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Chishti et al.

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(54) **TOOTH PATH TREATMENT PLAN**

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(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 39 days.

This patent is subject to a terminal disclaimer.

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(22) Filed: **Aug. 29, 2001**

(65) **Prior Publication Data**

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Related U.S. Application Data

(63) Continuation-in-part of application No. 09/313,289, filed on May 13, 1999, now Pat. No. 6,318,994.

(51) **Int. Cl.**[7] **A61C 3/00**
(52) **U.S. Cl.** **433/24**
(58) **Field of Search** 433/24, 213

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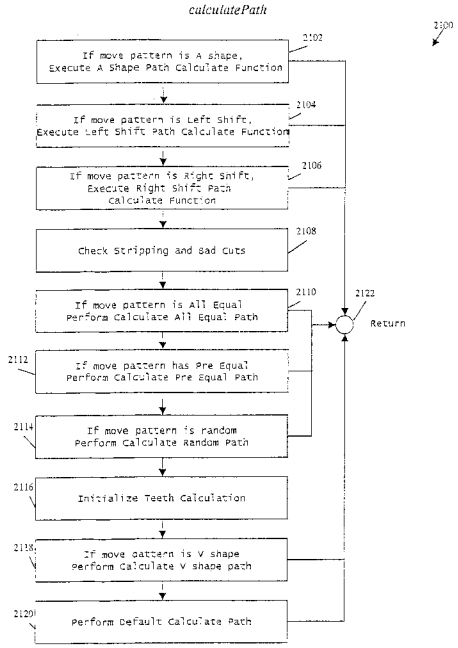
(57) **ABSTRACT**

Systems and methods are disclosed to prepare a malocclusion treatment plan by selecting a tooth treatment pattern from a library of predetermined tooth treatment patterns; and generating the malocclusion treatment plan implementing the selected tooth treatment pattern.

31 Claims, 20 Drawing Sheets



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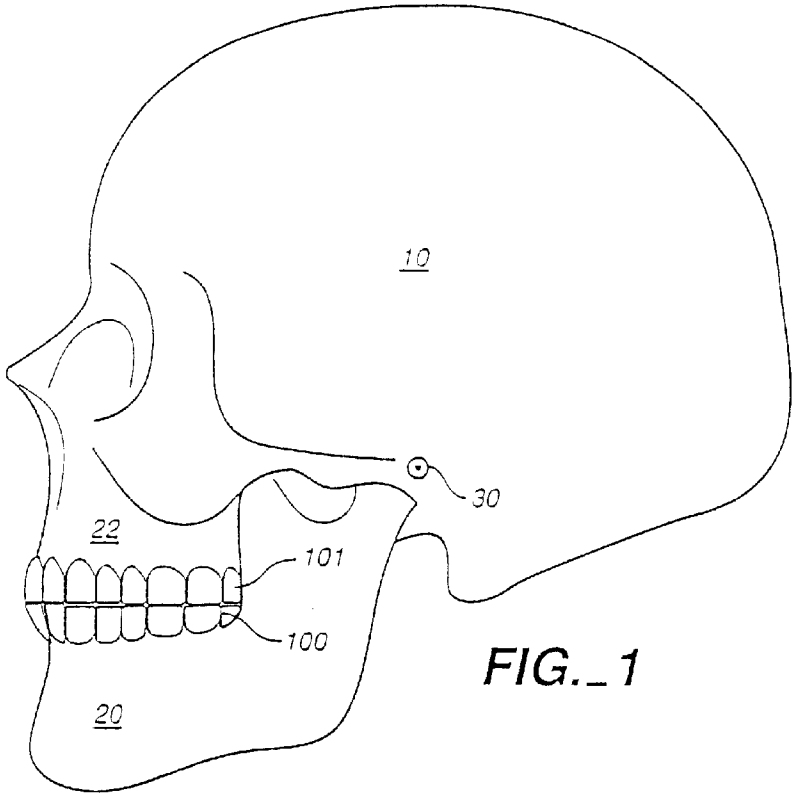

