system 100. The display 110 may be a touch screen display capable of receiving user input through direct, physical interaction with the display 110.

In another aspect, the display may include an autostereoscopic display capable of displaying stereo images.

[0031] Communications between the computer 108 and the scanner 102 may use any suitable communications link including, for example, a wired connection or a wireless connection based upon, for example, IEEE 802.11 (also known as wireless Ethernet), BlueTooth, or any other suitable wireless standard using, e.g., a radio frequency, infrared, or other wireless communication medium. In medical imaging or other sensitive applications, wireless image transmission from the scanner 102 to the computer 108 may be secured. The computer 108 may generate control signals to the scanner 102 which, in addition to image acquisition commands, may include conventional camera controls such as focus or zoom.

[0032] In an example of general operation of a three-dimensional image capture system 100, the scanner 102 may acquire two-dimensional image sets at a video rate while the scanner 102 is passed over a surface of the subject. The two-dimensional image sets may be forwarded to the computer 108 for derivation of three-dimensional point clouds. The three-dimensional data for each newly acquired two-dimensional image set may be derived and fitted or “stitched” to existing three-dimensional data using a number of different techniques. Such a system employs camera motion estimation to avoid the need for independent tracking of the position of the scanner 102. One useful example of such a technique is described in commonly-owned U.S. App. No. 11/270,135, filed on November 9, 2005, the entire content of which is incorporated herein by reference. However, it will be appreciated that this example is not limiting, and that the principles described herein may be applied to a wide range of three-dimensional image capture systems.

[0033] The display 110 may include any display suitable for video or other rate rendering at a level of detail corresponding to the acquired data. Suitable displays include cathode ray tube displays, liquid crystal displays, light emitting diode displays and the like. In general, the display 110 may be operatively coupled to, and capable of receiving display signals from, the computer 108. This display may include a CRT or flat panel monitor, a three-dimensional display (such as an anaglyph display), an autostereoscopic three-dimensional display or any other suitable two-dimensional or three-dimensional

rendering hardware. In some embodiments, the display may include a touch screen interface using, for example capacitive, resistive, or surface acoustic wave (also referred to as dispersive signal) touch screen technologies, or any other suitable technology for sensing physical interaction with the display 110.

[0034] The system 100 may include a computer-usable or computer-readable medium. The computer-usable medium 118 may include one or more memory chips (or other chips, such as a processor, that include memory), optical disks, magnetic disks or other magnetic media, and so forth. The computer-usable medium 118 may in various embodiments include removable memory (such as a USB device, tape drive, external hard drive, and so forth), remote storage (such as network attached storage), volatile or non-volatile computer memory, and so forth. The computer-usable medium 118 may contain computer-readable instructions for execution by the computer 108 to perform the processes described herein such as the process described in detail with reference to Fig. 3. The computer-usable medium 118 may also, or instead, store data received from the scanner 102, store a three-dimensional model of the object 104, store computer code for rendering and display, and so forth.

[0035] Fig. 2 depicts an optical system 200 for a three-dimensional scanner that may be used with the systems and methods described herein, such as for the scanner 102 described above with reference to Fig. 1.

[0036] The optical system 200 may include a primary optical facility 202, which may be employed in any kind of image processing system. In general, a primary optical facility refers herein to an optical system having one optical channel. Typically, this optical channel shares at least one lens, and has a shared image plane within the optical system, although in the following description, variations to this may be explicitly described or otherwise clear from the context. The optical system 200 may include a single primary lens, a group of lenses, an object lens, mirror systems (including traditional mirrors, digital mirror systems, digital light processors, or the like), confocal mirrors, and any other optical facilities suitable for use with the systems described herein. The optical system 200 may be used, for example in a stereoscopic or other multiple image camera system. Other optical facilities may include holographic optical elements or the like. In various configurations, the primary optical facility 202 may include one or

more lenses, such as an object lens (or group of lenses) 202b, a field lens 202d, a relay lens 202f, and so forth. The object lens 202b may be located at or near an entrance pupil 202a of the optical system 200. The field lens 202d may be located at or near a first image plane 202c of the optical system 200. The relay lens 202f may relay bundles of light rays within the optical system 200. The optical system 200 may further include components such as aperture elements 208 with one or more apertures 212, a refocusing facility 210 with one or more refocusing elements 204, one or more sampling facilities 218, and/or a number of sensors 214a, 214b, 214c.

[0037] The optical system 200 may be designed for active wavefront sampling, which should be understood to encompass any technique used to sample a series or collection of optical data from an object 220 or objects, including optical data used to help detect two- or three-dimensional characteristics of the object 220, using optical data to detect motion, using optical data for velocimetry or object tracking, or the like. Further details of an optical system that may be employed as the optical system 200 of Fig. 2 are provided in U.S. Pat. No. 7,372,642, the entire content of which is incorporated herein by reference. More generally, it will be understood that, while Fig. 2 depicts one embodiment of an optical system 200, numerous variations are possible. One salient feature of the optical system related to the discussion below is the use of a center optical channel that captures conventional video or still images at one of the sensors 214b concurrent with various offset data (at, e.g., 214a and 214c) used to capture three-dimensional measurements. This center channel image may be presented in a user interface to permit inspection, marking, and other manipulation by a user during a user session as describe below.

[0038] Fig. 3 shows a three-dimensional reconstruction system 300 employing a high-speed pipeline and a high-accuracy pipeline. In general, the high-speed processing pipeline 330 aims to provide three-dimensional data in real time, such as at a video frame rate used by an associated display, while the high-accuracy processing pipeline 350 aims to provide the highest accuracy possible from scanner measurements, subject to any external computation or time constraints imposed by system hardware or an intended use of the results. A data source 310 such as the scanner 102 described above provides image data or the like to the system 300. The data source 310 may for example include

hardware such as LED ring lights, wand sensors, a frame grabber, a computer, an operating system and any other suitable hardware and/or software for obtaining data used in a three-dimensional reconstruction. Images from the data source 310, such as center channel images containing conventional video images and side channels containing disparity data used to recover depth information may be passed to the real-time processing controller 316. The real-time processing controller 316 may also provide camera control information or other feedback to the data source 310 to be used in subsequent data acquisition or for specifying data already obtained in the data source 310 that is needed by the real-time processing controller 316. Full resolution images and related image data may be retained in a full resolution image store 322. The stored images may, for example, be provided to the high-accuracy processing controller 324 during processing, or be retained for image review by a human user during subsequent processing steps.

[0039] The real-time processing controller 316 may provide images or frames to the high-speed (video rate) processing pipeline 330 for reconstruction of three-dimensional surfaces from the two-dimensional source data in real time. In an exemplary embodiment, two-dimensional images from an image set such as side channel images, may be registered by a two-dimensional image registration module 332. Based on the results of the two-dimensional image registration, a three-dimensional point cloud generation module 334 may create a three-dimensional point cloud or other three-dimensional representation. The three-dimensional point clouds from individual image sets may be combined by a three-dimensional stitching module 336. Finally, the stitched measurements may be combined into an integrated three-dimensional model by a three-dimensional model creation module 338. The resulting model may be stored as a high-speed three-dimensional model 340.

[0040] The high-accuracy processing controller 324 may provide images or frames to the high-accuracy processing pipeline 350. Separate image sets may have two-dimensional image registration performed by a two-dimensional image registration module 352. Based on the results of the two-dimensional image registration a three-dimensional point cloud or other three-dimensional representation may be generated by a three-dimensional point cloud generation module 354. The three-dimensional point

clouds from individual image sets may be connected using a three-dimensional stitching module 356. Global motion optimization, also referred to herein as global path optimization or global camera path optimization, may be performed by a global motion optimization module 357 in order to reduce errors in the resulting three-dimensional model 358. In general, the path of the camera as it obtains the image frames may be calculated as a part of the three-dimensional reconstruction process. In a post-processing refinement procedure, the calculation of camera path may be optimized – that is, the accumulation of errors along the length of the camera path may be minimized by supplemental frame-to-frame motion estimation with some or all of the global path information. Based on global information such as individual frames of data in the image store 322, the high-speed three-dimensional model 340, and intermediate results in the high-accuracy processing pipeline 350, the high-accuracy model 370 may be processed to reduce errors in the camera path and resulting artifacts in the reconstructed model. As a further refinement, a mesh may be projected onto the high-speed model by a mesh projection module 360. The resulting images may be warped or deformed by a warping module 362. Warped images may be utilized to ease alignment and stitching between images, such as by reducing the initial error in a motion estimation. The warped images may be provided to the two-dimensional image registration module 352. The feedback of the high-accuracy three-dimensional model 370 into the pipeline may be repeated until some metric is obtained, such as a stitching accuracy or a minimum error threshold.

[0041] Various aspects of the system 300 of Fig. 3 are described in greater detail below. It should be understood that various processing modules, or the steps implied by the modules, shown in this figure are exemplary in nature and that the order of processing, or the steps of the processing sequence, may be modified, omitted, repeated, re-ordered, or supplemented, without departing from the scope of this disclosure.

[0042] Fig. 4A shows an object 410 for imaging, along with a path 415 that a camera may follow while obtaining a three-dimensional scan of a surface of the object 410. The direction of the path 415 is indicated generally by an arrow 416. The object 410 may be an upper dental impression (as shown) or any other object from which three-dimensional surface data is sought. Starting the camera at a starting point 420, the camera may follow an arc 430 to a second point 422. The camera may then follow a segment 432

to a third point 424. The camera may then follow a second arc 434 to a fourth point 426. The camera may then follow a second segment 436 to return approximately to the starting point 420. It should be noted that the path 415 followed by the camera may be irregular rather than smooth, and that while a particular path 415 is depicted, more generally any path may be taken by the camera including paths that double back upon themselves, cross over identical regions two or more times, and/or entirely skip various surfaces of the object 410. It should also be noted that the camera path 415 may usefully return to the starting point 420, but this is not strictly required for three-dimensional reconstruction as described herein. The camera may take hundreds or thousands of images or more as the camera traverses the path around such a dental object 410.

[0043] Fig. 4B shows locations where additional scan data might usefully be acquired to improve the accuracy of a three-dimensional reconstruction. For example, arcs 440, 442, 444, and 446 may be scanned (e.g., traversed by the camera path) to provide cross linking between various lengths of the camera path. Data might usefully be acquired, for example, from any area that can improve computational accuracy of a three-dimensional reconstruction such as regions where the length of a camera path between two measurements of the surface (e.g., image sets or image data) is significantly greater than the distance between the two corresponding surface locations in the world coordinate system for the camera path. It will be appreciated that this may be a Euclidean distance or any suitable proxy for distance. For example, the length of the camera path may be measured in terms of the number of camera path segments, or the number of camera path segments from key frame to key frame, between two camera poses in Euclidean space. As another example, this may include regions where separate three-dimensional measurements for a general region of the reconstructed three-dimensional model fail to register to one another, or other indicia of accumulated error in the global camera path might be present.

[0044] Fig. 5 shows a user interface depicting a graphical request for additional scan data. After the camera follows the path 415 illustrated above, a software tool may be utilized to identify various locations where additional data might usefully be acquired to reduce accumulated error in a global camera path, such as two frames of image data that represent a candidate for an accumulated error in camera path relative to one another

using, for example, any of the techniques described above. A monitor 510 may display an image 520 such as a three-dimensional reconstruction of scanned subject matter, and an arrow 530 may be displayed on the monitor 510 indicating where additional scanning is recommended. The user may then proceed to use a scanner, such as the scanner 102 from Fig. 1, to scan the area indicated by the arrow 530. More generally, areas for additional scanning may be identified to a user in a graphical user interface that displays a reconstructed three-dimensional model from the camera path, along with arrows or other identifiers or graphical annotations that illustrate a recommended scan path. After a user augments a camera path with additional scans, the resulting data can be employed to resolve differences (i.e., errors) in the global camera path, as described generally throughout this disclosure.

[0045] Fig. 6A illustrates a simple camera path in a world coordinate system. The camera starts at a starting point 610 and follows a path 620 in a counterclockwise direction as indicated by an arrow 625, returning to an ending point coincident with the starting point 610 in a fixed coordinate system, such as an arbitrarily selected world coordinate system.

[0046] Fig. 6B shows a simple camera path in a camera coordinate system. When a camera traverses the path 620 in the world coordinate system, errors may accumulate in a calculated camera path 635 so that a measured ending point 640 appears to be located away from the measured starting point 630 in the camera coordinate system, even though these points are identical in the world coordinate system. In one aspect, one or more cross links such as those described above with reference to Fig. 4 may be employed to mitigate accumulated errors in the calculated camera path 635.

[0047] Fig. 7 is a flow chart of a three-dimensional reconstruction process including global path optimization for improved accuracy.

[0048] The process 700 may begin with preprocessing as shown in step 710. It will be understood that preprocessing as described herein presupposes the availability of a number of frames of image data from which a camera path and three-dimensional model can be reconstructed. The information for the three-dimensional reconstruction may be generated in numerous ways including coming from structured light projection, shading based three-dimensional reconstruction, or disparity data. Disparity data may be

generated by a conventional image plus one or more other channels or side channels. The preprocessing may include determining the number of available frames, the time duration over which all the frames were taken, the amount of overlap between neighboring frames, identification and elimination of frames with blurred or badly distorted images, and any other suitable preprocessing steps. An estimate of the number of desired key frames may be initially determined during the preprocessing step.

[0049] As shown in step 712, key frames may be selected from among all of the frames of data acquired from a scanner along a camera path. In general, computational costs can be reduced by storing certain data and performing certain calculations and processing steps exclusively with reference to key frames. In principle, these key frames should be related to one another in a manner that permits characterization of a camera path, typically through the registration of overlapping three-dimensional data in respective key frames. Various methods are known in the art for selecting a subset of frames of data as key frames, including techniques based on image overlap, camera path distance, the number of intervening non-key frames and so forth. For example, key frames may be selected based on time duration from an immediately preceding key frame. Key frames may also or instead be selected based upon an amount of image overlap from the preceding key frame and/or a candidate for a following key frame (if available). Too little overlap makes frame-to-frame registration difficult. Too much overlap drives larger numbers of key frames and therefore larger amounts of data to analyze. Key frames may be selected based on spatial displacement, meaning that an upper limit may be placed on the amount of overlap from one key frame to the next. Key frames may also be selected based on sequential displacement. This type of sequential displacement could mean that every tenth frame is determined to be a key frame, for example. In one aspect, key frames may be selected as data is acquired based on any number of suitable criteria. In another aspect, key frame pairs may be determined post hoc by examining all possible candidate key frames. All possible key frame pairs may be examined and candidates may be removed, for example, where there is insufficient overlap to form a stitch. Still more generally, any technique suitable for selecting a subset of frames in a data set may be usefully employed to select key frames for processing in order to reduce computational complexity.

[0050] Once key frames have been selected, additional processing may be performed. For example, full image data (e.g., full resolution center and side channel images) may be stored for each key frame, along with image signature data, point cloud centroid calculations, and any other measured or calculated data to support use of the key frames in a three-dimensional reconstruction process as described herein.

[0051] As shown in step 714, candidate stitches may be identified. In general, a stitch is a relationship between two separate three-dimensional measurements from two different camera positions. Once a stitch is established, a rotation and a translation may be determined for the path of a camera between the two different camera positions. In a complementary fashion, the three-dimensional measurements from the two different camera positions may be combined into a portion of a three-dimensional model. Candidate stitches may be analyzed around each key frame, such as from the key frame to some or all of the frames of data between the key frame and neighboring key frames. Stitches may be based on the originally imaged frames. It may also be useful to deform or warp two-dimensional images during registration and other steps in a stitching process in order to improve accuracy and/or speed each stitch calculation. Stitches may also or instead be based on other observed epipolar relationships in source data.

[0052] As shown in step 716, stitches may be selected for the complete camera path from the universe of candidate stitches. The selection of stitches may be made based upon, e.g., the lowest calculated error in resulting portions of the three-dimensional model.

[0053] As shown in step 718, a graph analysis may be performed using the key frames and the associated stitching to calculate a global path for the camera used to obtain a three-dimensional model. The graph analysis may consider each key frame as a node or vertex and each stitch as an edge between a pair of nodes. A key frame is selected as a starting point. A breadth- or depth-first search may be performed through the graph to identify stitches which may connect the current key frame to another key frame. Each key frame is marked as the graph is proceeded through. A check may be performed to see if all key frames have been reached within the graph. If all key frames have not been reached through traversing stitches in the graph analysis, the largest sub-

graph is identified. This sub-graph may be examined to see if the entire three-dimensional image may be modeled.

[0054] It may be that certain sub-graphs are not required to complete the three-dimensional imaging. If the camera lingered over a particular region of a surface of an object, or if the camera looped on a region multiple times, the associated sub-graph(s) may not be needed. If a separate sub-graph is identified, which is needed to complete the three-dimensional imaging, an optional branch back to step 712 may be performed. For example, a set of key frames may have been selected which did not have sufficient stitching from one key frame to the next key frame. By choosing a different set of key frames, sufficient stitching may be obtained in order to obtain a complete graph of all needed aspects of the three-dimensional imaging. A key frame which is too sparse, meaning it has insufficient stitches to aid in building a graph, may indicate that a different set of key frames should be selected. Based on the graph analysis, a global path may be selected, and the graph may then be analyzed to optimize the path calculation.

[0055] As shown in step 720, a numerical optimization may be performed to reduce errors in the calculated camera path based upon available data for the complete camera path such as, for example, cross links that interrelate temporally distant measurements. In general, the objective of numerical optimization is to minimize a calculated error based upon an error function for the camera path and/or reconstructed three-dimensional model. A useful formulation of the error minimization problem for a global camera path is presented below.

[0056] There may be a set of candidate camera positions and orientations referenced to a world coordinate system. A camera position and orientation collectively may be referred to as a camera pose. There may be a set of measured frame-to-frame camera motions. A camera translation and rotation collectively may be referred to as a camera motion. A measured camera motion may be referenced in the coordinate system of one camera pose. An example set of three key frames may be obtained from three camera positions, *A*, *B*, and *C*, each of which may be referenced to an origin, *O*, of a world coordinate system in three-dimensional space. In addition to the position of these points, a camera at each of these points may have a different orientation. A combination of the position and orientation is generally referred to as a camera pose. Between each of

these points are motion parameters including a translation (a change in position) and a rotation (a change in orientation). The relationship between a point, X , expressed in the world coordinate system as X_O and the same point expressed in the A coordinate system, X_A may be given by equation (1):

$$(1) \quad X_A = R_{OA}X_O + T_{OA}$$

R_{OA} is the rotation, taking points from the world to the A coordinate system. T_{OA} is the translation of the world coordinate system as represented in the A coordinate system. It should be understood that symbols X and T may represent a vector, rather than a scalar, e.g. where X includes x , y , and z coordinate values. Further, it should be understood that symbol R may represent a matrix. Equations (2) and (3) may similarly represent a transform transformation between the world and the B and C coordinate systems respectively:

$$(2) \quad X_B = R_{OB}X_O + T_{OB}$$

$$(3) \quad X_C = R_{OC}X_O + T_{OC}$$

[0057] By rearranging, equation (1) and equation (2) may be represented as shown in equation (4):

$$(4) \quad X_O = R_{OA}^{-1}(X_A - T_{OA}) = R_{OB}^{-1}(X_B - T_{OB})$$

[0058] The representation of a point in one camera's coordinate system may be related to the same point in another coordinate system. For example, as in equations 1-3, coordinates of a point, X , may be transformed from the A coordinate system to the B coordinate system as follows:

$$(5) \quad X_B = R_{AB}X_A + T_{AB}$$

[0059] The rotation R_{AB} rotates points from the A to the B coordinate system and T_{AB} is the position translation of the origin of the A coordinate system in the B coordinate system.