FIG._1

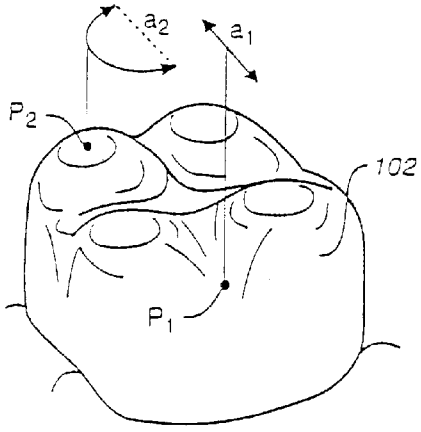

FIG._2B

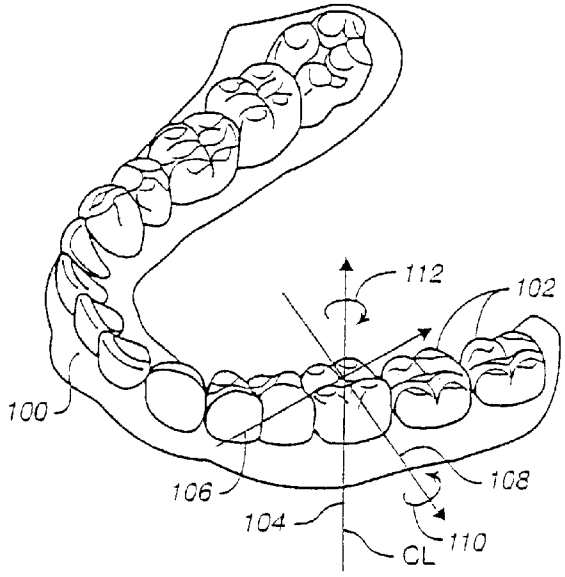

FIG._2A

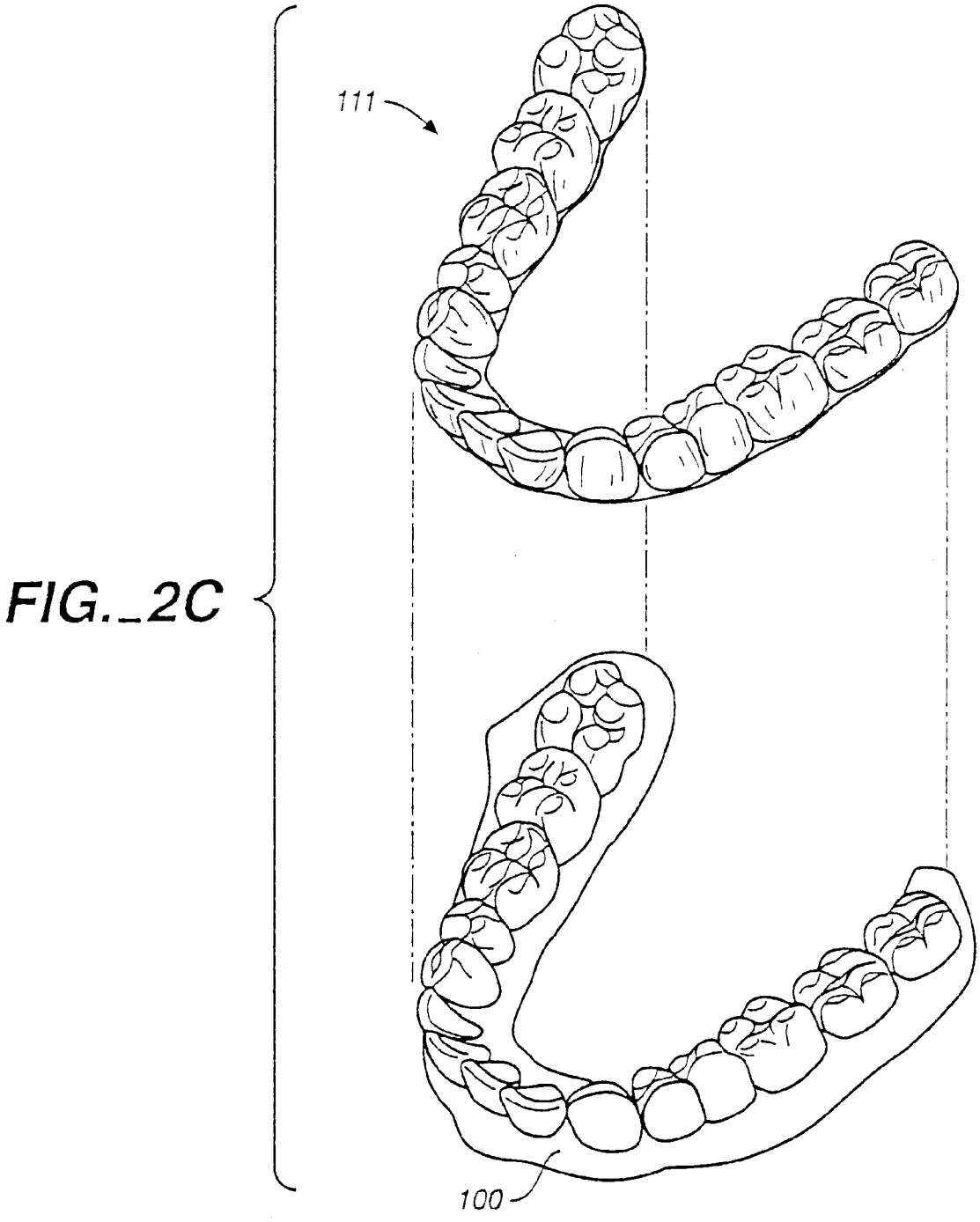

FIG._2C

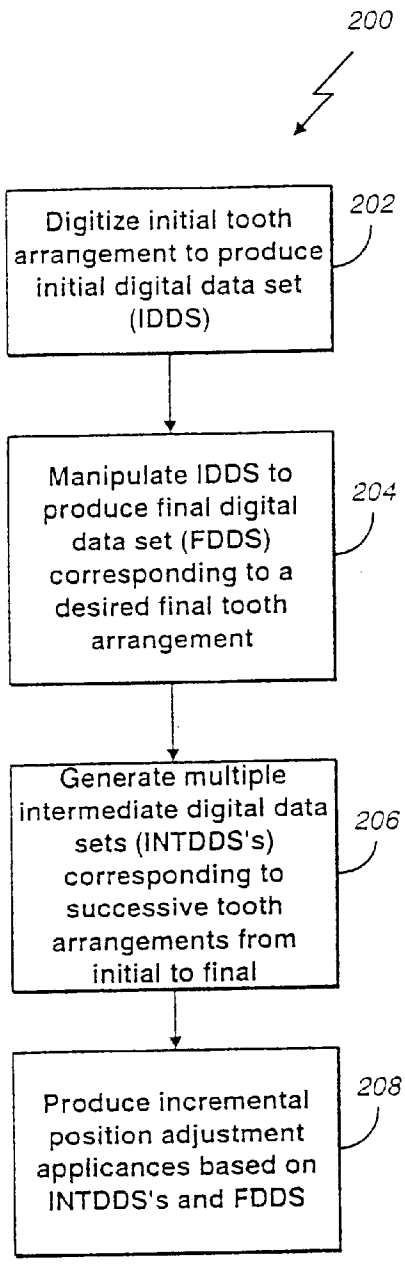
200
Digitize initial tooth arrangement to produce initial digital data set (IDDS)
202
Manipulate IDDS to produce final digital data set (FDDS) corresponding to a desired final tooth arrangement
204
Generate multiple intermediate digital data sets (INTDDS's) corresponding to successive tooth arrangements from initial to final
206
Produce incremental position adjustment applicances based on INTDDS's and FDDS
208