[0060] In an optimization, the pose of every camera may be optimized based on measured transforms between camera poses. That is, a number of camera-to-world or world-to-camera rotations and translations, e.g., R_{On} and T_{On} may be performed. It will be appreciated that the world coordinate system is arbitrary, and one of these transforms

may conveniently be an identity rotation with zero translation, or a constant motion transfer can be applied to all camera poses without altering the underlying optimization.

[0061] The rotations and translations may be measured for many pairs of cameras. For the i th such measured frame-to-frame motion, let one of the cameras of the pair be camera A and the other be camera B . This may also be considered the i th stitch that relates the camera poses for A and B . Let R_{AB}^i be the measured rotation taking points in the A system to the B system and T_{AB}^i be the coordinates of the A position expressed in the B system, as in equation (5).

[0062] The rotations and translations for all cameras, R_{On} and T_{On} may be optimized. It will be appreciated that, while these expressions and the following discussion are cast in terms of rotations and translations from the individual camera coordinate systems to a single world coordinate system, this characterization is not intended to limit the generality of this disclosure. A similar or complementary analysis may be performed using the reverse of these transforms, or any other transform or collection of transforms (typically, although not necessarily rigid transforms) capable of describing a camera path across multiple poses. The constraints on camera motion from one pose, A , to another pose, B , for an i th stitch or relationship may be expressed relative to a world coordinate system as rotations, $R_{C,OA}^i$ and $R_{C,OB}^i$, and translations, $T_{C,OA}^i$ and $T_{C,OB}^i$. This relationship is further constrained by the camera path from A to B , which may be expressed as a rotation and a translation as follows:

$$(6) \quad R_{C,AB}^i = R_{C,OB}^i (R_{C,OA}^i)^{-1}$$

$$(7) \quad T_{C,AB}^i = T_{C,OB}^i - R_{C,AB}^i T_{C,OA}^i$$

[0063] Note that with sufficient stitches, these relationships may form an overdetermined system of motion constraint equations. Using these equations as a starting point, numerical optimization may be performed on the rotational and translational components of each camera pose based on the measured stitches.

[0064] In a decoupled optimization, the rotational and translational components may be independently optimized. This approach may generally be used where there are constraints on one component (e.g., rotation) that do not depend on the

other component. Given a candidate set of camera rotations, R_C^i , the corresponding candidate camera-to-camera rotations, $R_{C,AB}^i$, may be computed that correspond to each of the measured camera-to-camera rotations, R_{AB}^i . The corresponding residual rotations, which should be identity in an error free camera path, are given by

$R_{residual,AB}^i = R_{C,AB}^i (R_{AB}^i)^{-1}$. A scalar-valued rotational cost function, e_r , may be computed that depends on the candidate camera rotations:

$$(8) \quad e_r(R_{C,On}) = \sum_{i=1}^{\#stitches} r_r^{iT} r_r^i, \quad \text{where } r_r^i = \log_{SO(3)} R_{residual,AB}^i$$

[0065] In equation (8), $\log_{SO(3)}(R)$ returns an axis-angle vector, v , that corresponds to the rotation R . In other words, $\log_{SO(3)}(R)$ returns the vector, v , that has a cross-product matrix, $[v]_\times$, that is the matrix logarithm of R .

[0066] Next, a similar scalar-valued cost function may be computed for translation that depends on the candidate rotations and translations.

$$(9) \quad e_t(R_{C,On}, T_{C,On}) = \sum_{i=1}^{\#stitches} r_t^{iT} r_t^i, \quad \text{where } r_t^i = T_{C,AB}^i - T_{AB}^i$$

[0067] In one conventional, decoupled approach to solving these simultaneous systems of equations, the rotational error function may be converted into a quaternion expression in order to translate the numerical problem into a linear system of equations for solution, as described for example in *Combining two-view constraints for motion estimation*, Govindu V., *Proc. of the Int. Conf. on Computer Vision and Pattern Recognition*, vol. 2, pp. 218–225 (July 2001). While this approach may be numerically convenient, it does not enforce the unit norm constraint for the quaternion solution, which may result in inaccuracy. Thus in one aspect, a path optimization technique may be improved by minimizing equation (8) for rotation as a nonlinear optimization and minimizing equation (9) for translation as a linear optimization. In another aspect, the more computationally efficient linear system of equations may be used to generate an initial estimate for an iterative optimization that uses non-linear optimization.

[0068] More generally, the decoupled approach described above may fail to provided a truly optimal result, in a maximum-likelihood sense, where it cannot use information from the translation portion of the stitches in determining rotation.

Nonetheless, a substantial amount of work in this field aims to overcome the disadvantages of decoupled optimization, as described for example in *A solution for the registration of multiple 3D point sets using unit quaternions*, Benjemaa R. and F. Shmitt, Proc. ECCV '98, pp. 34–50 (June 1998); *Global registration of multiple 3D point sets via optimization-on-a-manifold*, Krishnan S., Lee P.Y., Moore J.B., Venkatasubramanian S., Eurographics Symp. Geometry Processing (2005); and *Simultaneous registration of multiple corresponding point sets*, Williams J., Bennamoun M., Computer Vision and Image Understanding, vol. 81, no. 1, pp. 117-142 (2001).

[0069] In one aspect disclosed herein, a coupled approach to optimization may instead be used to minimize overall error in a camera path. In order to achieve a coupled optimization a weighting may be used to balance the contributions of rotational and translational components to a combined cost function:

$$(10) \quad e_c(R_{C,On}, T_{C,On}) = \sum_{i=1}^{\#stitches} \left(\begin{bmatrix} r_t^i \\ r_r^i \end{bmatrix}^T W_c^i \begin{bmatrix} r_t^i \\ r_r^i \end{bmatrix} \right)$$

Multiple approaches may be used to weight the relative contribution of translations and rotations. In one embodiment the weights may be expressed as matrices, with different stitches receiving different weightings based upon any of a number of factors. For example, the weights may be based on the number of points in a stitch (e.g., the shared content), the quality of a particular three-dimensional measurement, and/or any other factors impacting the known reliability of a stitch. In one approach, the weight matrices may also account for anisotropic error in the individual points collected, such as due to acquisition of depth information from disparity measurements, which results in measurement precision that varies with distance from the camera.

[0070] In some cases, equation (10) may be reformulated so that the rotation and translation weights are decoupled for each stitch (i.e., W_c^i is a block diagonal). In particular, this may occur in the case that the motion stitches are recovered from three-dimensional point correspondences with isotropic point error. In that case, for a given stitch i , between poses A and B , the optimal solution may bring the point cloud as seen from pose A into correspondence with that seen from pose B . If $\bar{X}_A^i$ and $\bar{X}_B^i$ are the positions of the center of the point cloud in the A and B systems respectively, then if r_t^i is

replaced in equation (10) with the residual displacement between the point-cloud centers based on the candidate camera pose. This latter residual displacement may be expressed as:

$$(11) \quad r_{t,ctr}^i = \bar{X}_B^i - (R_{C,AB}^i \bar{X}_A^i + T_{C,AB}^i)$$

Equation (10) may then be reformulated as:

$$(12) \quad e_c(R_{C,On}, T_{C,On}) = \sum_{i=1}^{\#stitches} \left(r_{t,ctr}^i{}^T W_r^i r_{t,ctr}^i + r_r^i{}^T W_r^i r_r^i \right)$$

[0071] In general, by minimizing equation (10), both rotational errors and translational errors may be minimized simultaneously. The weight matrices can be chosen for example according to “First Order Error Propagation of the Procrustes Method for 3D Attitude Estimation” by Leo Dorst, IEEE Transactions on Pattern Analysis and Machine Intelligence, Vol. 27, No. 2, pp. 221-9 (Feb. 2005) which is incorporated in its entirety by reference. Once a more consistent set of motion parameters has been generated the three-dimensional model may be updated.

[0072] When total error or some portion of error has been minimized, the resulting value may be evaluated. The calibration state of the scanner and associated equipment may be evaluated based on the minimized error values. If a minimized error falls beyond a certain threshold then calibration for the scanner and associated hardware may be recommended. The threshold value may be empirically determined based on the specific scanner hardware equipment or it may be learned experientially over time for a given system. When a system is new or has been freshly aligned, expected minimized error values may be obtained. When minimized error values deviate from these expected values, a calibration state evaluation flag may be set indicating that the tool should be calibrated. Thus in one aspect, a coupled (or uncoupled) error function may be employed to validate calibration and determine when re-calibration of a device is appropriate.

[0073] As shown in step 722, upsampling may be performed to augment a three-dimensional model with data from non-key frames. In general, upsampling may include any technique for addition of data to a result. For example, while the global optimization described above generally refers to optimization among key frames in a contiguous camera path, the resulting optimized three-dimensional model may be supplemented by registering non-key frames to one or more nearby key frames in a

manner that creates small, local reconstruction patches that include additional three-dimensional detail available from non-key frames. Or upsampling may be performed by correcting the corresponding camera path for non-key frames according to a globally optimized path for the key frames. Thus in one aspect, upsampling may more generally be understood as any use of optimized data to incorporate related, non-optimized data into a camera path or three-dimensional model.

[0074] Fig. 8 shows a reconstruction process 800 using numerical optimization as described above. In one aspect, this optimization technique may be usefully applied to minimize errors in a camera path where spatial links between non-sequential camera poses (or corresponding data sets used to recover three-dimensional surface data) can be identified. For example, where a scan path covers a buccal surface followed by an occlusal or lingual surface, many spatial links might be identified between non-contiguous camera path segments associated with each surface. Under these conditions, a global optimization may significantly improve the accuracy of a three-dimensional reconstruction by reducing errors in the motion estimation parameters for the camera path. It will be understood that the disclosed method may also or instead be embodied in a computer program, a computer program product, or an apparatus embodying any of the foregoing.

[0075] As shown in step 802, the process may begin with acquiring data sets such as a data set from a surface of a dental object with a hand-held scanner from each one of a sequence of poses along a camera path, thereby providing a plurality of data sets. The hand-held scanner may, for example, be the video-based scanner described above. The hand-held scanner may instead include any other type of hand-held scanner suitable for intraoral dental scanning, such as a time-of-flight scanner, a structured light scanner, and so forth. The data sets may be any corresponding data acquired for each camera pose that is used to recover three-dimensional data.

[0076] It should be understood that in this context, the camera path may correspond to a physical camera path that describes the path actually taken by a scanner during a scan, or the camera path may also or instead include a virtual camera path formed from a plurality of different physical camera paths or other virtual camera paths that intersect with one another. Such a virtual camera path may be created wherever

poses from two or more physical paths can be interrelated in a global coordinate system, as established for example by three-dimensionally registering two different scans of the same physical subject matter. The use of virtual camera paths may be particularly useful, for example, where a large scan such as a full arch scan is created from data acquired during two or more discontinuous scanning sessions. Under these conditions, global optimization of a virtual camera path can be used to improve consistency of the combined data in a global coordinate system.

[0077] As shown in step 804 each one of the poses in the sequence of poses may be associated with a previous pose and a next pose by a spatial link such as motion estimation parameters or other camera path information. It should also be understood that while a system may infer camera path from the resulting three-dimensional measurements at each camera position and orientation, the camera path may also, or instead be obtained using a hardware-based positioning system based upon, e.g., accelerometers, a geopositioning system, external position sensors, transducers in an articulating arm or any other combination of sensors and techniques suitable for detecting camera position and/or orientation with sufficient accuracy for the intended three-dimensional reconstruction.

[0078] This spatial link data reflects the physical camera path in the order in which data was acquired, thus providing a plurality of spatial links that characterize the camera path during a data acquisition process. The sequence of poses may, for example, be made up of key frames (or sequential pairs of key frames) as generally described above, where additional data sets are acquired from one or more additional poses between each sequential pair of key frames. Key frames may be usefully employed, e.g., to reduce the computational complexity of path optimization while retaining a contiguous camera path of sequential poses. After path optimization is complete, additional three-dimensional data may be added based upon the one or more additional data sets and the one or more additional poses from between key frames. As described above, key frames may be selected from a larger set of poses using a metric to evaluate a quality of a resulting three-dimensional reconstruction, a quality of the estimated motion parameters between poses, a degree of overlap in scanned subject matter, a graph analysis or any other useful technique or metric.

[0079] As shown in step 806, at least one non-sequential spatial link may be identified between two non-sequential ones of the poses based upon the data set for each of the two non-sequential ones of the poses. Thus for example two data sets from a buccal and lingual scan segment may be related to one another based upon camera position, the three-dimensional data recovered from the respective data sets, or any other data acquired during a scanning process. In one aspect, a metric may be employed to identify candidates for non-sequential spatial links, such as a ratio of spatial distance between two data sets to the length of an intervening camera path. Thus the non-sequential spatial link(s) may associate two of the sequence of poses that are separated by a substantially greater distance along the camera path than along the surface of the dental object. This may be based on the data set for each of the two non-sequential ones of the poses, such as by using camera pose data to determine a surface position or by identifying an overlap in the reconstructed three-dimensional data obtained using the data set for two non-sequential poses. This may also include displaying a region for one or more candidate links in a user interface and receiving a supplemental scan of the region, as described above for example with reference to Fig. 5.

[0080] As shown in step 808, a global motion optimization may be performed on the camera path to minimize an error among the plurality of spatial links and the at least one non-sequential spatial link, thereby providing an optimized camera path. This may employ, for example, any of the optimization techniques described above. More generally, this may include any technique for minimizing errors in motion estimation parameters expressed as a function of one or more of rotation, translation, coupled rotation and translation, and decoupled rotation and translation, and/or any technique for aligning the three-dimensional data reconstructed from the data sets in a global coordinate system or improving a consistency of the sequence of poses along the camera path in the global coordinate system.

[0081] As shown in step 810, a three-dimensional model of the dental object may be reconstructed using known techniques based upon the optimized camera path and the plurality of data sets.

[0082] Thus by observing the actual camera paths typical of intra-oral dental scanning, the applicants have devised improved techniques for error minimization when

camera path is used for three-dimensional reconstruction. More specifically, by observing that intra-oral scanning often employs a number of adjacent, relatively straight global paths such as for lingual, occlusal, and buccal surfaces (as dictated in part by the relatively restricted oral access to the relatively large surfaces of dentition) , and by observing that intra-oral scanning regularly returns to earlier scan positions, the applicants have devised an optimization technique that takes advantage of the spatial relationship between certain non-sequential frames of data. The approach described above solves the problem of conflicting data for local measurements by using an error minimization technique that globally addresses the camera path, including the interrelationship of non-sequential frames of data. This may be particularly useful, for example for scans covering gums, soft tissue, full arches, orthodontic components and the like where scanning a large area typically entails multiple passes over various regions of the scanned surface.

[0083] Fig. 9 is a flow chart of a hybrid stitching process for combining disparate three-dimensional scans of a common surface. In scanning techniques that use a camera path for reconstruction, the full scan data for an object may include any number of disparate scans with camera paths, or more generally stitch graphs, that are not directly spatially related to one another. The following process 900 provides a technique for establishing spatial relationships between such stitch graphs through a series of local geometry-based registrations. The resulting, combined model may then be subjected to any of the optimization techniques described above as though it had been obtained from a single, continuous scan.

[0084] As shown in step 902, the process 900 may begin with obtaining a first three-dimensional model including a first plurality of frames of data, each including sets of three-dimensional points spatially related to one another by a first camera path. It will be understood that a 'camera path' generally refers to a sequential series of poses connected by a number of transforms from one to the next. However, the camera path of the model may more generally include any number of interrelationships or 'stitches' between non-sequential poses that can be inferred from other spatial information such as overlapping regions of an object surface in the accompanying sets of three-dimensional points. In the foregoing description, terms such as camera path and stitch graph should be

broadly interpreted to include any rigid transformations and/or other descriptive data that characterizes camera motion (and reliability thereof) in a manner that permits path-based reconstruction of a three-dimensional surface. Step 902 may also include obtaining a second three-dimensional model including a second plurality of frames of data, each including sets of three-dimensional points spatially related one another by a second camera path. The second model may, for example, be obtained after a first scan is automatically or manually interrupted, or after a first scan is completed and additional data is required or desired, either by a user or in response to prompting from a scanning system as contemplated above. More generally, the second three-dimensional model may be any disparate data set that is not directly spatially related to the first three-dimensional model through a single scan or camera path.

[0085] As shown in step 904 one of the first plurality of sets of three-dimensional points may be registered to one of the second plurality of sets of three-dimensional points. This registration may use an iterative closest point algorithm, image-based registration or any suitable technique for three-dimensional registration of points and/or surfaces. In one aspect, a surface mesh may be obtained for use in the registration process. Thus a surface mesh of the first and second plurality of sets of three-dimensional points may be generated with a mesh generation algorithm to obtain polygonal surface representations of each model (or portions thereof). This may generally include generating a surface mesh of the entire first and second models, or a known overlapping surface of the first and second data sets, or a neighborhood surrounding a known common surface, or each of the entire first and second models. The resulting first surface mesh and second surface mesh may then be registered to one another using any suitable techniques, resulting in a known, rigid transformation between the first model and the second model (or between the first surface mesh from the first model and the second surface mesh from the second model). As a result of this spatial relationship, the first three-dimensional model and the second three-dimensional model can be placed in a shared coordinate system that permits subsequent processing using data from both models as a combined surface.

[0086] As shown in step 906, the process 900 may include creating a virtual stitch graph that spatially relates individual ones of the first plurality of sets and the

second plurality of sets using virtual stitches between the data sets, thereby providing a combined model that includes the first plurality of sets and the second plurality of sets all spatially related by the virtual stitch graph. Numerous techniques may be employed for synthesizing a virtual stitch graph to inter-relate the models. The details of one particular approach are provided below with reference to Fig. 10. It will be appreciated that the term ‘virtual’ as used in this context is intended to distinguish models using data from multiple disparate scans. Thus while the source of data (multiple camera paths) used to calculate ‘virtual stitches’ and/or virtual stitch graphs may be different from the data (single camera paths) used to calculate other stitches and graphs, the resulting data can advantageously be provided in a form for use interchangeably with and undistinguishable from data derived from a single scan. As such, in a preferred embodiment, there may be little to distinguish a ‘virtual’ stitch or a virtual stitch graph from those that are not virtual, except perhaps for their absence from the two or more disparate models from which they were derived.

[0087] As shown in step 908, the process 900 may include refining the combined model with a global motion optimization of the virtual stitch graph. With a single virtual stitch graph that inter-relates all of the data from each of the disparate sets (acquired from different scans), any of the global motion optimization techniques described above may be suitably employed to minimize errors on a stitch-by-stitch basis among the combined data sets. In one aspect, this optimization includes a deformable registration where, as distinguished from calculating error-minimized rigid transformations, each stitch or step of the camera path can be moved spatially to minimize global error. Thus in one aspect, the process 900 includes refining the combined model with a deformable registration.

[0088] As shown in step 910, the combined model may be stored and/or displayed. This may include, for example, displaying the combined model at a chairside scanning location or a dental laboratory. The combined model may also be stored locally at a scanner site, or transmitted to a central repository for project management including, without limitation, billing, quality assurance, and scheduling fabrication of a dental object at a dental laboratory. The original source data from the disparate scans (e.g., disparate camera paths, frames of image data, etc.) may be retained for further processing or for

evaluation of the combined model, or the source data may be deleted once the combined model is obtained.

[0089] Fig. 10 is a flow chart of a process for creating of a virtual stitch graph. In the following description, it is assume that two disparate three-dimensional models are provided, each obtained from a sequence of frames of data spatially related by a camera path as generally described above, and that the two models have been registered to establish an initial rigid transformation between them. It will be appreciated that modifications or adaptations of the foregoing may be appropriate where other three-dimensional scanning techniques are employed, or where three or more disparate data sets are concurrently reconciled, all of which is intended to fall within the scope of this disclosure.

[0090] As shown in step 1002, the process 1000 may include selecting overlapping data sets. This may, for example, include selecting a first selected one of the first plurality of sets and a second selected one of the second plurality of sets that overlap on the combined surface obtained from the coarse registration described above with reference to Fig. 9. An initial selection of one of the first or second plurality of sets may be, for example, a random selection or a parameterized selection based on, e.g., location within the first or second meshes or proximity to a centroid or other feature of interest in the combined or separate surfaces.

[0091] All of the frames or sets of data from the first plurality of sets (e.g., the first model) in a neighborhood about the first selected one may then also be selected for use as a local processing neighborhood. This may, for example, be all sets of data within a certain number of stitches away, such as all sets within five stitches, or a certain number of steps along a camera path. In order to reduce redundant processing, the sets within this local processing neighborhood may optionally be marked or otherwise identified as unavailable for future processing after the local hybrid stitching operations of the process 1000 are completed. Using the coarse registration of surface meshes, one of the second plurality of sets (e.g., a frame from the second model) may be selected that is near (or nearest) to the local processing neighborhood. All of the frames or sets of data from the second plurality of sets in a neighborhood about the second selected one of the second plurality of sets may then be identified in a similar manner to the selection of the local

processing neighborhood, e.g., by selecting frames or sets of data in the second plurality of sets of data that are within a certain number of stitches or sequential camera poses from the second selected one. It will be appreciated in this context that the use of a stitch graph (of stitches, which may extend in numerous directions from a single camera pose) can provide a significant processing advantage over a camera path (of individual transforms from one camera pose to the next) by affording more options for coverage of relevant regions of a surface of an object.

[0092] The selection of local processing neighborhoods for frames from the first and second plurality of data sets may be further refined, such as by restricting or prohibiting use of data sets outside a surface or region common to the two neighborhoods.

[0093] As shown in step 1004, data may be optimized in the local processing neighborhoods. For example, where each data set is represented by a camera path or stitch graph that inter-relates sets of three-dimensional points through a sequence of camera poses or the like, a sub-graph of the camera path or stitch graph may be selected for each of the models that only contains data (frames or sets of three-dimensional data points, along with stitches or camera path information) from within the local processing neighborhoods. This approach advantageously removes the influence of data external to the local processing neighborhoods. At this point in the processing, the data still generally comprises two disparate models – in this case, sub-graphs of the full data set – that are associated by a single rigid transform obtained from the coarse registration of surface meshes. This data may be further optimized prior to hybrid stitching by, e.g., performing a global motion optimization (as described above) on each of the extracted sub-graphs. With the sub-graphs so optimized, the registration between the two sub-graphs may be refined by repeating an iterative closest point algorithm or other suitable registration process for the two point clouds represented by the optimized sub-graphs. While this approach to optimization is effective in a three-dimensional surface reconstruction based upon camera paths, it will be appreciated that a variety of other optimizations are known in the art for three-dimensional reconstructions, any of which may be adapted to optimization of the local processing neighborhoods contemplated herein.

[0094] As shown in step 1006, links for a virtual stitch graph (also referred to as ‘hybrid’ or ‘virtual’ stitches) may be created. This may include finding a frame from each of the two sub-graphs closest to a centroid of the overlapping region between the two sub-graphs. These two frames may then be directly spatially related to one another by a rigid transformation, which may be a newly calculated rigid transformation or a refinement of the rigid transformation obtained in the optimization steps described above. Using this transformation, data from the two sub-graphs may be transposed into a common coordinate system, such as the original coordinate system of one of the sub-graphs. This may be repeated for one or more other frames of data in the two sub-graphs to provide a number of direct spatial relationships or ‘virtual stitches’ between frames in the first sub-graph and frames in the second sub-graph. These relationships may be used directly as stitches in a combined, virtual stitch graph, or further processed as appropriate to express these new relationships in the same form as existing stitches in the stitch graphs or camera paths of the initial models.

[0095] In order to facilitate concurrent processing of the actual stitches in the original models and the virtual stitches created for the virtual stitch graph that combines the models, additional characterizing data may be included in each virtual link. For example, a covariance matrix that weights confidence in each link according to multiple degrees of freedom (e.g., six degrees of freedom for full translation and rotation) may be provided. While such a covariance matrix results from, for example, the iterative closest point registration process, the use of a particular form is less significant than sufficient commonality between the expression of actual stitches and the virtual stitches for undifferentiated processing of data from both sources in a combined model.

[0096] As shown in step 1008, if there are additional neighborhoods of overlapping data to be locally optimized, the process may return to step 1002 where additional overlapping data sets can be selected to create additional virtual links. This may be repeated as often as necessary or desired. If there are no further local neighborhoods for processing, or if some other termination condition such as a threshold number of virtual links or percentage coverage of the full surface area of the combined model has been reached, then the process 1000 may proceed to step 1010.

[0097] As shown in step 1010, a combined model may be created that combines the actual stitch graphs from the two original models and the virtual stitches established between the two models as described above. In addition, any number of additional virtual stitches may be added based upon other data in the global models (as distinguished from the local processing neighborhoods), such as nearly identical and/or substantially co-located data sets in the first and second models. In addition, the combined model may be analyzed for completeness and to identify further opportunities for establishing additional stitches between data sets either with or without regard for whether the data sets are from the first model or the second model.

[0098] As shown in step 1012, the combined model may be optimized using, e.g., global motion optimization as described above to minimize errors in the transformations between related camera poses of the combined model (as distinguished from either of the original stitch graphs or camera paths).

[0099] As shown in step 1014, a point cloud may be generated for the combined model that places all of the three-dimensional points of the combined model into a single, common coordinate system.

[00100] As shown in step 1016, a surface mesh may be generated for the point cloud using any suitable surface meshing techniques. The model may also be stored, displayed, transmitted or otherwise processed or handled as generally contemplated by the foregoing description.

[00101] It will be appreciated that any of the above system and/or methods may be realized in hardware, software, or any combination of these suitable for the data acquisition and modeling technologies described herein. This includes realization in one or more microprocessors, microcontrollers, embedded microcontrollers, programmable digital signal processors or other programmable devices, along with internal and/or external memory. The may also, or instead, include one or more application specific integrated circuits, programmable gate arrays, programmable array logic components, or any other device or devices that may be configured to process electronic signals. It will further be appreciated that a realization may include computer executable code created using a structured programming language such as C, an object oriented programming language such as C++, or any other high-level or low-level programming language

(including assembly languages, hardware description languages, and database programming languages and technologies) that may be stored, compiled or interpreted to run on one of the above devices, as well as heterogeneous combinations of processors, processor architectures, or combinations of different hardware and software. Thus in one aspect there is disclosed herein a computer program product comprising computer executable code that, when executing on one or more computing devices, performs any and/or all of the steps described above.

[00102] At the same time, processing may be distributed across devices such as a camera and/or computer and/or fabrication facility and/or dental laboratory and/or server in a number of ways or all of the functionality may be integrated into a dedicated, standalone device.

[00103] In another aspect, a system disclosed herein includes means such as any of the structures described above for performing the functions expressed or implied in the flow charts and other portions of the above description.

[00104] All such permutations and combinations that would be apparent to one of ordinary skill in the art are intended to fall within the scope of the present disclosure, which along with the claims is intended to be interpreted in the broadest sense allowable by law.

CLAIMS

What is claimed is:

1. A method comprising:
 - obtaining a first three-dimensional model including a first plurality of sets of three-dimensional points spatially related to one another by a first camera path;
 - obtaining a second three-dimensional model including a second plurality of sets of three-dimensional points spatially related to one another by a second camera path;
 - registering one of the first plurality of sets of three-dimensional points to one of the second plurality of sets of three-dimensional points to place the first three-dimensional model and the second three-dimensional model in a shared coordinate system;
 - creating a virtual stitch graph that spatially relates the first plurality of sets and the second plurality of sets, thereby providing a combined model that includes the first plurality of sets and the second plurality of sets all spatially related by the virtual stitch graph; and
 - refining the combined model with a global motion optimization of the virtual stitch graph.
2. The method of claim 1 further comprising generating a first surface mesh of the first three-dimensional model and a second surface mesh of the second three-dimensional model.
3. The method of claim 2 wherein registering includes registering the first surface mesh to the second surface mesh, thereby providing a combined surface.
4. The method of claim 3 wherein registering includes registering with an iterative closest point algorithm.

5. The method of claim 3 further comprising selecting a first selected one of the first plurality of sets and a second selected one of the second plurality of sets that overlap on the combined surface.

6. The method of claim 5 wherein at least one of the first selected one and the second selected one is a set of three-dimensional data closest to a centroid of the combined surface.

7. The method of claim 5 further comprising calculating a rigid transformation and a mean error between the first selected one and the second selected one.

8. The method of claim 7 further comprising selecting a first neighborhood of the first plurality of sets from about the one of the first plurality of sets and a second neighborhood of the second plurality of sets from about the one of the second plurality of sets.

9. The method of claim 8 further comprising:
extracting a sub-region of the combined surface;
spatially relating two or more of the first plurality of sets to two or more of the second plurality of sets within the sub-region to provide a virtual stitch graph; and
minimizing an error among spatial relationships in the virtual stitch graph, thereby providing a combined data set for the sub-region.

10. The method of claim 9 further comprising creating at least one virtual stitch between two unstitched ones of the first plurality of sets.

11. The method of claim 1 further comprising refining the combined model with a deformable registration.

12. A computer program product comprising computer executable code embodied on a non-transitory computer readable medium that, when executing on one or more computing devices, performs the steps of:

- obtaining a first three-dimensional model including a first plurality of sets of three-dimensional points spatially related to one another by a first camera path;

- obtaining a second three-dimensional model including a second plurality of sets of three-dimensional points spatially related to one another by a second camera path;

- registering one of the first plurality of sets of three-dimensional points to one of the second plurality of sets of three-dimensional points to place the first three-dimensional model and the second three-dimensional model in a shared coordinate system;

- creating a virtual stitch graph that spatially relates the first plurality of sets and the second plurality of sets, thereby providing a combined model that includes the first plurality of sets and the second plurality of sets all spatially related by the virtual stitch graph; and

- refining the combined model with a global motion optimization of the virtual stitch graph.

13. The computer program product of claim 12 further comprising code that performs the step of generating a first surface mesh of the first three-dimensional model and a second surface mesh of the second three-dimensional model.

14. The computer program product of claim 13 wherein registering includes registering the first surface mesh to the second surface mesh, thereby providing a combined surface.

15. The computer program product of claim 14 wherein registering includes registering with an iterative closest point algorithm.

16. The computer program product of claim 14 further comprising code that performs the step of selecting a first selected one of the first plurality of sets and a second selected one of the second plurality of sets that overlap on the combined surface.

17. The computer program product of claim 16 wherein at least one of the first selected one and the second selected one is a set of three-dimensional data closest to a centroid of the combined surface.

18. The computer program product of claim 16 further comprising code that performs the step of calculating a rigid transformation and a mean error between the first selected one and the second selected one.

19. The computer program product of claim 18 further comprising code that performs the step of selecting a first neighborhood of the first plurality of sets from about the one of the first plurality of sets and a second neighborhood of the second plurality of sets from about the one of the second plurality of sets.

20. The computer program product of claim 19 further comprising code that performs the steps of:

- extracting a sub-region of the combined surface;
- spatially relating two or more of the first plurality of sets to two or more of the second plurality of sets within the sub-region to provide a virtual stitch graph; and
- minimizing an error among spatial relationships in the virtual stitch graph, thereby providing a combined data set for the sub-region.

21. The computer program product of claim 20 further comprising code that performs the step of creating at least one virtual stitch between two unstitched ones of the first plurality of sets.

22. The computer program product of claim 12 further comprising code that performs the step of refining the combined model with a deformable registration.

23. A system comprising:

a scanner configured to obtain a first three-dimensional model including a first plurality of sets of three-dimensional points spatially related to one another by a first camera path and a second three-dimensional model including a second plurality of sets of three-dimensional points spatially related with one another by a second camera path;

a processor and memory configured to register one of the first plurality of sets of three-dimensional points to one of the second plurality of sets of three-dimensional points to place the first three-dimensional model and the second three-dimensional model in a shared coordinate system, to create a virtual stitch graph that spatially relates the first plurality of sets and the second plurality of sets, thereby providing a combined model that includes the first plurality of sets and the second plurality of sets all spatially related by the virtual stitch graph, and to refine the combined model with a global motion optimization of the virtual stitch graph; and

a display configured to render the combined model.

24. A system comprising:

scanning means for obtaining a first three-dimensional model including a first plurality of sets of three-dimensional points spatially related to one another by a first camera path and a second three-dimensional model including a second plurality of sets of three-dimensional points spatially related with one another by a second camera path; and

processing means for registering one of the first plurality of sets of three-dimensional points to one of the second plurality of sets of three-dimensional points to place the first three-dimensional model and the second three-dimensional model in a shared coordinate system, creating a virtual stitch graph that spatially relates the first plurality of sets and the second plurality of sets, thereby providing a combined model that includes the first plurality of sets and the second plurality of sets all spatially related by the virtual stitch graph, and refining the combined model with a global motion optimization of the virtual stitch graph.

ABSTRACT

[00105] In a system or method where three-dimensional data is acquired as a sequence of frames of data along a camera path, disparate sequences are related to one another through a number of geometric stitches obtained by direct registration of three-dimensional data between frames in the disparate sequences. These geometric stitches are then used in addition to or in place of other camera path relationships to form a single virtual stitch graph for the combined model, upon which an integrated global path optimization can be performed.

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Document Number	Document Description	File Name	File Size(Bytes)/ Message Digest	Multi Part /.zip	Pages (if appl.)
1	Application Data Sheet	BRNT-0022-P60_022211_ADS.pdf	1357829	no	4
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	Specification		1	34	
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If a timely submission to enter the national stage of an international application is compliant with the conditions of 35 U.S.C. 371 and other applicable requirements a Form PCT/DO/EO/903 indicating acceptance of the application as a national stage submission under 35 U.S.C. 371 will be issued in addition to the Filing Receipt, in due course.

New International Application Filed with the USPTO as a Receiving Office

If a new international application is being filed and the international application includes the necessary components for an international filing date (see PCT Article 11 and MPEP 1810), a Notification of the International Application Number and of the International Filing Date (Form PCT/RO/105) will be issued in due course, subject to prescriptions concerning national security, and the date shown on this Acknowledgement Receipt will establish the international filing date of the application.

DOCUMENT MADE AVAILABLE UNDER THE PATENT COOPERATION TREATY (PCT)

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From the INTERNATIONAL BUREAU

To:

VIETZKE, Lance L.,
3M Center Office of Intellectual Property Counsel
Post Office Box 33427
Saint Paul, Minnesota 55133-3427
ETATS-UNIS D'AMERIQUE

Date of mailing (day/month/year) 16 May 2012 (16.05.2012)	IMPORTANT NOTIFICATION
Applicant's or agent's file reference 67245WO003	
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1. The following indications appeared on record concerning:			
☒ the applicant	☒ the inventor	☐ the agent	☐ the common representative
Name and Address FRANTZDALE, Benjamin 21 Wormwood Street No. 420 Boston, Massachusetts 02421 United States of America		State of Nationality US	State of Residence US
		Telephone No.	
		Facsimile No.	
		E-mail address	
2. The International Bureau hereby notifies the applicant that the following change has been recorded concerning:			
☐ the person	☐ the name	☒ the address	☐ the nationality ☐ the residence
Name and Address FRANTZDALE, Benjamin 86 Foster Street Littleton, Massachusetts 01460 United States of America		State of Nationality US	State of Residence US
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3. Further observations, if necessary:			
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The International Bureau of WIPO 34, chemin des Colombettes 1211 Geneva 20, Switzerland	Authorized officer Fujino Kaori
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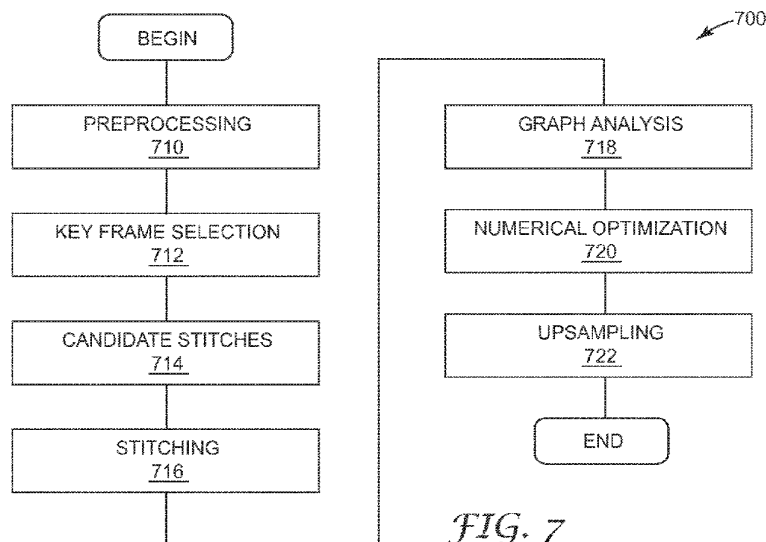
(54) **Title:** HYBRID STITCHING

FIG. 7

(57) **Abstract:** In a system or method where three-dimensional data is acquired as a sequence of frames of data along a camera path, disparate sequences are related to one another through a number of geometric stitches obtained by direct registration of three-dimensional data between frames in the disparate sequences. These geometric stitches are then used in addition to or in place of other camera path relationships to form a single virtual stitch graph for the combined model, upon which an integrated global path optimization can be performed.



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- (72) **Inventors; and**
- (75) **Inventors/Applicants (for US only):** **KRIVESHKO, Ilya, A.** [US/US]; 86 Foster Street, Littleton, MA 01460 (US). **FRANTZDALE, Benjamin** [US/US]; 86 Foster Street, Littleton, MA 01460 (US).
- (74) **Agents:** **VIETZKE, Lance, L.** et al.; 3M Center Office of Intellectual Property Counsel, Post Office Box 33427, Saint Paul, MN 55133-3427 (US).

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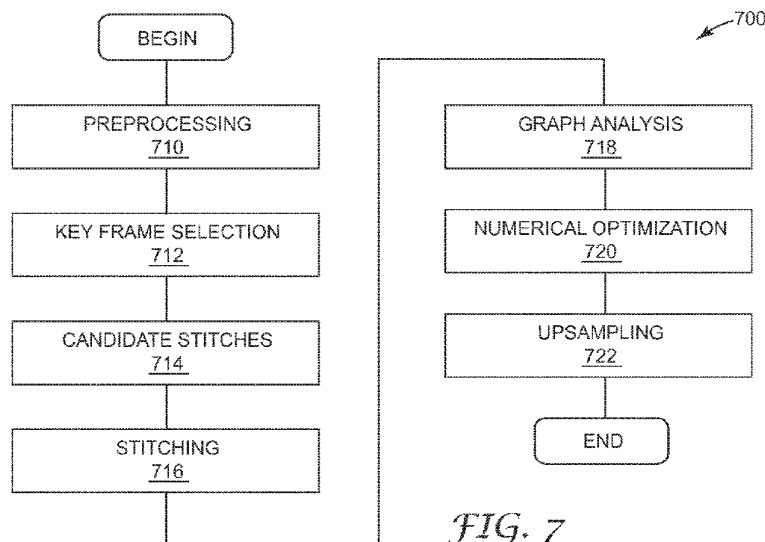


FIG. 7

(57) **Abstract:** In a system or method where three-dimensional data is acquired as a sequence of frames of data along a camera path, disparate sequences are related to one another through a number of geometric stitches obtained by direct registration of three-dimensional data between frames in the disparate sequences. These geometric stitches are then used in addition to or in place of other camera path relationships to form a single virtual stitch graph for the combined model, upon which an integrated global path optimization can be performed.