FIG._3

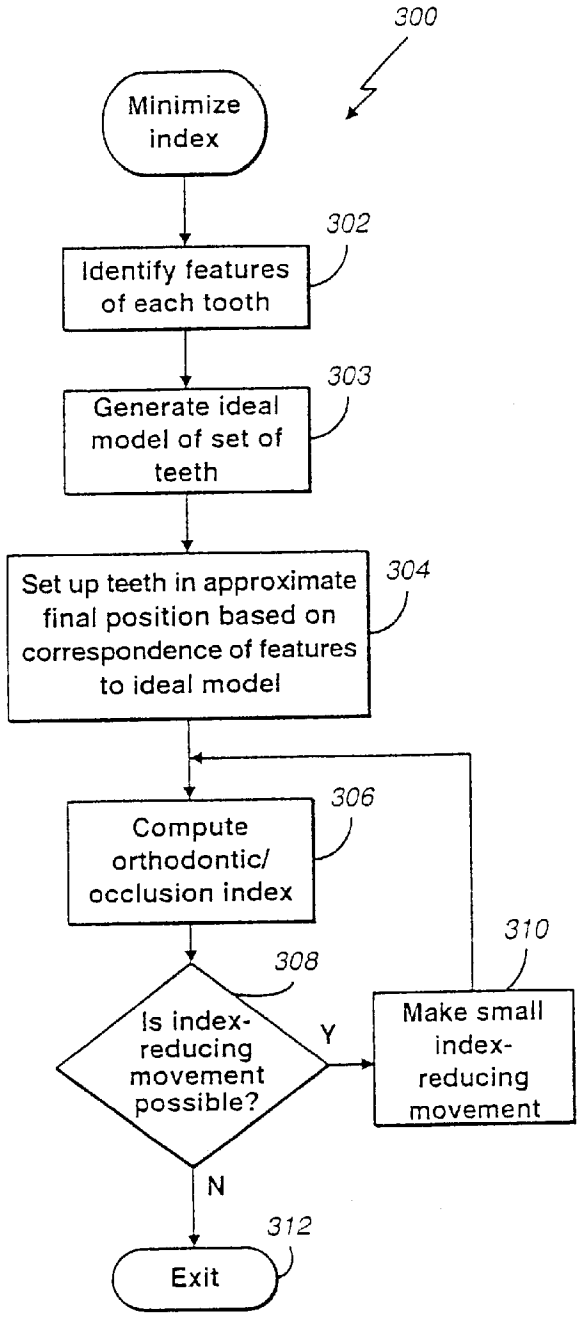
300
Minimize index
Identify features of each tooth
302
Generate ideal model of set of teeth
303
Set up teeth in approximate final position based on correspondence of features to ideal model
304
Compute orthodontic/ occlusion index
306
Is index-reducing movement possible?
308
Y
Make small index-reducing movement
310
N
Exit
312