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HYBRID STITCHING

FIELD OF INVENTION

[0001] This invention relates generally to three-dimensional imaging and more specifically techniques for combining disparate scans of a common three-dimensional surface.

BACKGROUND

[0002] In one technique for three-dimensional image reconstruction, a number of images or image sets of an object are captured with a camera that travels in a path over the surface of the object. A three-dimensional model of the object can then be obtained from a description of the camera path and individual three-dimensional measurements captured along the camera path. In certain applications, data from a surface of an object is available in multiple, disparate data sets, such as where a scan is interrupted prior to completion or where additional scans are performed to augment an initial scan. The resulting multiple models can be registered to one another to obtain a combined model. While conventional registration techniques can minimize an error in alignment between two such resulting models, this approach does not afford an opportunity to refine the individual models in view of the combined data.

[0003] There remains a need for improved techniques to combine disparate three-dimensional data sets, particularly disparate data sets based upon a path of poses of a three-dimensional scanner.

SUMMARY

[0004] In a system or method where three-dimensional data is acquired as a sequence of frames of data along a camera path, disparate sequences are related to one another through a number of geometric stitches obtained by direct registration of three-dimensional data between frames in the disparate sequences. These geometric stitches are then used in addition to or in place of other camera path relationships to form a single virtual stitch graph for the combined model, upon which an integrated global path optimization can be performed.

BRIEF DESCRIPTION OF THE DRAWINGS

[0005] The invention and the following detailed description of certain embodiments thereof may be understood by reference to the following figures.

[0006] Fig. 1 shows a three-dimensional scanning system.

[0007] Fig. 2 shows a schematic diagram of an optical system for a three-dimensional scanner.

[0008] Fig. 3 shows a processing pipeline for obtaining three-dimensional data from a video scanner.

[0009] Fig. 4A and 4B illustrate camera paths for a three-dimensional scanner.

[0010] Fig. 5 shows a user interface image where additional data is requested by a software tool.

[0011] Fig. 6A and 6B illustrate accumulated error in camera paths.

[0012] Fig. 7 is a flow chart of a three-dimensional reconstruction process including global path optimization for improved accuracy.

[0013] Fig. 8 is a flow chart of a dental object reconstruction process using numerical optimization.

[0014] Fig. 9 is a flow chart of a hybrid stitching process for combining disparate three-dimensional scans of a common surface.

[0015] Fig. 10 is a flow chart of a process for creating of a virtual stitch graph.

DETAILED DESCRIPTION

[0016] In the following text, references to items in the singular should be understood to include items in the plural, and vice versa, unless explicitly stated otherwise or clear from the text. Grammatical conjunctions are intended to express any and all disjunctive and conjunctive combinations of conjoined clauses, sentences, words, and the like, unless otherwise stated or clear from the context.

[0017] In the systems and methods described herein, a number of techniques for global motion optimization are employed to improve accuracy of three-dimensional reconstructions based upon camera path.

[0018] The following description details specific scanning technologies and focuses on dental applications of three-dimensional imaging; however, it will be appreciated that variations, adaptations, and combinations of the methods and systems below will be apparent to one of ordinary skill in the art. For example, while an image-based system is described, non-image based scanning techniques such as infrared time-of-flight techniques or structured light techniques using patterned projections may similarly employ reconstruction based on camera path that may benefit from the improvements described herein. As another example, while digital dentistry is one useful application of the improved accuracy that results from the techniques described herein, global path optimization may also usefully be employed to refine three-

dimensional animation models or three-dimensional scans for machine vision applications or for mapping applications. All such variations, adaptations, and combinations are intended to fall within the scope of this disclosure.

[0019] In the following description, the term “image” generally refers to a two-dimensional set of pixels forming a two-dimensional view of a subject within an image plane. The term “image set” generally refers to a set of related two-dimensional images that might be resolved into three-dimensional data. The term “point cloud” generally refers to a three-dimensional set of points forming a three-dimensional view of the subject reconstructed from a number of two-dimensional images. In a three-dimensional image capture system, a number of such point clouds may also be registered and combined into an aggregate point cloud constructed from images captured by a moving camera. Thus it will be understood that pixels generally refer to two-dimensional data and points generally refer to three-dimensional data, unless another meaning is specifically indicated or clear from the context.

[0020] The terms “three-dimensional model”, “three-dimensional surface representation”, “digital surface representation”, “three-dimensional surface map”, and the like, as used herein, are intended to refer to any three-dimensional surface map of an object, such as a point cloud of surface data, a set of two-dimensional polygons, or any other data representing all or some of the surface of an object, as might be obtained through the capture and/or processing of three-dimensional scan data, unless a different meaning is explicitly provided or otherwise clear from the context. A “three-dimensional representation” may include any of the three-dimensional surface representations described above, as well as volumetric and other representations, unless a different meaning is explicitly provided or otherwise clear from the context.

[0021] In general, the terms “render” or “rendering” refer to a two-dimensional visualization of a three-dimensional object, such as for display on a monitor. However, it will be understood that a variety of three-dimensional rendering technologies exist, and may be usefully employed with the systems and methods disclosed herein. For example, the system and methods described herein may usefully employ a holographic display, an autostereoscopic display, an anaglyph display, a head-mounted stereo display, or any other two-dimensional and/or three-dimensional display. As such, rendering as described herein should be interpreted broadly unless a narrower meaning is explicitly provided or otherwise clear from the context.

[0022] The term “dental object”, as used herein, is intended to refer broadly to subject matter related to dentistry. This may include intraoral structures such as dentition, and more typically human dentition, such as individual teeth, quadrants, full arches, pairs of arches (which may be separate or in occlusion of various types), soft tissue, and the like, as well bones

and any other supporting or surrounding structures. As used herein, the term “intraoral structures” refers to both natural structures within a mouth as described above and artificial structures such as any of the dental objects described below that might be present in the mouth. Dental objects may include “restorations”, which may be generally understood to include components that restore the structure or function of existing dentition, such as crowns, bridges, veneers, inlays, onlays, amalgams, composites, and various substructures such as copings and the like, as well as temporary restorations for use while a permanent restoration is being fabricated. Dental objects may also include a “prosthesis” that replaces dentition with removable or permanent structures, such as dentures, partial dentures, implants, retained dentures, and the like. Dental objects may also include “appliances” used to correct, align, or otherwise temporarily or permanently adjust dentition, such as removable orthodontic appliances, surgical stents, bruxism appliances, snore guards, indirect bracket placement appliances, and the like. Dental objects may also include “hardware” affixed to dentition for an extended period, such as implant fixtures, implant abutments, orthodontic brackets, and other orthodontic components. Dental objects may also include “interim components” of dental manufacture such as dental models (full and/or partial), wax-ups, investment molds, and the like, as well as trays, bases, dies, and other components employed in the fabrication of restorations, prostheses, and the like. Dental objects may also be categorized as natural dental objects such as the teeth, bone, and other intraoral structures described above or as artificial dental objects such as the restorations, prostheses, appliances, hardware, and interim components of dental manufacture as described above.

[0023] Terms such as “digital dental model”, “digital dental impression” and the like, are intended to refer to three-dimensional representations of dental objects that may be used in various aspects of acquisition, analysis, prescription, and manufacture, unless a different meaning is otherwise provided or clear from the context. Terms such as “dental model” or “dental impression” are intended to refer to a physical model, such as a cast, printed, or otherwise fabricated physical instance of a dental object. Unless specified, the term “model”, when used alone, may refer to either or both of a physical model and a digital model.

[0024] It will further be understood that terms such as “tool” or “control”, when used to describe aspects of a user interface, are intended to refer generally to a variety of techniques that may be employed within a graphical user interface or other user interface to receive user input that stimulates or controls processing including without limitation drop-down lists, radio buttons, cursor and/or mouse actions (selections by point, selections by area, drag-and-drop operations, and so forth), check boxes, command lines, text input fields, messages and alerts, progress bars, and so forth. A tool or control may also include any physical hardware relating to

the user input, such as a mouse, keyboard, display, keypad, track ball, and/or any other device that receives physical input from a user and converts the physical input into an input for use in a computerized system. Thus in the following description the terms “tool”, “control” and the like should be broadly construed unless a more specific meaning is otherwise provided or clear from the context.

[0025] Fig. 1 depicts a three-dimensional scanning system that may be used with the systems and methods described herein. In general, the system 100 may include a scanner 102 that captures images from a surface 106 of an object 104, such as a dental patient, and forwards the images to a computer 108, which may include a display 110 and one or more user-input devices 112, 114 such as a mouse 112 or a keyboard 114. The scanner 102 may also include an integrated input or output device 116 such as a control input (for example, button, touchpad, thumbwheel, etc.) or a display (for example, LCD or LED display) to provide status information.

[0026] The scanner 102 may include any camera or camera system suitable for capturing images from which a three-dimensional point cloud or other three-dimensional data may be recovered. For example, the scanner 102 may employ a multi-aperture system as disclosed in U.S. Pat. No. 7,372,642 to Rohály et al. While Rohály discloses one multi-aperture system, it will be appreciated that any multi-aperture system suitable for reconstructing a three-dimensional point cloud from a number of two-dimensional images may similarly be employed. In one multi-aperture embodiment, the scanner 102 may include a plurality of apertures including a center aperture positioned along a center optical axis of a lens that provides a center channel for the scanner 102, along with any associated imaging hardware. In such embodiments, the center channel may provide a conventional video image of the scanned subject matter, while a number of axially offset channels yield image sets containing disparity information that can be employed in three-dimensional reconstruction of a surface. In other embodiments, a separate video camera and/or channel may be provided to achieve the same result, that is, a video of an object corresponding temporally to a three-dimensional scan of the object, preferably from the same perspective, or from a perspective having a fixed, known relationship to the perspective of the scanner 102. The scanner 102 may also, or instead, include a stereoscopic, triscopic or other multi-camera or other configuration in which a number of cameras or optical paths are maintained in fixed relation to one another to obtain two-dimensional images of an object from a number of different perspectives. The scanner 102 may include suitable processing for deriving a three-dimensional point cloud from an image set or a number of image sets, or each two-dimensional image set may be transmitted to an external processor such as contained in the computer 108 described below. In other embodiments, the scanner 102 may employ structured light, laser

scanning, direct ranging, or any other technology suitable for acquiring three-dimensional data, or two-dimensional data that can be resolved into three-dimensional data. While the techniques described below can usefully employ video data acquired by a video-based three-dimensional scanning system, it will be understood that any other three-dimensional scanning system may be supplemented with a video acquisition system that captures suitable video data contemporaneously with, or otherwise synchronized with, the acquisition of three-dimensional data.

[0027] In one embodiment, the scanner 102 is a handheld, freely-positionable probe having at least one user-input device 116, such as a button, lever, dial, thumb wheel, switch, or the like, for user control of the image capture system 100 such as starting and stopping scans. In an embodiment, the scanner 102 may be shaped and sized for dental scanning. More particularly, the scanner may be shaped and sized for intraoral scanning and data capture, such as by insertion into a mouth of an imaging subject and passing over an intraoral surface 106 at a suitable distance to acquire surface data from teeth, gums, and so forth. The scanner 102 may, through such a continuous data acquisition process, capture a point cloud of surface data having sufficient spatial resolution and accuracy to prepare dental objects such as prosthetics, hardware, appliances, and the like therefrom, either directly or through a variety of intermediate processing steps. In other embodiments, surface data may be acquired from a dental model such as a dental prosthetic, to ensure proper fitting using a previous scan of corresponding dentition, such as a tooth surface prepared for the prosthetic.

[0028] Although not shown in Fig. 1, it will be appreciated that a number of supplemental lighting systems may be usefully employed during image capture. For example, environmental illumination may be enhanced with one or more spotlights illuminating the object 104 to speed image acquisition and improve depth of field (or spatial resolution depth). The scanner 102 may also, or instead, include a strobe, flash, or other light source to supplement illumination of the object 104 during image acquisition.

[0029] The object 104 may be any object, collection of objects, portion of an object, or other subject matter. More particularly with respect to the dental techniques discussed herein, the object 104 may include human dentition captured intraorally from a dental patient's mouth. A scan may capture a three-dimensional representation of some or all of the dentition according to particular purpose of the scan. Thus the scan may capture a digital model of a tooth, a quadrant of teeth, or a full collection of teeth including two opposing arches, as well as soft tissue or any other relevant intraoral structures. The scan may capture multiple representations, such as a tooth surface before and after preparation for a restoration. As will be noted below, this data may be

employed for subsequent modeling such as designing a restoration or determining a margin line for same. During the scan, a center channel of the scanner 102 or a separate video system may capture video of the dentition from the point of view of the scanner 102. In other embodiments where, for example, a completed fabrication is being virtually test fitted to a surface preparation, the scan may include a dental prosthesis such as an inlay, a crown, or any other dental prosthesis, dental hardware, dental appliance, or the like. The object 104 may also, or instead, include a dental model, such as a plaster cast, wax-up, impression, or negative impression of a tooth, teeth, soft tissue, or some combination of these.

[0030] The computer 108 may include, for example, a personal computer or other processing device. In one embodiment, the computer 108 includes a personal computer with a dual 2.8GHz Opteron central processing unit, 2 gigabytes of random access memory, a TYAN Thunder K8WE motherboard, and a 250 gigabyte, 10,000 rpm hard drive. In one current embodiment, the system can be operated to capture more than five thousand points per image set in real time using the techniques described herein, and store an aggregated point cloud of several million points. Of course, this point cloud may further processed to accommodate subsequent data handling, such as by decimating the point cloud data or generating a corresponding mesh of surface data. As used herein, the term “real time” means generally with no observable latency between processing and display. In a video-based scanning system, real time more specifically refers to processing within the time between frames of video data, which may vary according to specific video technologies between about fifteen frames per second and about thirty frames per second. More generally, processing capabilities of the computer 108 may vary according to the size of the object 104, the speed of image acquisition, and the desired spatial resolution of three-dimensional points. The computer 108 may also include peripheral devices such as a keyboard 114, display 110, and mouse 112 for user interaction with the camera system 100. The display 110 may be a touch screen display capable of receiving user input through direct, physical interaction with the display 110. In another aspect, the display may include an autostereoscopic display capable of displaying stereo images.

[0031] Communications between the computer 108 and the scanner 102 may use any suitable communications link including, for example, a wired connection or a wireless connection based upon, for example, IEEE 802.11 (also known as wireless Ethernet), BlueTooth, or any other suitable wireless standard using, for example, a radio frequency, infrared, or other wireless communication medium. In medical imaging or other sensitive applications, wireless image transmission from the scanner 102 to the computer 108 may be secured. The computer 108 may

generate control signals to the scanner 102 which, in addition to image acquisition commands, may include conventional camera controls such as focus or zoom.

[0032] In an example of general operation of a three-dimensional image capture system 100, the scanner 102 may acquire two-dimensional image sets at a video rate while the scanner 102 is passed over a surface of the subject. The two-dimensional image sets may be forwarded to the computer 108 for derivation of three-dimensional point clouds. The three-dimensional data for each newly acquired two-dimensional image set may be derived and fitted or “stitched” to existing three-dimensional data using a number of different techniques. Such a system employs camera motion estimation to avoid the need for independent tracking of the position of the scanner 102. One useful example of such a technique is described in commonly-owned U.S. App. No. 11/270,135, filed on November 9, 2005. However, it will be appreciated that this example is not limiting, and that the principles described herein may be applied to a wide range of three-dimensional image capture systems.

[0033] The display 110 may include any display suitable for video or other rate rendering at a level of detail corresponding to the acquired data. Suitable displays include cathode ray tube displays, liquid crystal displays, light emitting diode displays and the like. In general, the display 110 may be operatively coupled to, and capable of receiving display signals from, the computer 108. This display may include a CRT or flat panel monitor, a three-dimensional display (such as an anaglyph display), an autostereoscopic three-dimensional display or any other suitable two-dimensional or three-dimensional rendering hardware. In some embodiments, the display may include a touch screen interface using, for example capacitive, resistive, or surface acoustic wave (also referred to as dispersive signal) touch screen technologies, or any other suitable technology for sensing physical interaction with the display 110.

[0034] The system 100 may include a computer-usable or computer-readable medium. The computer-usable medium 118 may include one or more memory chips (or other chips, such as a processor, that include memory), optical disks, magnetic disks or other magnetic media, and so forth. The computer-usable medium 118 may in various embodiments include removable memory (such as a USB device, tape drive, external hard drive, and so forth), remote storage (such as network attached storage), volatile or non-volatile computer memory, and so forth. The computer-usable medium 118 may contain computer-readable instructions for execution by the computer 108 to perform the processes described herein such as the process described in detail with reference to Fig. 3. The computer-usable medium 118 may also, or instead, store data received from the scanner 102, store a three-dimensional model of the object 104, store computer code for rendering and display, and so forth.

[0035] Fig. 2 depicts an optical system 200 for a three-dimensional scanner that may be used with the systems and methods described herein, such as for the scanner 102 described above with reference to Fig. 1.

[0036] The optical system 200 may include a primary optical facility 202, which may be employed in any kind of image processing system. In general, a primary optical facility refers herein to an optical system having one optical channel. Typically, this optical channel shares at least one lens, and has a shared image plane within the optical system, although in the following description, variations to this may be explicitly described or otherwise clear from the context. The optical system 200 may include a single primary lens, a group of lenses, an object lens, mirror systems (including traditional mirrors, digital mirror systems, digital light processors, or the like), confocal mirrors, and any other optical facilities suitable for use with the systems described herein. The optical system 200 may be used, for example in a stereoscopic or other multiple image camera system. Other optical facilities may include holographic optical elements or the like. In various configurations, the primary optical facility 202 may include one or more lenses, such as an object lens (or group of lenses) 202b, a field lens 202d, a relay lens 202f, and so forth. The object lens 202b may be located at or near an entrance pupil 202a of the optical system 200. The field lens 202d may be located at or near a first image plane 202c of the optical system 200. The relay lens 202f may relay bundles of light rays within the optical system 200. The optical system 200 may further include components such as aperture elements 208 with one or more apertures 212, a refocusing facility 210 with one or more refocusing elements 204, one or more sampling facilities 218, and/or a number of sensors 214a, 214b, 214c.

[0037] The optical system 200 may be designed for active wavefront sampling, which should be understood to encompass any technique used to sample a series or collection of optical data from an object 220 or objects, including optical data used to help detect two- or three-dimensional characteristics of the object 220, using optical data to detect motion, using optical data for velocimetry or object tracking, or the like. Further details of an optical system that may be employed as the optical system 200 of Fig. 2 are provided in U.S. Pat. No. 7,372,642. More generally, it will be understood that, while Fig. 2 depicts one embodiment of an optical system 200, numerous variations are possible. One salient feature of the optical system related to the discussion below is the use of a center optical channel that captures conventional video or still images at one of the sensors 214b concurrent with various offset data (at, for example, 214a and 214c) used to capture three-dimensional measurements. This center channel image may be presented in a user interface to permit inspection, marking, and other manipulation by a user during a user session as describe below.

[0038] Fig. 3 shows a three-dimensional reconstruction system 300 employing a high-speed pipeline and a high-accuracy pipeline. In general, the high-speed processing pipeline 330 aims to provide three-dimensional data in real time, such as at a video frame rate used by an associated display, while the high-accuracy processing pipeline 350 aims to provide the highest accuracy possible from scanner measurements, subject to any external computation or time constraints imposed by system hardware or an intended use of the results. A data source 310 such as the scanner 102 described above provides image data or the like to the system 300. The data source 310 may for example include hardware such as LED ring lights, wand sensors, a frame grabber, a computer, an operating system and any other suitable hardware and/or software for obtaining data used in a three-dimensional reconstruction. Images from the data source 310, such as center channel images containing conventional video images and side channels containing disparity data used to recover depth information may be passed to the real-time processing controller 316. The real-time processing controller 316 may also provide camera control information or other feedback to the data source 310 to be used in subsequent data acquisition or for specifying data already obtained in the data source 310 that is needed by the real-time processing controller 316. Full resolution images and related image data may be retained in a full resolution image store 322. The stored images may, for example, be provided to the high-accuracy processing controller 324 during processing, or be retained for image review by a human user during subsequent processing steps.

[0039] The real-time processing controller 316 may provide images or frames to the high-speed (video rate) processing pipeline 330 for reconstruction of three-dimensional surfaces from the two-dimensional source data in real time. In an exemplary embodiment, two-dimensional images from an image set such as side channel images, may be registered by a two-dimensional image registration module 332. Based on the results of the two-dimensional image registration, a three-dimensional point cloud generation module 334 may create a three-dimensional point cloud or other three-dimensional representation. The three-dimensional point clouds from individual image sets may be combined by a three-dimensional stitching module 336. Finally, the stitched measurements may be combined into an integrated three-dimensional model by a three-dimensional model creation module 338. The resulting model may be stored as a high-speed three-dimensional model 340.

[0040] The high-accuracy processing controller 324 may provide images or frames to the high-accuracy processing pipeline 350. Separate image sets may have two-dimensional image registration performed by a two-dimensional image registration module 352. Based on the results of the two-dimensional image registration a three-dimensional point cloud or other three-

dimensional representation may be generated by a three-dimensional point cloud generation module 354. The three-dimensional point clouds from individual image sets may be connected using a three-dimensional stitching module 356. Global motion optimization, also referred to herein as global path optimization or global camera path optimization, may be performed by a global motion optimization module 357 in order to reduce errors in the resulting three-dimensional model 358. In general, the path of the camera as it obtains the image frames may be calculated as a part of the three-dimensional reconstruction process. In a post-processing refinement procedure, the calculation of camera path may be optimized – that is, the accumulation of errors along the length of the camera path may be minimized by supplemental frame-to-frame motion estimation with some or all of the global path information. Based on global information such as individual frames of data in the image store 322, the high-speed three-dimensional model 340, and intermediate results in the high-accuracy processing pipeline 350, the high-accuracy model 370 may be processed to reduce errors in the camera path and resulting artifacts in the reconstructed model. As a further refinement, a mesh may be projected onto the high-speed model by a mesh projection module 360. The resulting images may be warped or deformed by a warping module 362. Warped images may be utilized to ease alignment and stitching between images, such as by reducing the initial error in a motion estimation. The warped images may be provided to the two-dimensional image registration module 352. The feedback of the high-accuracy three-dimensional model 370 into the pipeline may be repeated until some metric is obtained, such as a stitching accuracy or a minimum error threshold.

[0041] Various aspects of the system 300 of Fig. 3 are described in greater detail below. It should be understood that various processing modules, or the steps implied by the modules, shown in this figure are exemplary in nature and that the order of processing, or the steps of the processing sequence, may be modified, omitted, repeated, re-ordered, or supplemented, without departing from the scope of this disclosure.

[0042] Fig. 4A shows an object 410 for imaging, along with a path 415 that a camera may follow while obtaining a three-dimensional scan of a surface of the object 410. The direction of the path 415 is indicated generally by an arrow 416. The object 410 may be an upper dental impression (as shown) or any other object from which three-dimensional surface data is sought. Starting the camera at a starting point 420, the camera may follow an arc 430 to a second point 422. The camera may then follow a segment 432 to a third point 424. The camera may then follow a second arc 434 to a fourth point 426. The camera may then follow a second segment 436 to return approximately to the starting point 420. It should be noted that the path 415 followed by the camera may be irregular rather than smooth, and that while a particular path 415 is depicted,

more generally any path may be taken by the camera including paths that double back upon themselves, cross over identical regions two or more times, and/or entirely skip various surfaces of the object 410. It should also be noted that the camera path 415 may usefully return to the starting point 420, but this is not strictly required for three-dimensional reconstruction as described herein. The camera may take hundreds or thousands of images or more as the camera traverses the path around such a dental object 410.

[0043] Fig. 4B shows locations where additional scan data might usefully be acquired to improve the accuracy of a three-dimensional reconstruction. For example, arcs 440, 442, 444, and 446 may be scanned (for example, traversed by the camera path) to provide cross linking between various lengths of the camera path. Data might usefully be acquired, for example, from any area that can improve computational accuracy of a three-dimensional reconstruction such as regions where the length of a camera path between two measurements of the surface (for example, image sets or image data) is significantly greater than the distance between the two corresponding surface locations in the world coordinate system for the camera path. It will be appreciated that this may be a Euclidean distance or any suitable proxy for distance. For example, the length of the camera path may be measured in terms of the number of camera path segments, or the number of camera path segments from key frame to key frame, between two camera poses in Euclidean space. As another example, this may include regions where separate three-dimensional measurements for a general region of the reconstructed three-dimensional model fail to register to one another, or other indicia of accumulated error in the global camera path might be present.

[0044] Fig. 5 shows a user interface depicting a graphical request for additional scan data. After the camera follows the path 415 illustrated above, a software tool may be utilized to identify various locations where additional data might usefully be acquired to reduce accumulated error in a global camera path, such as two frames of image data that represent a candidate for an accumulated error in camera path relative to one another using, for example, any of the techniques described above. A monitor 510 may display an image 520 such as a three-dimensional reconstruction of scanned subject matter, and an arrow 530 may be displayed on the monitor 510 indicating where additional scanning is recommended. The user may then proceed to use a scanner, such as the scanner 102 from Fig. 1, to scan the area indicated by the arrow 530. More generally, areas for additional scanning may be identified to a user in a graphical user interface that displays a reconstructed three-dimensional model from the camera path, along with arrows or other identifiers or graphical annotations that illustrate a recommended scan path. After a user augments a camera path with additional scans, the resulting data can be employed to

resolve differences (that is, errors) in the global camera path, as described generally throughout this disclosure.

[0045] Fig. 6A illustrates a simple camera path in a world coordinate system. The camera starts at a starting point 610 and follows a path 620 in a counterclockwise direction as indicated by an arrow 625, returning to an ending point coincident with the starting point 610 in a fixed coordinate system, such as an arbitrarily selected world coordinate system.

[0046] Fig. 6B shows a simple camera path in a camera coordinate system. When a camera traverses the path 620 in the world coordinate system, errors may accumulate in a calculated camera path 635 so that a measured ending point 640 appears to be located away from the measured starting point 630 in the camera coordinate system, even though these points are identical in the world coordinate system. In one aspect, one or more cross links such as those described above with reference to Fig. 4 may be employed to mitigate accumulated errors in the calculated camera path 635.

[0047] Fig. 7 is a flow chart of a three-dimensional reconstruction process including global path optimization for improved accuracy.

[0048] The process 700 may begin with preprocessing as shown in step 710. It will be understood that preprocessing as described herein presupposes the availability of a number of frames of image data from which a camera path and three-dimensional model can be reconstructed. The information for the three-dimensional reconstruction may be generated in numerous ways including coming from structured light projection, shading based three-dimensional reconstruction, or disparity data. Disparity data may be generated by a conventional image plus one or more other channels or side channels. The preprocessing may include determining the number of available frames, the time duration over which all the frames were taken, the amount of overlap between neighboring frames, identification and elimination of frames with blurred or badly distorted images, and any other suitable preprocessing steps. An estimate of the number of desired key frames may be initially determined during the preprocessing step.

[0049] As shown in step 712, key frames may be selected from among all of the frames of data acquired from a scanner along a camera path. In general, computational costs can be reduced by storing certain data and performing certain calculations and processing steps exclusively with reference to key frames. In principle, these key frames should be related to one another in a manner that permits characterization of a camera path, typically through the registration of overlapping three-dimensional data in respective key frames. Various methods are known in the art for selecting a subset of frames of data as key frames, including techniques

based on image overlap, camera path distance, the number of intervening non-key frames and so forth. For example, key frames may be selected based on time duration from an immediately preceding key frame. Key frames may also or instead be selected based upon an amount of image overlap from the preceding key frame and/or a candidate for a following key frame (if available). Too little overlap makes frame-to-frame registration difficult. Too much overlap drives larger numbers of key frames and therefore larger amounts of data to analyze. Key frames may be selected based on spatial displacement, meaning that an upper limit may be placed on the amount of overlap from one key frame to the next. Key frames may also be selected based on sequential displacement. This type of sequential displacement could mean that every tenth frame is determined to be a key frame, for example. In one aspect, key frames may be selected as data is acquired based on any number of suitable criteria. In another aspect, key frame pairs may be determined post hoc by examining all possible candidate key frames. All possible key frame pairs may be examined and candidates may be removed, for example, where there is insufficient overlap to form a stitch. Still more generally, any technique suitable for selecting a subset of frames in a data set may be usefully employed to select key frames for processing in order to reduce computational complexity.

[0050] Once key frames have been selected, additional processing may be performed. For example, full image data (for example, full resolution center and side channel images) may be stored for each key frame, along with image signature data, point cloud centroid calculations, and any other measured or calculated data to support use of the key frames in a three-dimensional reconstruction process as described herein.

[0051] As shown in step 714, candidate stitches may be identified. In general, a stitch is a relationship between two separate three-dimensional measurements from two different camera positions. Once a stitch is established, a rotation and a translation may be determined for the path of a camera between the two different camera positions. In a complementary fashion, the three-dimensional measurements from the two different camera positions may be combined into a portion of a three-dimensional model. Candidate stitches may be analyzed around each key frame, such as from the key frame to some or all of the frames of data between the key frame and neighboring key frames. Stitches may be based on the originally imaged frames. It may also be useful to deform or warp two-dimensional images during registration and other steps in a stitching process in order to improve accuracy and/or speed each stitch calculation. Stitches may also or instead be based on other observed epipolar relationships in source data.

[0052] As shown in step 716, stitches may be selected for the complete camera path from the universe of candidate stitches. The selection of stitches may be made based upon, for example, the lowest calculated error in resulting portions of the three-dimensional model.

[0053] As shown in step 718, a graph analysis may be performed using the key frames and the associated stitching to calculate a global path for the camera used to obtain a three-dimensional model. The graph analysis may consider each key frame as a node or vertex and each stitch as an edge between a pair of nodes. A key frame is selected as a starting point. A breadth- or depth-first search may be performed through the graph to identify stitches which may connect the current key frame to another key frame. Each key frame is marked as the graph is proceeded through. A check may be performed to see if all key frames have been reached within the graph. If all key frames have not been reached through traversing stitches in the graph analysis, the largest sub-graph is identified. This sub-graph may be examined to see if the entire three-dimensional image may be modeled.

[0054] It may be that certain sub-graphs are not required to complete the three-dimensional imaging. If the camera lingered over a particular region of a surface of an object, or if the camera looped on a region multiple times, the associated sub-graph(s) may not be needed. If a separate sub-graph is identified, which is needed to complete the three-dimensional imaging, an optional branch back to step 712 may be performed. For example, a set of key frames may have been selected which did not have sufficient stitching from one key frame to the next key frame. By choosing a different set of key frames, sufficient stitching may be obtained in order to obtain a complete graph of all needed aspects of the three-dimensional imaging. A key frame which is too sparse, meaning it has insufficient stitches to aid in building a graph, may indicate that a different set of key frames should be selected. Based on the graph analysis, a global path may be selected, and the graph may then be analyzed to optimize the path calculation.

[0055] As shown in step 720, a numerical optimization may be performed to reduce errors in the calculated camera path based upon available data for the complete camera path such as, for example, cross links that interrelate temporally distant measurements. In general, the objective of numerical optimization is to minimize a calculated error based upon an error function for the camera path and/or reconstructed three-dimensional model. A useful formulation of the error minimization problem for a global camera path is presented below.

[0056] There may be a set of candidate camera positions and orientations referenced to a world coordinate system. A camera position and orientation collectively may be referred to as a camera pose. There may be a set of measured frame-to-frame camera motions. A camera translation and rotation collectively may be referred to as a camera motion. A measured camera

motion may be referenced in the coordinate system of one camera pose. An example set of three key frames may be obtained from three camera positions, A , B , and C , each of which may be referenced to an origin, O , of a world coordinate system in three-dimensional space. In addition to the position of these points, a camera at each of these points may have a different orientation. A combination of the position and orientation is generally referred to as a camera pose. Between each of these points are motion parameters including a translation (a change in position) and a rotation (a change in orientation). The relationship between a point, X , expressed in the world coordinate system as X_O and the same point expressed in the A coordinate system, X_A may be given by equation (1):

$$(1) \quad X_A = R_{OA}X_O + T_{OA}$$

R_{OA} is the rotation, taking points from the world to the A coordinate system. T_{OA} is the translation of the world coordinate system as represented in the A coordinate system. It should be understood that symbols X and T may represent a vector, rather than a scalar, for example where X includes x , y , and z coordinate values. Further, it should be understood that symbol R may represent a matrix. Equations (2) and (3) may similarly represent a transform transformation between the world and the B and C coordinate systems respectively:

$$(2) \quad X_B = R_{OB}X_O + T_{OB}$$

$$(3) \quad X_C = R_{OC}X_O + T_{OC}$$

[0057] By rearranging, equation (1) and equation (2) may be represented as shown in equation (4):

$$(4) \quad X_O = R_{OA}^{-1}(X_A - T_{OA}) = R_{OB}^{-1}(X_B - T_{OB})$$

[0058] The representation of a point in one camera's coordinate system may be related to the same point in another coordinate system. For example, as in equations 1-3, coordinates of a point, X , may be transformed from the A coordinate system to the B coordinate system as follows:

$$(5) \quad X_B = R_{AB}X_A + T_{AB}$$

[0059] The rotation R_{AB} rotates points from the A to the B coordinate system and T_{AB} is the position translation of the origin of the A coordinate system in the B coordinate system.

[0060] In an optimization, the pose of every camera may be optimized based on measured transforms between camera poses. That is, a number of camera-to-world or world-to-camera rotations and translations, for example, R_{On} and T_{On} may be performed. It will be appreciated that the world coordinate system is arbitrary, and one of these transforms may conveniently be an identity rotation with zero translation, or a constant motion transfer can be applied to all camera poses without altering the underlying optimization.

[0061] The rotations and translations may be measured for many pairs of cameras. For the i th such measured frame-to-frame motion, let one of the cameras of the pair be camera A and the other be camera B . This may also be considered the i th stitch that relates the camera poses for A and B . Let R_{AB}^i be the measured rotation taking points in the A system to the B system and T_{AB}^i be the coordinates of the A position expressed in the B system, as in equation (5).

[0062] The rotations and translations for all cameras, R_{O_n} and T_{O_n} may be optimized. It will be appreciated that, while these expressions and the following discussion are cast in terms of rotations and translations from the individual camera coordinate systems to a single world coordinate system, this characterization is not intended to limit the generality of this disclosure. A similar or complementary analysis may be performed using the reverse of these transforms, or any other transform or collection of transforms (typically, although not necessarily rigid transforms) capable of describing a camera path across multiple poses. The constraints on camera motion from one pose, A , to another pose, B , for an i^{th} stitch or relationship may be expressed relative to a world coordinate system as rotations, $R_{C,OA}^i$ and $R_{C,OB}^i$, and translations, $T_{C,OA}^i$ and $T_{C,OB}^i$. This relationship is further constrained by the camera path from A to B , which may be expressed as a rotation and a translation as follows:

$$(6) \quad R_{C,AB}^i = R_{C,OB}^i (R_{C,OA}^i)^{-1}$$

$$(7) \quad T_{C,AB}^i = T_{C,OB}^i - R_{C,AB}^i T_{C,OA}^i$$

[0063] Note that with sufficient stitches, these relationships may form an overdetermined system of motion constraint equations. Using these equations as a starting point, numerical optimization may be performed on the rotational and translational components of each camera pose based on the measured stitches.

[0064] In a decoupled optimization, the rotational and translational components may be independently optimized. This approach may generally be used where there are constraints on one component (for example, rotation) that do not depend on the other component. Given a candidate set of camera rotations, R_C^i , the corresponding candidate camera-to-camera rotations, $R_{C,AB}^i$, may be computed that correspond to each of the measured camera-to-camera rotations, R_{AB}^i . The corresponding residual rotations, which should be identity in an error free camera path, are given by $R_{\text{residual},AB}^i = R_{C,AB}^i (R_{AB}^i)^{-1}$. A scalar-valued rotational cost function, e_r , may be computed that depends on the candidate camera rotations:

$$(8) \quad e_r(R_{C,On}) = \sum_{i=1}^{\#stitches} r_r^{iT} r_r^i, \quad \text{where } r_r^i = \log_{SO(3)} R_{residual,AB}^i$$

[0065] In equation (8), $\log_{SO(3)}(R)$ returns an axis-angle vector, v , that corresponds to the rotation R . In other words, $\log_{SO(3)}(R)$ returns the vector, v , that has a cross-product matrix, $[v]_\times$, that is the matrix logarithm of R .

[0066] Next, a similar scalar-valued cost function may be computed for translation that depends on the candidate rotations and translations.

$$(9) \quad e_t(R_{C,On}, T_{C,On}) = \sum_{i=1}^{\#stitches} r_t^{iT} r_t^i, \quad \text{where } r_t^i = T_{C,AB}^i - T_{AB}^i$$

[0067] In one conventional, decoupled approach to solving these simultaneous systems of equations, the rotational error function may be converted into a quaternion expression in order to translate the numerical problem into a linear system of equations for solution, as described for example in *Combining two-view constraints for motion estimation*, Govindu V., *Proc. of the Int. Conf. on Computer Vision and Pattern Recognition*, vol. 2, pp. 218–225 (July 2001). While this approach may be numerically convenient, it does not enforce the unit norm constraint for the quaternion solution, which may result in inaccuracy. Thus in one aspect, a path optimization technique may be improved by minimizing equation (8) for rotation as a nonlinear optimization and minimizing equation (9) for translation as a linear optimization. In another aspect, the more computationally efficient linear system of equations may be used to generate an initial estimate for an iterative optimization that uses non-linear optimization.

[0068] More generally, the decoupled approach described above may fail to provided a truly optimal result, in a maximum-likelihood sense, where it cannot use information from the translation portion of the stitches in determining rotation. Nonetheless, a substantial amount of work in this field aims to overcome the disadvantages of decoupled optimization, as described for example in *A solution for the registration of multiple 3D point sets using unit quaternions*, Benjemaa R. and F. Shmitt, *Proc. ECCV '98*, pp. 34–50 (June 1998); *Global registration of multiple 3D point sets via optimization-on-a-manifold*, Krishnan S., Lee P.Y., Moore J.B., Venkatasubramanian S., *Eurographics Symp. Geometry Processing* (2005); and *Simultaneous registration of multiple corresponding point sets*, Williams J., Bennamoun M., *Computer Vision and Image Understanding*, vol. 81, no. 1, pp. 117-142 (2001).