FIG._4

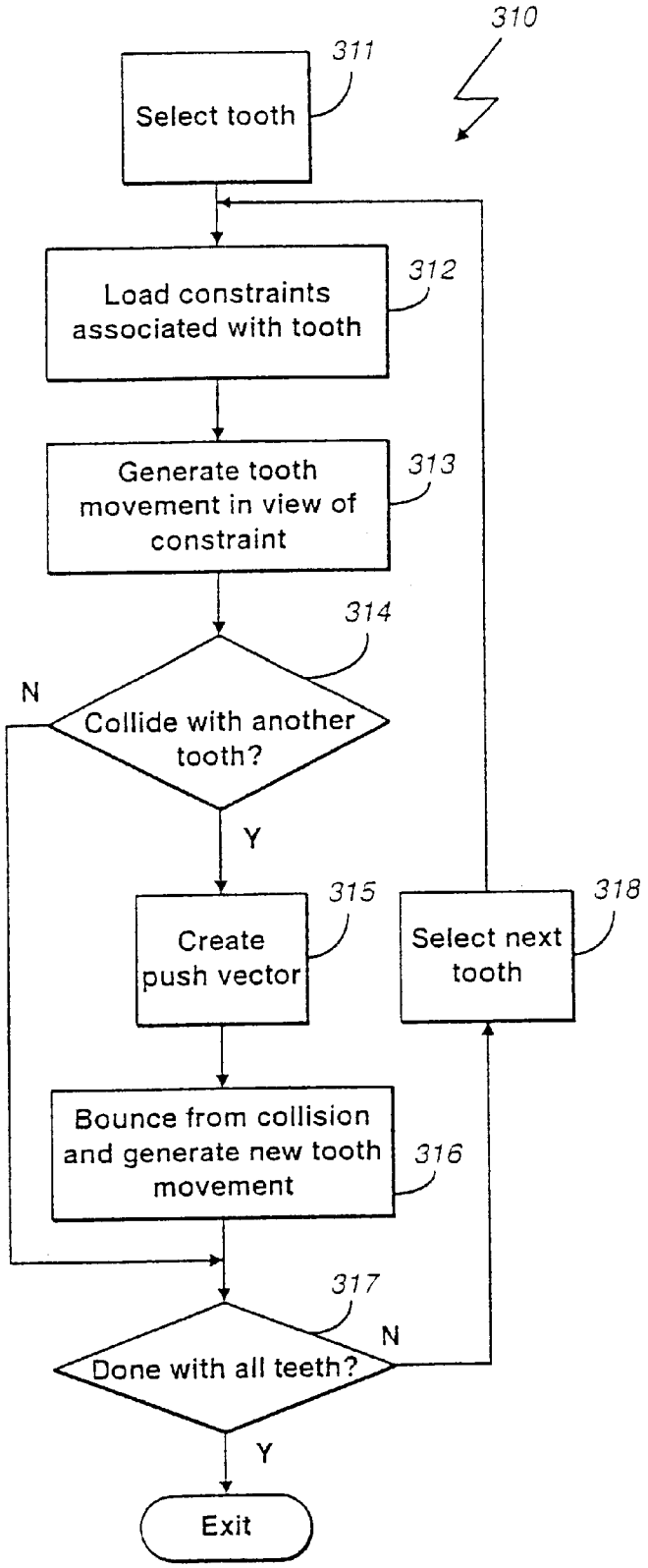
310
311
Select tooth
312
Load constraints associated with tooth
313
Generate tooth movement in view of constraint
314
Collide with another tooth?
N
Y
315
Create push vector
318
Select next tooth
Bounce from collision and generate new tooth movement
316
317
Done with all teeth?
N
Y
Exit

FIG._5

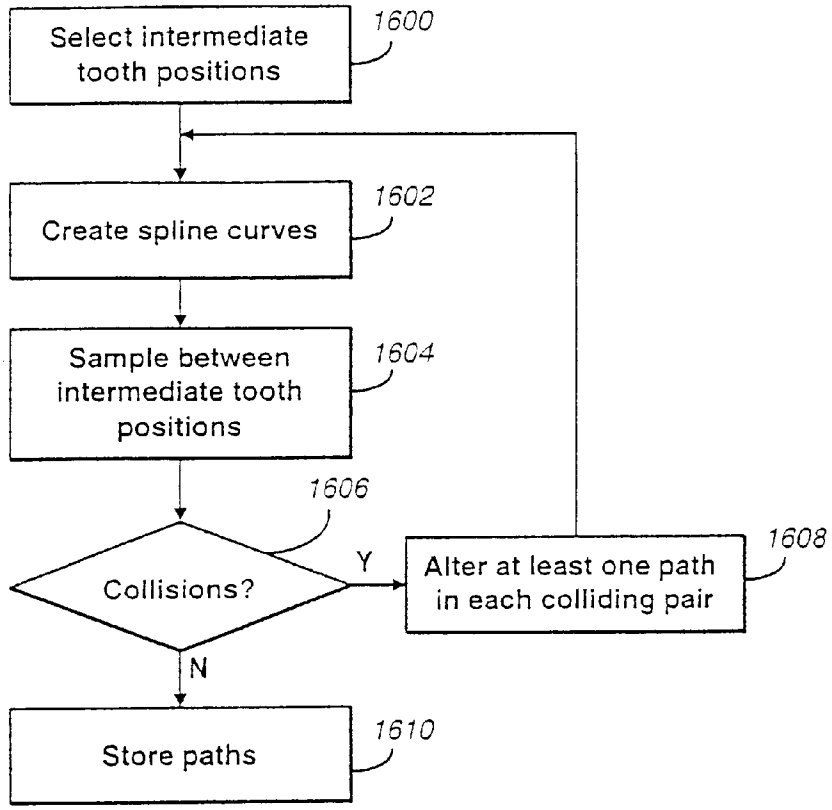
Select intermediate tooth positions
1600
Create spline curves
1602
Sample between intermediate tooth positions
1604
1606
Collisions?
Y
Alter at least one path in each colliding pair
1608
N
Store paths
1610

FIG._6

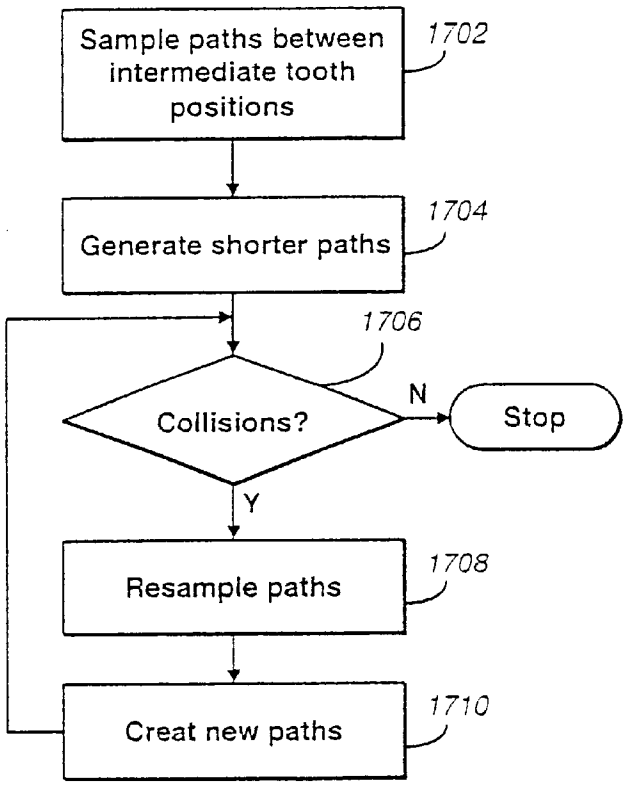
Sample paths between intermediate tooth positions
1702
Generate shorter paths
1704
1706
Collisions?
N
Stop
Y
Resample paths
1708
Creat new paths
1710