[0069] In one aspect disclosed herein, a coupled approach to optimization may instead be used to minimize overall error in a camera path. In order to achieve a coupled optimization a weighting may be used to balance the contributions of rotational and translational components to a combined cost function:

$$(10) \quad e_c(R_{C,On}, T_{C,On}) = \sum_{i=1}^{\#stitches} \left(\begin{bmatrix} r_t^i \\ r_r^i \end{bmatrix}^T W_c^i \begin{bmatrix} r_t^i \\ r_r^i \end{bmatrix} \right)$$

Multiple approaches may be used to weight the relative contribution of translations and rotations. In one embodiment the weights may be expressed as matrices, with different stitches receiving different weightings based upon any of a number of factors. For example, the weights may be based on the number of points in a stitch (for example, the shared content), the quality of a particular three-dimensional measurement, and/or any other factors impacting the known reliability of a stitch. In one approach, the weight matrices may also account for anisotropic error in the individual points collected, such as due to acquisition of depth information from disparity measurements, which results in measurement precision that varies with distance from the camera.

[0070] In some cases, equation (10) may be reformulated so that the rotation and translation weights are decoupled for each stitch (that is, W_c^i is a block diagonal). In particular, this may occur in the case that the motion stitches are recovered from three-dimensional point correspondences with isotropic point error. In that case, for a given stitch i , between poses A and B , the optimal solution may bring the point cloud as seen from pose A into correspondence with that seen from pose B . If $\bar{X}_A^i$ and $\bar{X}_B^i$ are the positions of the center of the point cloud in the A and B systems respectively, then if r_t^i is replaced in equation (10) with the residual displacement between the point-cloud centers based on the candidate camera pose. This latter residual displacement may be expressed as:

$$(11) \quad r_{t,ctr}^i = \bar{X}_B^i - (R_{C,AB}^i \bar{X}_A^i + T_{C,AB}^i)$$

Equation (10) may then be reformulated as:

$$(12) \quad e_c(R_{C,On}, T_{C,On}) = \sum_{i=1}^{\#stitches} \left(r_{t,ctr}^i{}^T W_r^i r_{t,ctr}^i + r_r^i{}^T W_r^i r_r^i \right)$$

[0071] In general, by minimizing equation (10), both rotational errors and translational errors may be minimized simultaneously. The weight matrices can be chosen for example according to “First Order Error Propagation of the Procrustes Method for 3D Attitude Estimation” by Leo Dorst, IEEE Transactions on Pattern Analysis and Machine Intelligence, Vol. 27, No. 2, pp. 221-9 (Feb. 2005). Once a more consistent set of motion parameters has been generated the three-dimensional model may be updated.

[0072] When total error or some portion of error has been minimized, the resulting value may be evaluated. The calibration state of the scanner and associated equipment may be evaluated based on the minimized error values. If a minimized error falls beyond a certain

threshold then calibration for the scanner and associated hardware may be recommended. The threshold value may be empirically determined based on the specific scanner hardware equipment or it may be learned experientially over time for a given system. When a system is new or has been freshly aligned, expected minimized error values may be obtained. When minimized error values deviate from these expected values, a calibration state evaluation flag may be set indicating that the tool should be calibrated. Thus in one aspect, a coupled (or uncoupled) error function may be employed to validate calibration and determine when re-calibration of a device is appropriate.

[0073] As shown in step 722, upsampling may be performed to augment a three-dimensional model with data from non-key frames. In general, upsampling may include any technique for addition of data to a result. For example, while the global optimization described above generally refers to optimization among key frames in a contiguous camera path, the resulting optimized three-dimensional model may be supplemented by registering non-key frames to one or more nearby key frames in a manner that creates small, local reconstruction patches that include additional three-dimensional detail available from non-key frames. Or upsampling may be performed by correcting the corresponding camera path for non-key frames according to a globally optimized path for the key frames. Thus in one aspect, upsampling may more generally be understood as any use of optimized data to incorporate related, non-optimized data into a camera path or three-dimensional model.

[0074] Fig. 8 shows a reconstruction process 800 using numerical optimization as described above. In one aspect, this optimization technique may be usefully applied to minimize errors in a camera path where spatial links between non-sequential camera poses (or corresponding data sets used to recover three-dimensional surface data) can be identified. For example, where a scan path covers a buccal surface followed by an occlusal or lingual surface, many spatial links might be identified between non-contiguous camera path segments associated with each surface. Under these conditions, a global optimization may significantly improve the accuracy of a three-dimensional reconstruction by reducing errors in the motion estimation parameters for the camera path. It will be understood that the disclosed method may also or instead be embodied in a computer program, a computer program product, or an apparatus embodying any of the foregoing.

[0075] As shown in step 802, the process may begin with acquiring data sets such as a data set from a surface of a dental object with a hand-held scanner from each one of a sequence of poses along a camera path, thereby providing a plurality of data sets. The hand-held scanner may, for example, be the video-based scanner described above. The hand-held scanner may instead

include any other type of hand-held scanner suitable for intraoral dental scanning, such as a time-of-flight scanner, a structured light scanner, and so forth. The data sets may be any corresponding data acquired for each camera pose that is used to recover three-dimensional data.

[0076] It should be understood that in this context, the camera path may correspond to a physical camera path that describes the path actually taken by a scanner during a scan, or the camera path may also or instead include a virtual camera path formed from a plurality of different physical camera paths or other virtual camera paths that intersect with one another. Such a virtual camera path may be created wherever poses from two or more physical paths can be interrelated in a global coordinate system, as established for example by three-dimensionally registering two different scans of the same physical subject matter. The use of virtual camera paths may be particularly useful, for example, where a large scan such as a full arch scan is created from data acquired during two or more discontinuous scanning sessions. Under these conditions, global optimization of a virtual camera path can be used to improve consistency of the combined data in a global coordinate system.

[0077] As shown in step 804 each one of the poses in the sequence of poses may be associated with a previous pose and a next pose by a spatial link such as motion estimation parameters or other camera path information. It should also be understood that while a system may infer camera path from the resulting three-dimensional measurements at each camera position and orientation, the camera path may also, or instead be obtained using a hardware-based positioning system based upon, for example, accelerometers, a geopositioning system, external position sensors, transducers in an articulating arm or any other combination of sensors and techniques suitable for detecting camera position and/or orientation with sufficient accuracy for the intended three-dimensional reconstruction.

[0078] This spatial link data reflects the physical camera path in the order in which data was acquired, thus providing a plurality of spatial links that characterize the camera path during a data acquisition process. The sequence of poses may, for example, be made up of key frames (or sequential pairs of key frames) as generally described above, where additional data sets are acquired from one or more additional poses between each sequential pair of key frames. Key frames may be usefully employed, for example, to reduce the computational complexity of path optimization while retaining a contiguous camera path of sequential poses. After path optimization is complete, additional three-dimensional data may be added based upon the one or more additional data sets and the one or more additional poses from between key frames. As described above, key frames may be selected from a larger set of poses using a metric to evaluate a quality of a resulting three-dimensional reconstruction, a quality of the estimated motion

parameters between poses, a degree of overlap in scanned subject matter, a graph analysis or any other useful technique or metric.

[0079] As shown in step 806, at least one non-sequential spatial link may be identified between two non-sequential ones of the poses based upon the data set for each of the two non-sequential ones of the poses. Thus for example two data sets from a buccal and lingual scan segment may be related to one another based upon camera position, the three-dimensional data recovered from the respective data sets, or any other data acquired during a scanning process. In one aspect, a metric may be employed to identify candidates for non-sequential spatial links, such as a ratio of spatial distance between two data sets to the length of an intervening camera path. Thus the non-sequential spatial link(s) may associate two of the sequence of poses that are separated by a substantially greater distance along the camera path than along the surface of the dental object. This may be based on the data set for each of the two non-sequential ones of the poses, such as by using camera pose data to determine a surface position or by identifying an overlap in the reconstructed three-dimensional data obtained using the data set for two non-sequential poses. This may also include displaying a region for one or more candidate links in a user interface and receiving a supplemental scan of the region, as described above for example with reference to Fig. 5.

[0080] As shown in step 808, a global motion optimization may be performed on the camera path to minimize an error among the plurality of spatial links and the at least one non-sequential spatial link, thereby providing an optimized camera path. This may employ, for example, any of the optimization techniques described above. More generally, this may include any technique for minimizing errors in motion estimation parameters expressed as a function of one or more of rotation, translation, coupled rotation and translation, and decoupled rotation and translation, and/or any technique for aligning the three-dimensional data reconstructed from the data sets in a global coordinate system or improving a consistency of the sequence of poses along the camera path in the global coordinate system.

[0081] As shown in step 810, a three-dimensional model of the dental object may be reconstructed using known techniques based upon the optimized camera path and the plurality of data sets.

[0082] Thus by observing the actual camera paths typical of intra-oral dental scanning, the applicants have devised improved techniques for error minimization when camera path is used for three-dimensional reconstruction. More specifically, by observing that intra-oral scanning often employs a number of adjacent, relatively straight global paths such as for lingual, occlusal, and buccal surfaces (as dictated in part by the relatively restricted oral access to the

relatively large surfaces of dentition) , and by observing that intra-oral scanning regularly returns to earlier scan positions, the applicants have devised an optimization technique that takes advantage of the spatial relationship between certain non-sequential frames of data. The approach described above solves the problem of conflicting data for local measurements by using an error minimization technique that globally addresses the camera path, including the interrelationship of non-sequential frames of data. This may be particularly useful, for example for scans covering gums, soft tissue, full arches, orthodontic components and the like where scanning a large area typically entails multiple passes over various regions of the scanned surface.

[0083] Fig. 9 is a flow chart of a hybrid stitching process for combining disparate three-dimensional scans of a common surface. In scanning techniques that use a camera path for reconstruction, the full scan data for an object may include any number of disparate scans with camera paths, or more generally stitch graphs, that are not directly spatially related to one another. The following process 900 provides a technique for establishing spatial relationships between such stitch graphs through a series of local geometry-based registrations. The resulting, combined model may then be subjected to any of the optimization techniques described above as though it had been obtained from a single, continuous scan.

[0084] As shown in step 902, the process 900 may begin with obtaining a first three-dimensional model including a first plurality of frames of data, each including sets of three-dimensional points spatially related to one another by a first camera path. It will be understood that a ‘camera path’ generally refers to a sequential series of poses connected by a number of transforms from one to the next. However, the camera path of the model may more generally include any number of interrelationships or ‘stitches’ between non-sequential poses that can be inferred from other spatial information such as overlapping regions of an object surface in the accompanying sets of three-dimensional points. In the foregoing description, terms such as camera path and stitch graph should be broadly interpreted to include any rigid transformations and/or other descriptive data that characterizes camera motion (and reliability thereof) in a manner that permits path-based reconstruction of a three-dimensional surface. Step 902 may also include obtaining a second three-dimensional model including a second plurality of frames of data, each including sets of three-dimensional points spatially related one another by a second camera path. The second model may, for example, be obtained after a first scan is automatically or manually interrupted, or after a first scan is completed and additional data is required or desired, either by a user or in response to prompting from a scanning system as contemplated above. More generally, the second three-dimensional model may be any disparate data set that is

not directly spatially related to the first three-dimensional model through a single scan or camera path.

[0085] As shown in step 904 one of the first plurality of sets of three-dimensional points may be registered to one of the second plurality of sets of three-dimensional points. This registration may use an iterative closest point algorithm, image-based registration or any suitable technique for three-dimensional registration of points and/or surfaces. In one aspect, a surface mesh may be obtained for use in the registration process. Thus a surface mesh of the first and second plurality of sets of three-dimensional points may be generated with a mesh generation algorithm to obtain polygonal surface representations of each model (or portions thereof). This may generally include generating a surface mesh of the entire first and second models, or a known overlapping surface of the first and second data sets, or a neighborhood surrounding a known common surface, or each of the entire first and second models. The resulting first surface mesh and second surface mesh may then be registered to one another using any suitable techniques, resulting in a known, rigid transformation between the first model and the second model (or between the first surface mesh from the first model and the second surface mesh from the second model). As a result of this spatial relationship, the first three-dimensional model and the second three-dimensional model can be placed in a shared coordinate system that permits subsequent processing using data from both models as a combined surface.

[0086] As shown in step 906, the process 900 may include creating a virtual stitch graph that spatially relates individual ones of the first plurality of sets and the second plurality of sets using virtual stitches between the data sets, thereby providing a combined model that includes the first plurality of sets and the second plurality of sets all spatially related by the virtual stitch graph. Numerous techniques may be employed for synthesizing a virtual stitch graph to inter-relate the models. The details of one particular approach are provided below with reference to Fig. 10. It will be appreciated that the term ‘virtual’ as used in this context is intended to distinguish models using data from multiple disparate scans. Thus while the source of data (multiple camera paths) used to calculate ‘virtual stitches’ and/or virtual stitch graphs may be different from the data (single camera paths) used to calculate other stitches and graphs, the resulting data can advantageously be provided in a form for use interchangeably with and undistinguishable from data derived from a single scan. As such, in a preferred embodiment, there may be little to distinguish a ‘virtual’ stitch or a virtual stitch graph from those that are not virtual, except perhaps for their absence from the two or more disparate models from which they were derived.

[0087] As shown in step 908, the process 900 may include refining the combined model with a global motion optimization of the virtual stitch graph. With a single virtual stitch graph that inter-relates all of the data from each of the disparate sets (acquired from different scans), any of the global motion optimization techniques described above may be suitable employed to minimize errors on a stitch-by-stitch basis among the combined data sets. In one aspect, this optimization includes a deformable registration where, as distinguished from calculating error-minimized rigid transformations, each stitch or step of the camera path can be moved spatially to minimize global error. Thus in one aspect, the process 900 includes refining the combined model with a deformable registration.

[0088] As shown in step 910, the combined model may be stored and/or displayed. This may include, for example, displaying the combined model at a chairside scanning location or a dental laboratory. The combined model may also be stored locally at a scanner site, or transmitted to a central repository for project management including, without limitation, billing, quality assurance, and scheduling fabrication of a dental object at a dental laboratory. The original source data from the disparate scans (for example, disparate camera paths, frames of image data, etc.) may be retained for further processing or for evaluation of the combined model, or the source data may be deleted once the combined model is obtained.

[0089] Fig. 10 is a flow chart of a process for creating of a virtual stitch graph. In the following description, it is assume that two disparate three-dimensional models are provided, each obtained from a sequence of frames of data spatially related by a camera path as generally described above, and that the two models have been registered to establish an initial rigid transformation between them. It will be appreciated that modifications or adaptations of the foregoing may be appropriate where other three-dimensional scanning techniques are employed, or where three or more disparate data sets are concurrently reconciled, all of which is intended to fall within the scope of this disclosure.

[0090] As shown in step 1002, the process 1000 may include selecting overlapping data sets. This may, for example, include selecting a first selected one of the first plurality of sets and a second selected one of the second plurality of sets that overlap on the combined surface obtained from the coarse registration described above with reference to Fig. 9. An initial selection of one of the first or second plurality of sets may be, for example, a random selection or a parameterized selection based on, for example, location within the first or second meshes or proximity to a centroid or other feature of interest in the combined or separate surfaces.

[0091] All of the frames or sets of data from the first plurality of sets (for example, the first model) in a neighborhood about the first selected one may then also be selected for use as a

local processing neighborhood. This may, for example, be all sets of data within a certain number of stitches away, such as all sets within five stitches, or a certain number of steps along a camera path. In order to reduce redundant processing, the sets within this local processing neighborhood may optionally be marked or otherwise identified as unavailable for future processing after the local hybrid stitching operations of the process 1000 are completed. Using the coarse registration of surface meshes, one of the second plurality of sets (for example, a frame from the second model) may be selected that is near (or nearest) to the local processing neighborhood. All of the frames or sets of data from the second plurality of sets in a neighborhood about the second selected one of the second plurality of sets may then be identified in a similar manner to the selection of the local processing neighborhood, for example, by selecting frames or sets of data in the second plurality of sets of data that are within a certain number of stitches or sequential camera poses from the second selected one. It will be appreciated in this context that the use of a stitch graph (of stitches, which may extend in numerous directions from a single camera pose) can provide a significant processing advantage over a camera path (of individual transforms from one camera pose to the next) by affording more options for coverage of relevant regions of a surface of an object.

[0092] The selection of local processing neighborhoods for frames from the first and second plurality of data sets may be further refined, such as by restricting or prohibiting use of data sets outside a surface or region common to the two neighborhoods.

[0093] As shown in step 1004, data may be optimized in the local processing neighborhoods. For example, where each data set is represented by a camera path or stitch graph that inter-relates sets of three-dimensional points through a sequence of camera poses or the like, a sub-graph of the camera path or stitch graph may be selected for each of the models that only contains data (frames or sets of three-dimensional data points, along with stitches or camera path information) from within the local processing neighborhoods. This approach advantageously removes the influence of data external to the local processing neighborhoods. At this point in the processing, the data still generally comprises two disparate models – in this case, sub-graphs of the full data set – that are associated by a single rigid transform obtained from the coarse registration of surface meshes. This data may be further optimized prior to hybrid stitching by, for example, performing a global motion optimization (as described above) on each of the extracted sub-graphs. With the sub-graphs so optimized, the registration between the two sub-graphs may be refined by repeating an iterative closest point algorithm or other suitable registration process for the two point clouds represented by the optimized sub-graphs. While this approach to optimization is effective in a three-dimensional surface reconstruction based upon camera paths,

it will be appreciated that a variety of other optimizations are known in the art for three-dimensional reconstructions, any of which may be adapted to optimization of the local processing neighborhoods contemplated herein.

[0094] As shown in step 1006, links for a virtual stitch graph (also referred to as ‘hybrid’ or ‘virtual’ stitches) may be created. This may include finding a frame from each of the two sub-graphs closest to a centroid of the overlapping region between the two sub-graphs. These two frames may then be directly spatially related to one another by a rigid transformation, which may be a newly calculated rigid transformation or a refinement of the rigid transformation obtained in the optimization steps described above. Using this transformation, data from the two sub-graphs may be transposed into a common coordinate system, such as the original coordinate system of one of the sub-graphs. This may be repeated for one or more other frames of data in the two sub-graphs to provide a number of direct spatial relationships or ‘virtual stitches’ between frames in the first sub-graph and frames in the second sub-graph. These relationships may be used directly as stitches in a combined, virtual stitch graph, or further processed as appropriate to express these new relationships in the same form as existing stitches in the stitch graphs or camera paths of the initial models.

[0095] In order to facilitate concurrent processing of the actual stitches in the original models and the virtual stitches created for the virtual stitch graph that combines the models, additional characterizing data may be included in each virtual link. For example, a covariance matrix that weights confidence in each link according to multiple degrees of freedom (for example, six degrees of freedom for full translation and rotation) may be provided. While such a covariance matrix results from, for example, the iterative closest point registration process, the use of a particular form is less significant than sufficient commonality between the expression of actual stitches and the virtual stitches for undifferentiated processing of data from both sources in a combined model.

[0096] As shown in step 1008, if there are additional neighborhoods of overlapping data to be locally optimized, the process may return to step 1002 where additional overlapping data sets can be selected to create additional virtual links. This may be repeated as often as necessary or desired. If there are no further local neighborhoods for processing, or if some other termination condition such as a threshold number of virtual links or percentage coverage of the full surface area of the combined model has been reached, then the process 1000 may proceed to step 1010.

[0097] As shown in step 1010, a combined model may be created that combines the actual stitch graphs from the two original models and the virtual stitches established between the

two models as described above. In addition, any number of additional virtual stitches may be added based upon other data in the global models (as distinguished from the local processing neighborhoods), such as nearly identical and/or substantially co-located data sets in the first and second models. In addition, the combined model may be analyzed for completeness and to identify further opportunities for establishing additional stitches between data sets either with or without regard for whether the data sets are from the first model or the second model.

[0098] As shown in step 1012, the combined model may be optimized using, for example, global motion optimization as described above to minimize errors in the transformations between related camera poses of the combined model (as distinguished from either of the original stitch graphs or camera paths).