FIG._7

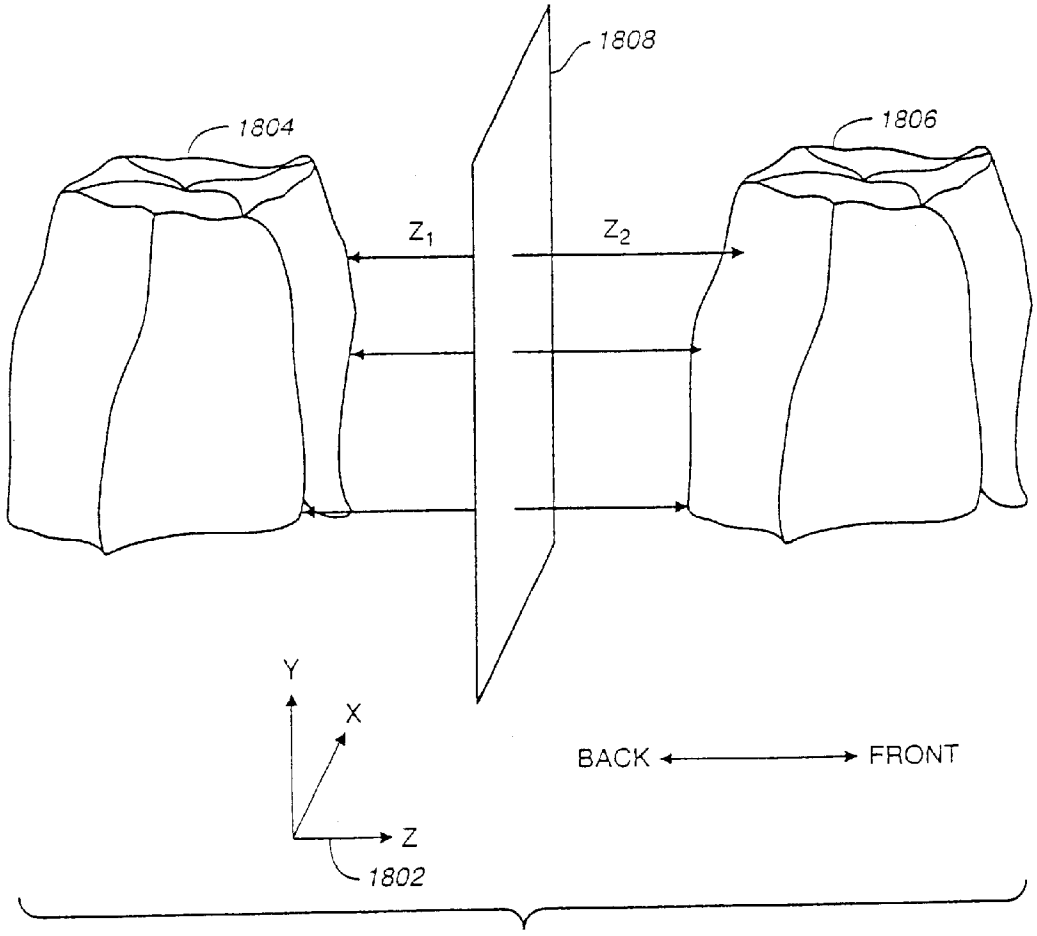

FIG._8

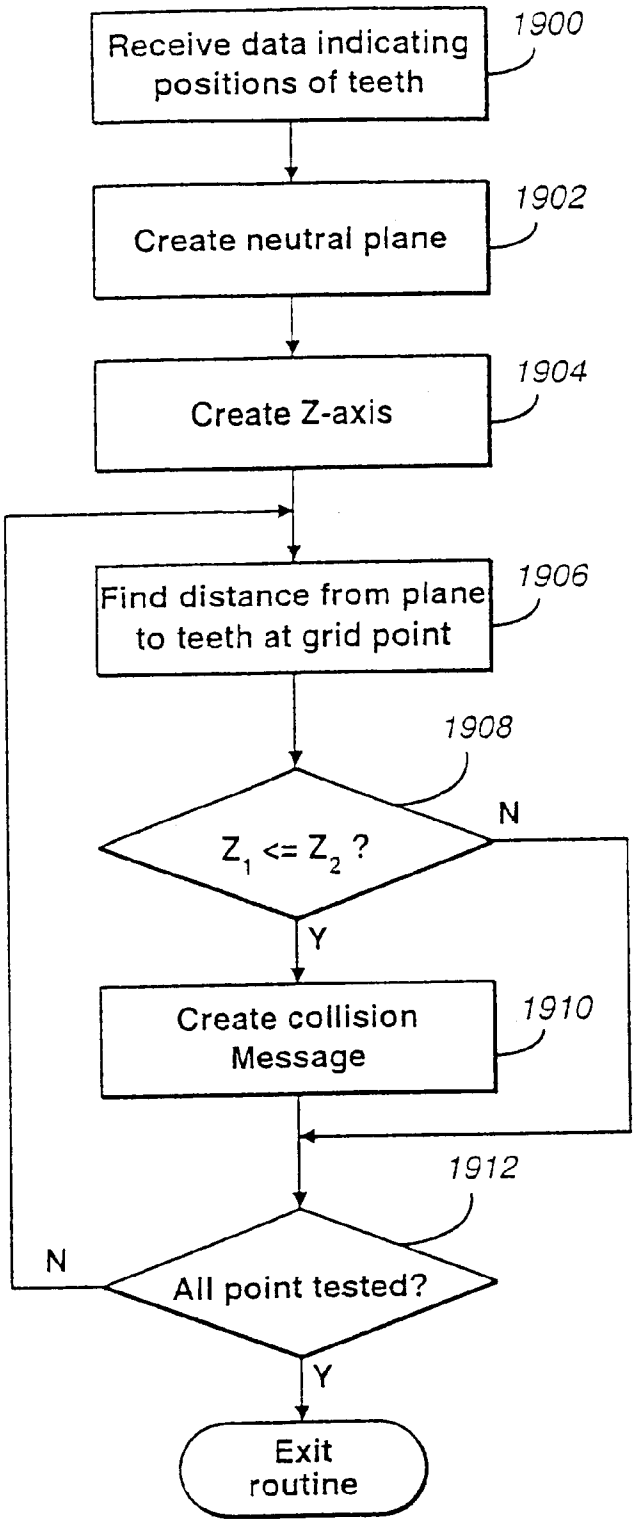
Receive data indicating positions of teeth
1900
Create neutral plane
1902
Create Z-axis
1904
Find distance from plane to teeth at grid point
1906
1908
$Z_1 <= Z_2$?
N
Y
Create collision Message
1910
1912
All point tested?
N
Y
Exit routine