[0099] As shown in step 1014, a point cloud may be generated for the combined model that places all of the three-dimensional points of the combined model into a single, common coordinate system.

[00100] As shown in step 1016, a surface mesh may be generated for the point cloud using any suitable surface meshing techniques. The model may also be stored, displayed, transmitted or otherwise processed or handled as generally contemplated by the foregoing description.

[00101] It will be appreciated that any of the above system and/or methods may be realized in hardware, software, or any combination of these suitable for the data acquisition and modeling technologies described herein. This includes realization in one or more microprocessors, microcontrollers, embedded microcontrollers, programmable digital signal processors or other programmable devices, along with internal and/or external memory. The may also, or instead, include one or more application specific integrated circuits, programmable gate arrays, programmable array logic components, or any other device or devices that may be configured to process electronic signals. It will further be appreciated that a realization may include computer executable code created using a structured programming language such as C, an object oriented programming language such as C++, or any other high-level or low-level programming language (including assembly languages, hardware description languages, and database programming languages and technologies) that may be stored, compiled or interpreted to run on one of the above devices, as well as heterogeneous combinations of processors, processor architectures, or combinations of different hardware and software. Thus in one aspect there is disclosed herein a computer program product comprising computer executable code that, when executing on one or more computing devices, performs any and/or all of the steps described above.

[00102] At the same time, processing may be distributed across devices such as a camera and/or computer and/or fabrication facility and/or dental laboratory and/or server in a number of ways or all of the functionality may be integrated into a dedicated, standalone device.

[00103] In another aspect, a system disclosed herein includes means such as any of the structures described above for performing the functions expressed or implied in the flow charts and other portions of the above description.

[00104] All such permutations and combinations that would be apparent to one of ordinary skill in the art are intended to fall within the scope of the present disclosure, which along with the claims is intended to be interpreted in the broadest sense allowable by law.

CLAIMS

What is claimed is:

1. A method comprising:
 - obtaining a first three-dimensional model including a first plurality of sets of three-dimensional points spatially related to one another by a first camera path;
 - obtaining a second three-dimensional model including a second plurality of sets of three-dimensional points spatially related to one another by a second camera path;
 - registering one of the first plurality of sets of three-dimensional points to one of the second plurality of sets of three-dimensional points to place the first three-dimensional model and the second three-dimensional model in a shared coordinate system;
 - creating a virtual stitch graph that spatially relates the first plurality of sets and the second plurality of sets, thereby providing a combined model that includes the first plurality of sets and the second plurality of sets all spatially related by the virtual stitch graph; and
 - refining the combined model with a global motion optimization of the virtual stitch graph.
2. The method of claim 1 further comprising generating a first surface mesh of the first three-dimensional model and a second surface mesh of the second three-dimensional model.
3. The method of claim 2 wherein registering includes registering the first surface mesh to the second surface mesh, thereby providing a combined surface.
4. The method of claim 3 wherein registering includes registering with an iterative closest point algorithm.
5. The method of claim 3 further comprising selecting a first selected one of the first plurality of sets and a second selected one of the second plurality of sets that overlap on the combined surface.
6. The method of claim 5 wherein at least one of the first selected one and the second selected one is a set of three-dimensional data closest to a centroid of the combined surface.

7. The method of claim 5 further comprising calculating a rigid transformation and a mean error between the first selected one and the second selected one.
8. The method of claim 7 further comprising selecting a first neighborhood of the first plurality of sets from about the one of the first plurality of sets and a second neighborhood of the second plurality of sets from about the one of the second plurality of sets.
9. The method of claim 8 further comprising:
 - extracting a sub-region of the combined surface;
 - spatially relating two or more of the first plurality of sets to two or more of the second plurality of sets within the sub-region to provide a virtual stitch graph; and
 - minimizing an error among spatial relationships in the virtual stitch graph, thereby providing a combined data set for the sub-region.
10. The method of claim 9 further comprising creating at least one virtual stitch between two unstitched ones of the first plurality of sets.
11. The method of claim 1 further comprising refining the combined model with a deformable registration.
12. A computer program product comprising computer executable code embodied on a non-transitory computer readable medium that, when executing on one or more computing devices, performs the steps of:
 - obtaining a first three-dimensional model including a first plurality of sets of three-dimensional points spatially related to one another by a first camera path;
 - obtaining a second three-dimensional model including a second plurality of sets of three-dimensional points spatially related to one another by a second camera path;
 - registering one of the first plurality of sets of three-dimensional points to one of the second plurality of sets of three-dimensional points to place the first three-dimensional model and the second three-dimensional model in a shared coordinate system;
 - creating a virtual stitch graph that spatially relates the first plurality of sets and the second plurality of sets, thereby providing a combined model that includes the first plurality of sets and the second plurality of sets all spatially related by the virtual stitch graph; and

refining the combined model with a global motion optimization of the virtual stitch graph.

13. The computer program product of claim 12 further comprising code that performs the step of generating a first surface mesh of the first three-dimensional model and a second surface mesh of the second three-dimensional model.

14. The computer program product of claim 13 wherein registering includes registering the first surface mesh to the second surface mesh, thereby providing a combined surface.

15. The computer program product of claim 14 wherein registering includes registering with an iterative closest point algorithm.

16. The computer program product of claim 14 further comprising code that performs the step of selecting a first selected one of the first plurality of sets and a second selected one of the second plurality of sets that overlap on the combined surface.

17. The computer program product of claim 16 wherein at least one of the first selected one and the second selected one is a set of three-dimensional data closest to a centroid of the combined surface.

18. The computer program product of claim 16 further comprising code that performs the step of calculating a rigid transformation and a mean error between the first selected one and the second selected one.

19. The computer program product of claim 18 further comprising code that performs the step of selecting a first neighborhood of the first plurality of sets from about the one of the first plurality of sets and a second neighborhood of the second plurality of sets from about the one of the second plurality of sets.

20. The computer program product of claim 19 further comprising code that performs the steps of:

extracting a sub-region of the combined surface;

spatially relating two or more of the first plurality of sets to two or more of the second plurality of sets within the sub-region to provide a virtual stitch graph; and

minimizing an error among spatial relationships in the virtual stitch graph, thereby providing a combined data set for the sub-region.

21. The computer program product of claim 20 further comprising code that performs the step of creating at least one virtual stitch between two unstitched ones of the first plurality of sets.

22. The computer program product of claim 12 further comprising code that performs the step of refining the combined model with a deformable registration.

23. A system comprising:

a scanner configured to obtain a first three-dimensional model including a first plurality of sets of three-dimensional points spatially related to one another by a first camera path and a second three-dimensional model including a second plurality of sets of three-dimensional points spatially related with one another by a second camera path;

a processor and memory configured to register one of the first plurality of sets of three-dimensional points to one of the second plurality of sets of three-dimensional points to place the first three-dimensional model and the second three-dimensional model in a shared coordinate system, to create a virtual stitch graph that spatially relates the first plurality of sets and the second plurality of sets, thereby providing a combined model that includes the first plurality of sets and the second plurality of sets all spatially related by the virtual stitch graph, and to refine the combined model with a global motion optimization of the virtual stitch graph; and

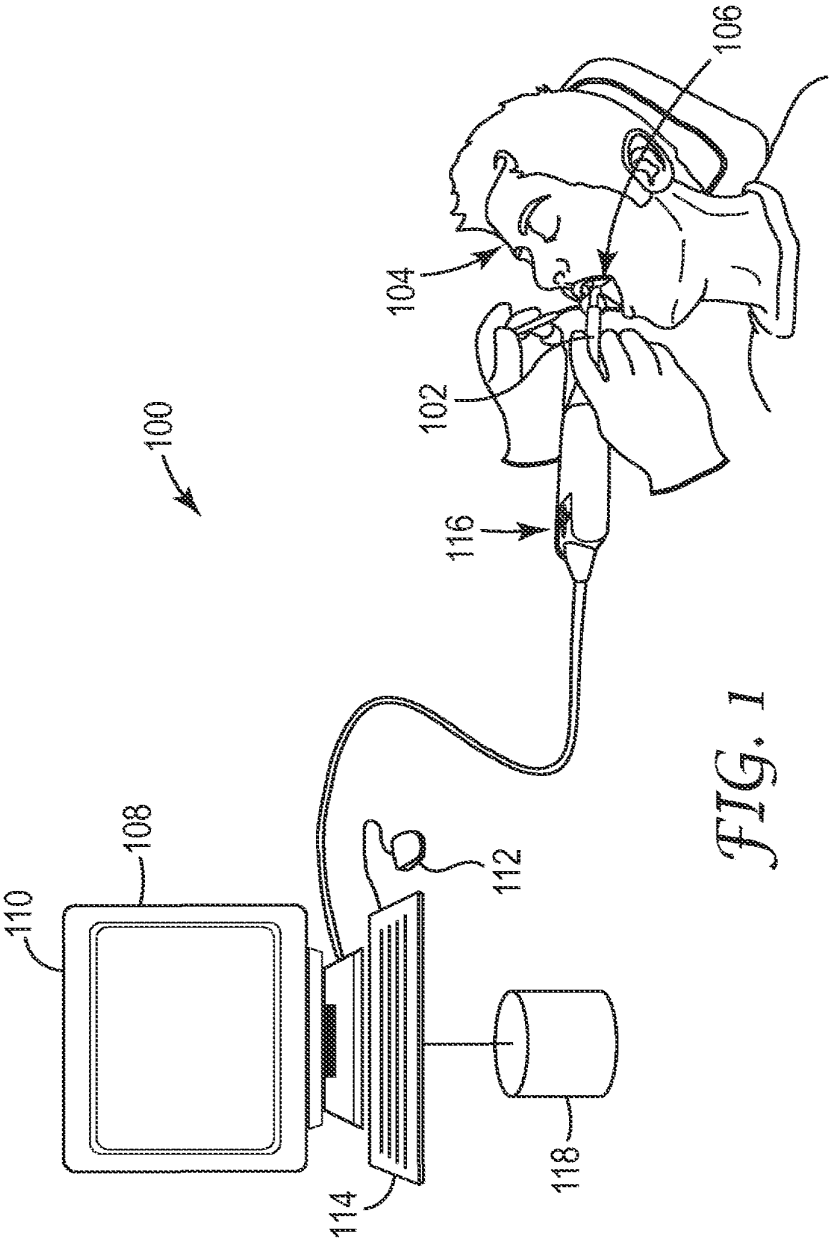
a display configured to render the combined model.

24. A system comprising:

scanning means for obtaining a first three-dimensional model including a first plurality of sets of three-dimensional points spatially related to one another by a first camera path and a second three-dimensional model including a second plurality of sets of three-dimensional points spatially related with one another by a second camera path; and

processing means for registering one of the first plurality of sets of three-dimensional points to one of the second plurality of sets of three-dimensional points to place the first three-dimensional model and the second three-dimensional model in a shared coordinate system, creating a virtual stitch graph that spatially relates the first plurality of sets and the second

plurality of sets, thereby providing a combined model that includes the first plurality of sets and the second plurality of sets all spatially related by the virtual stitch graph, and refining the combined model with a global motion optimization of the virtual stitch graph.



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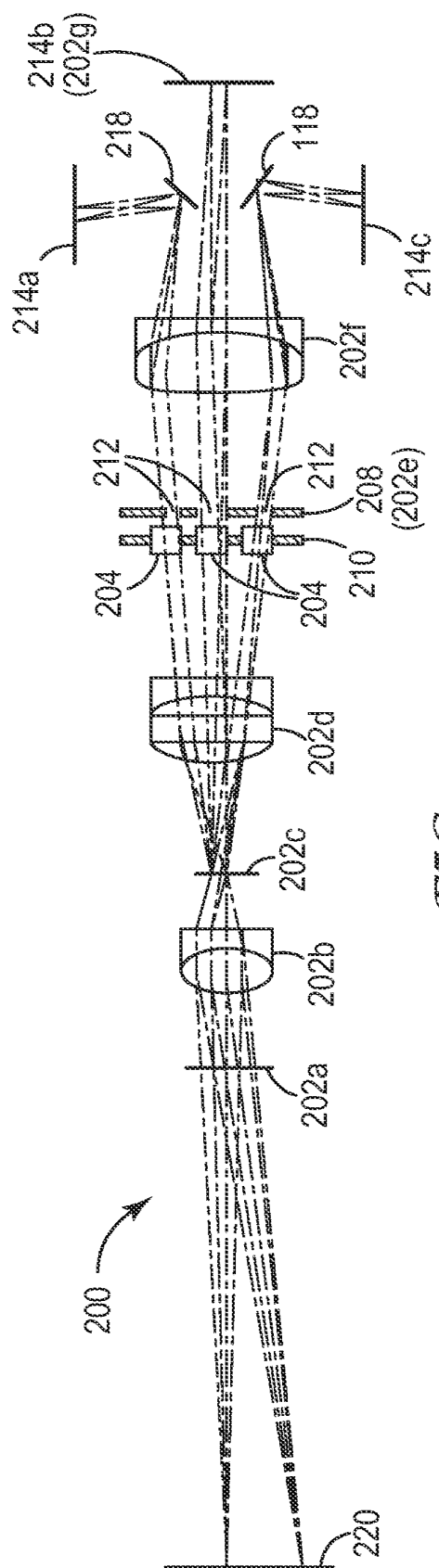


FIG. 2

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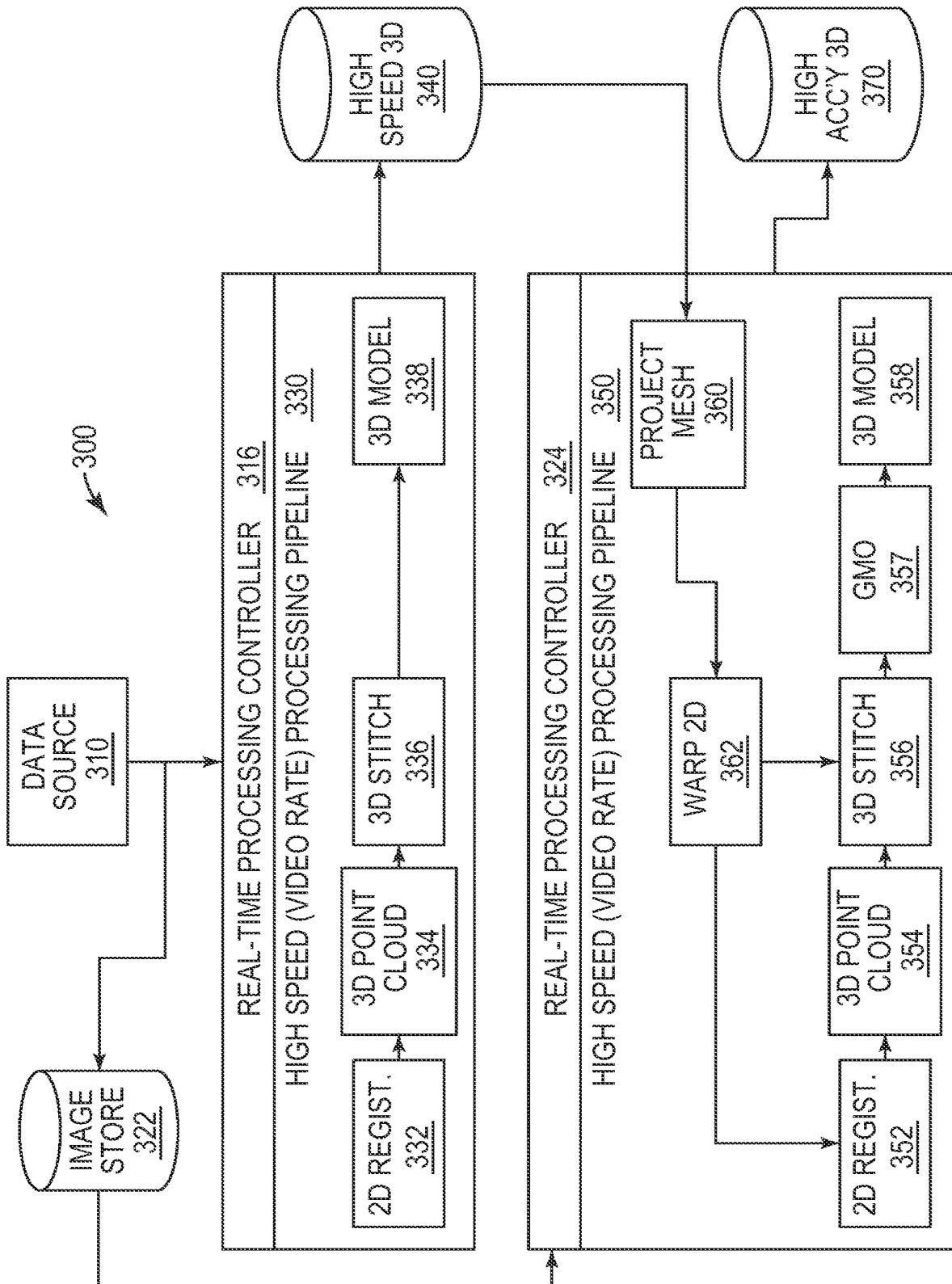


FIG. 3

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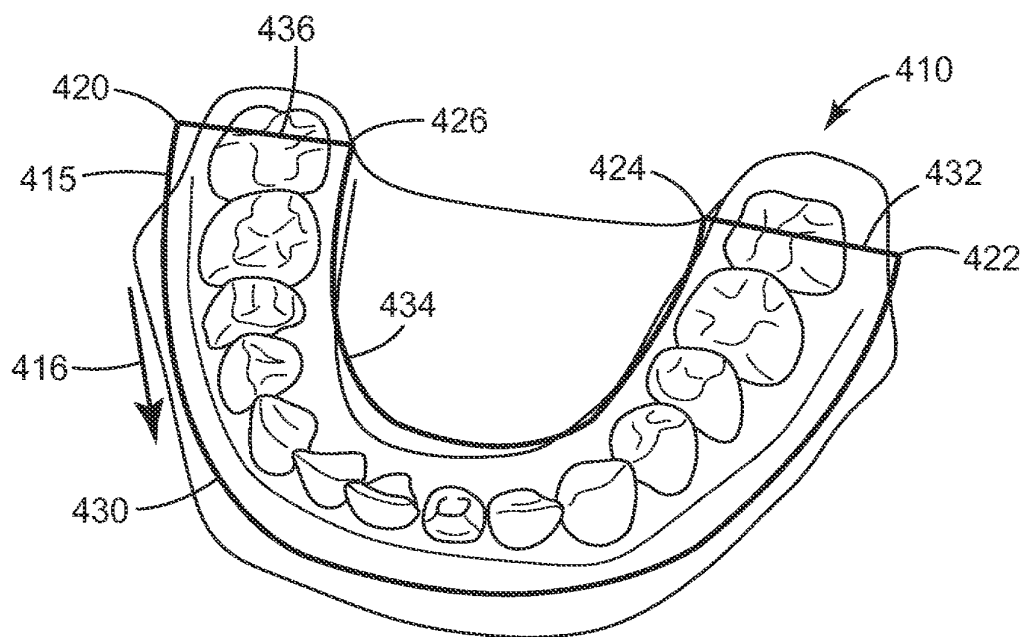


FIG. 4A

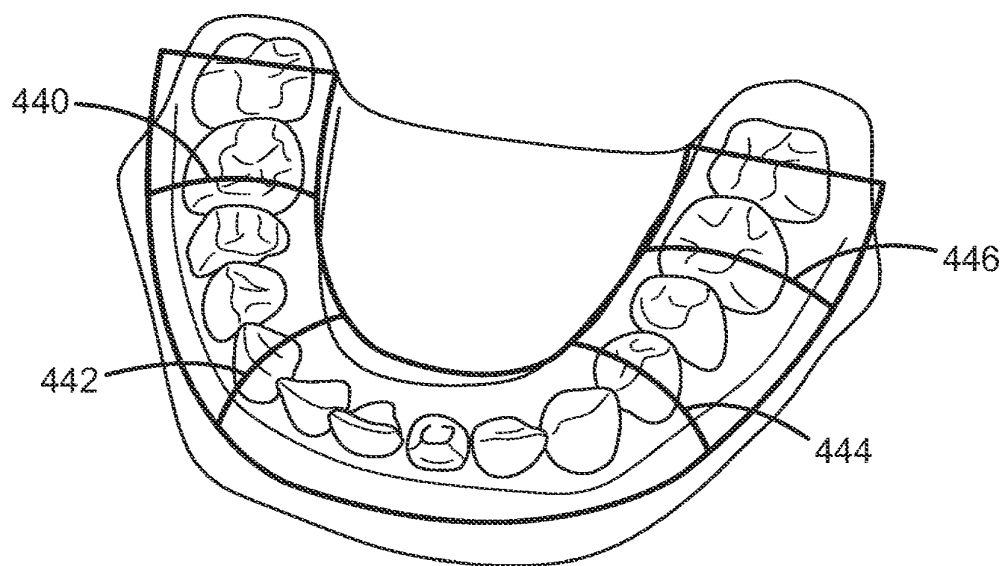


FIG. 4B

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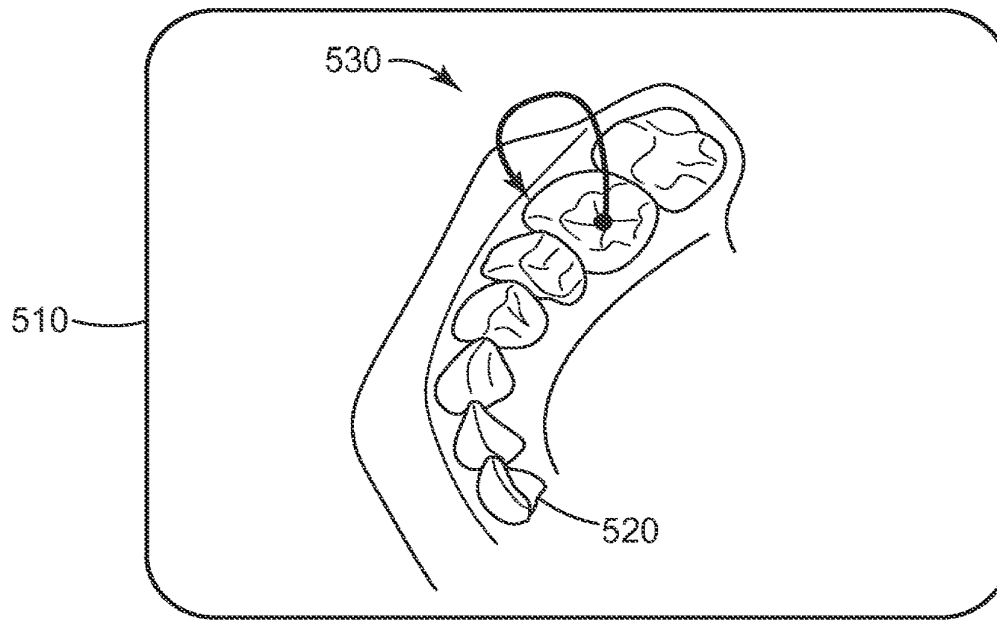


FIG. 5

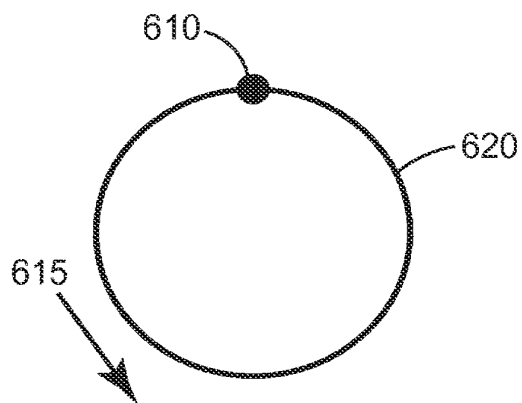


FIG. 6A

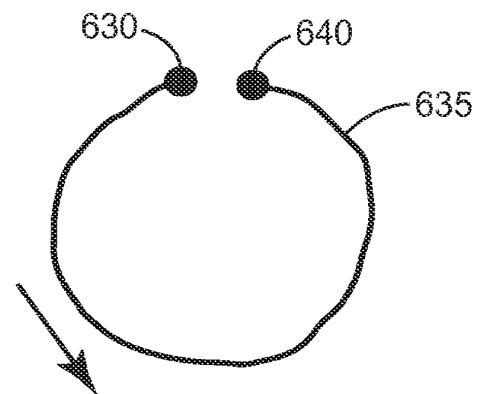


FIG. 6AB

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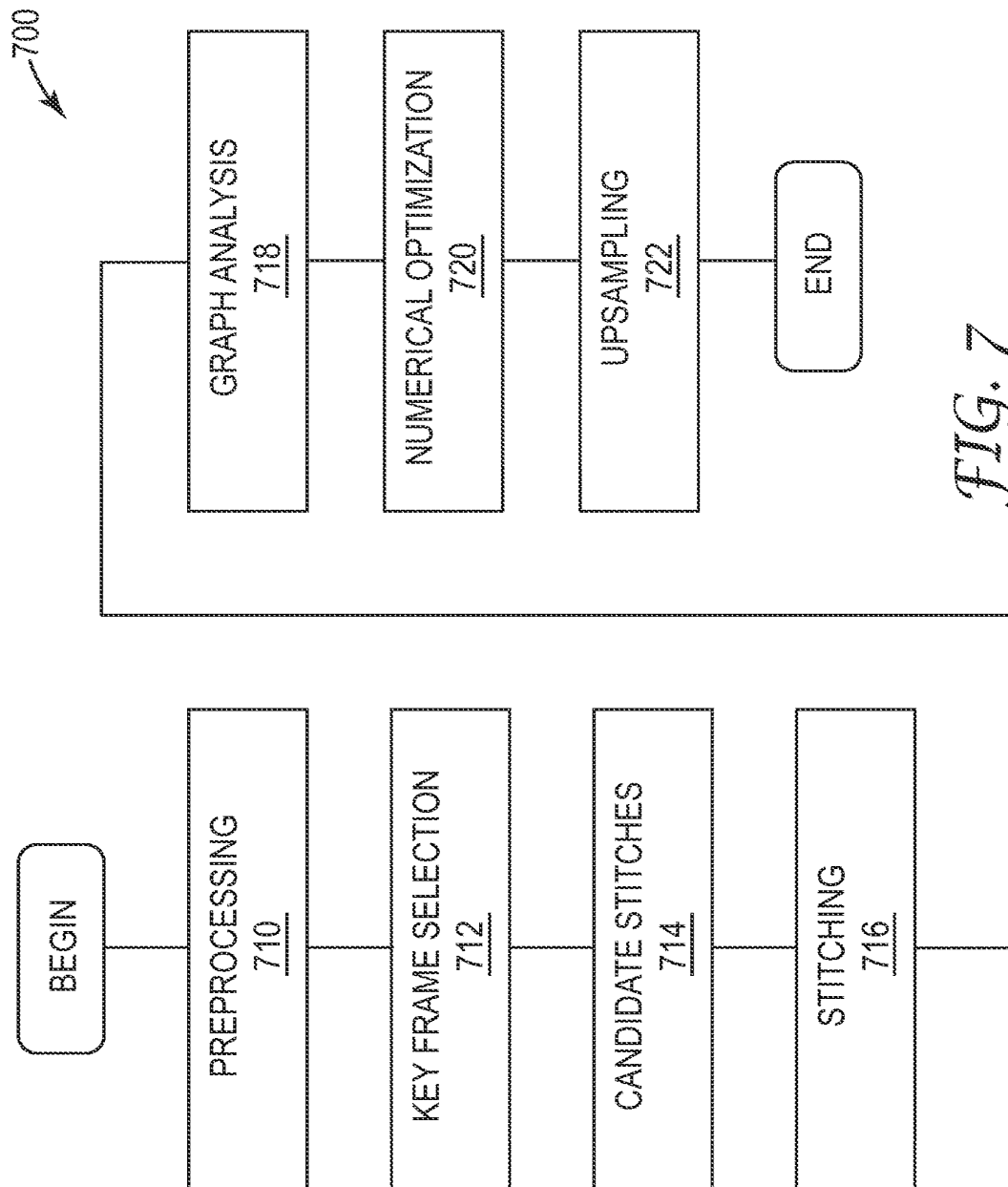


FIG. 7

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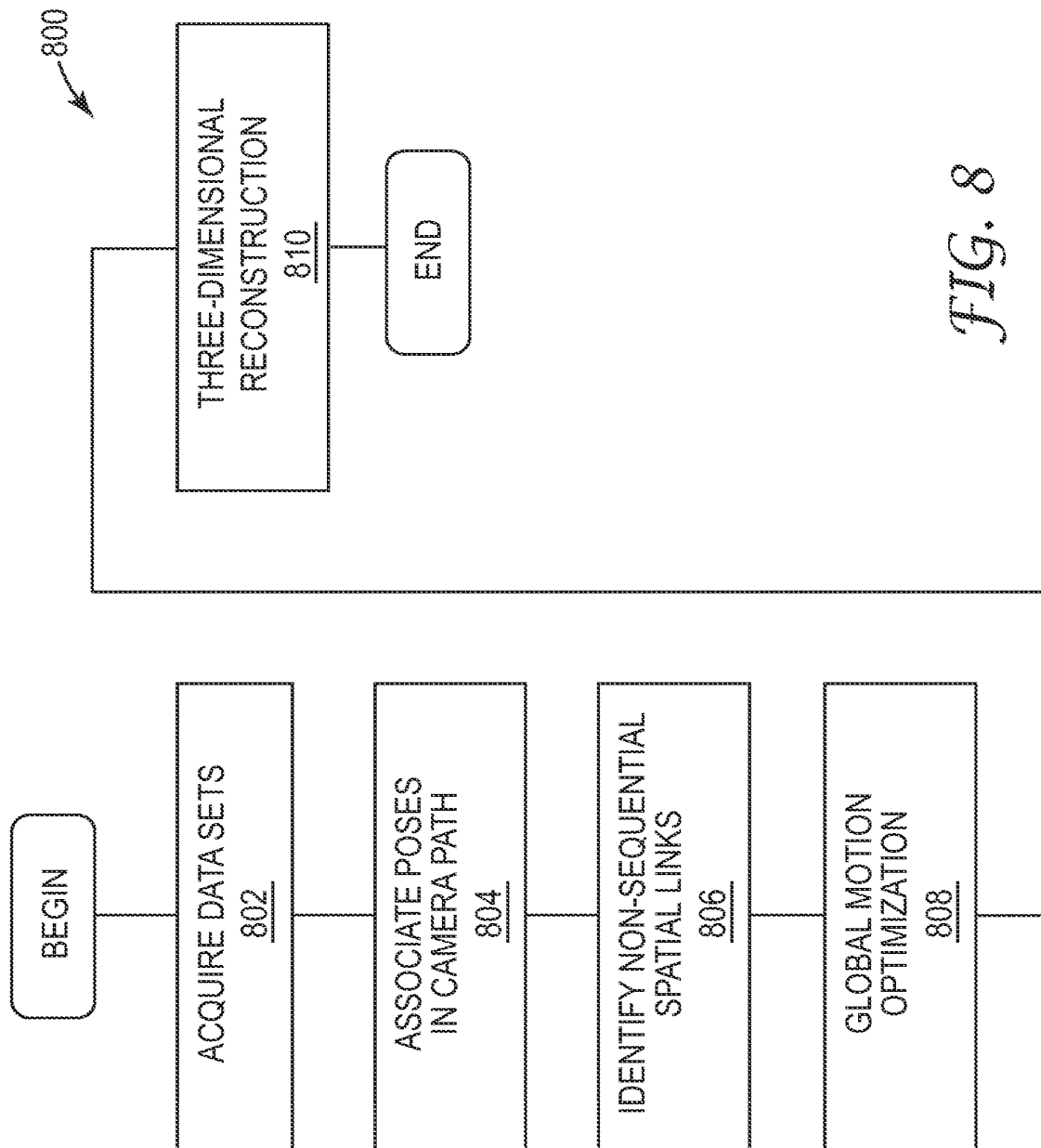


FIG. 8

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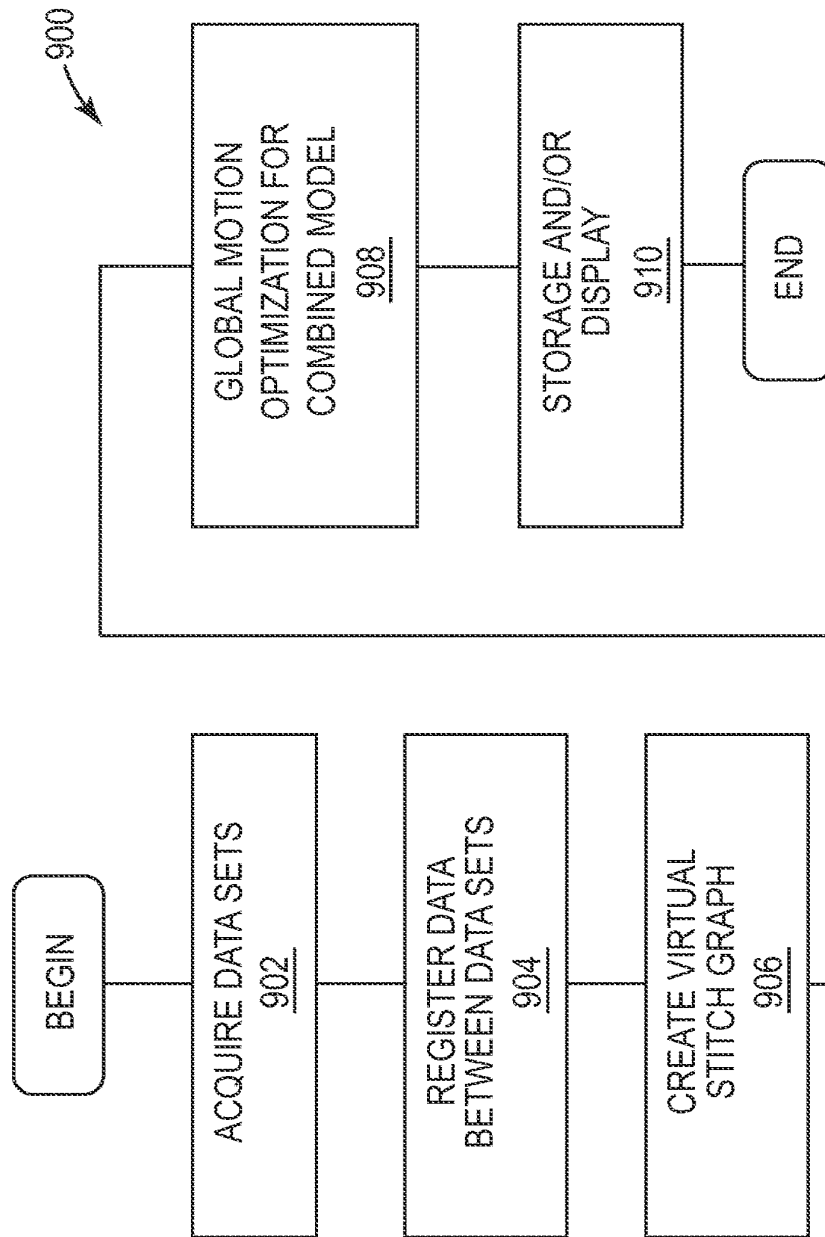


FIG. 9

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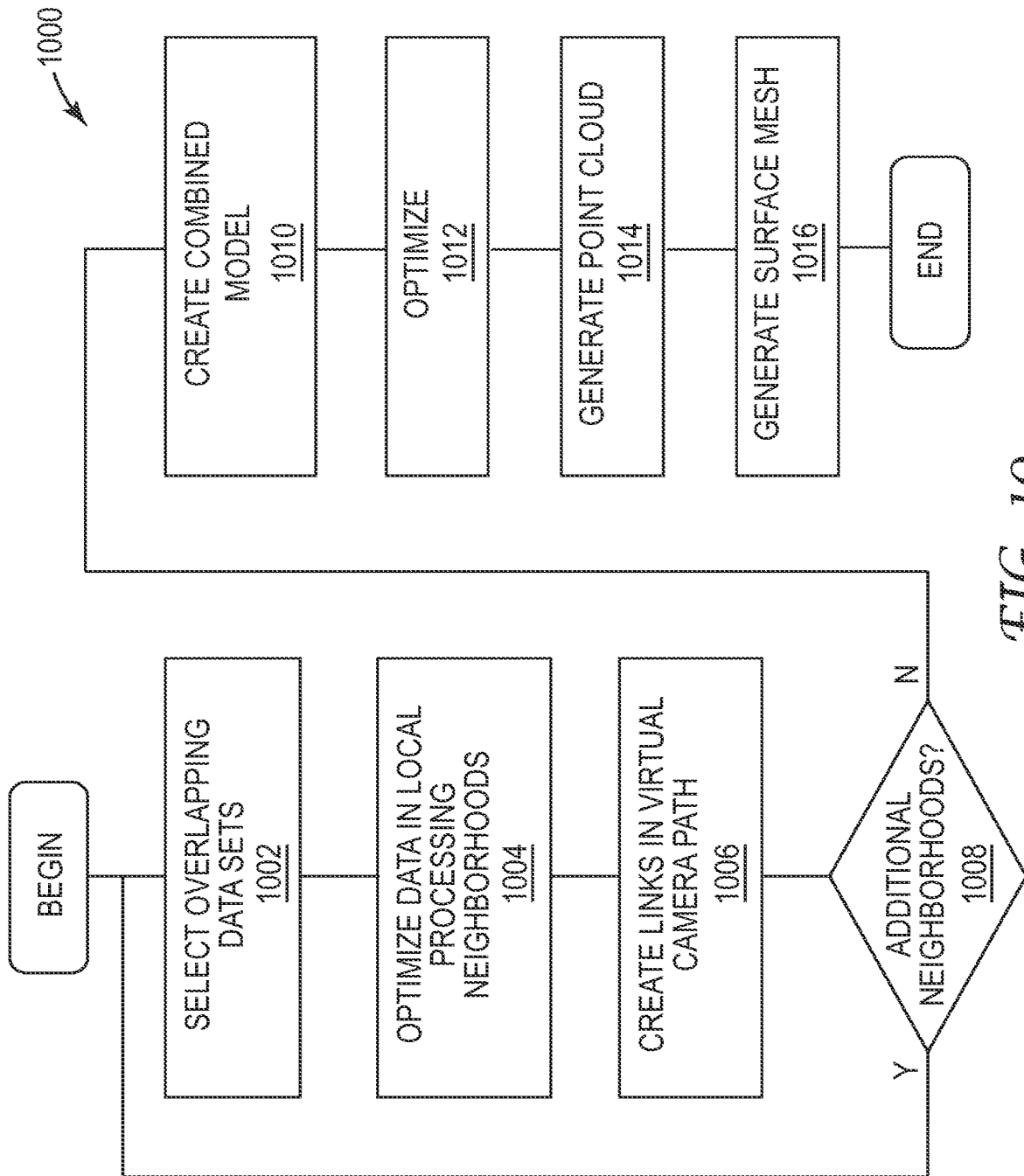


FIG. 10