FIG._9

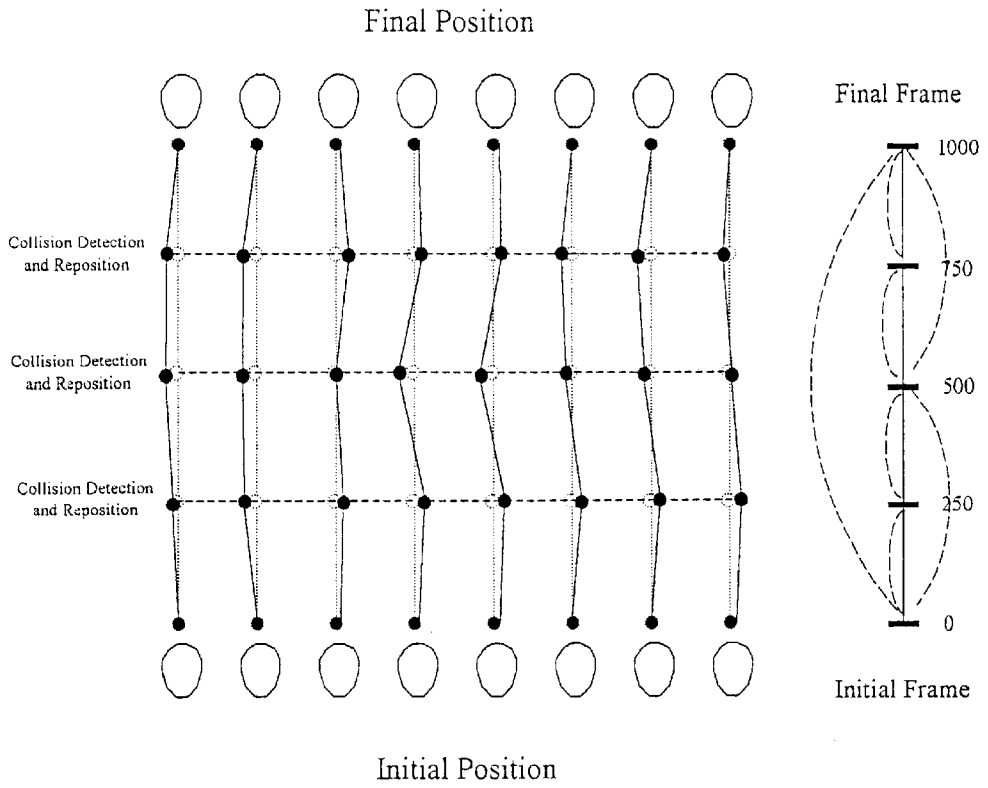
Final Position
Final Frame
1000
750
500
250
0
Collision Detection and Reposition
Collision Detection and Reposition
Collision Detection and Reposition
Initial Frame
Initial Position

FIG. 10

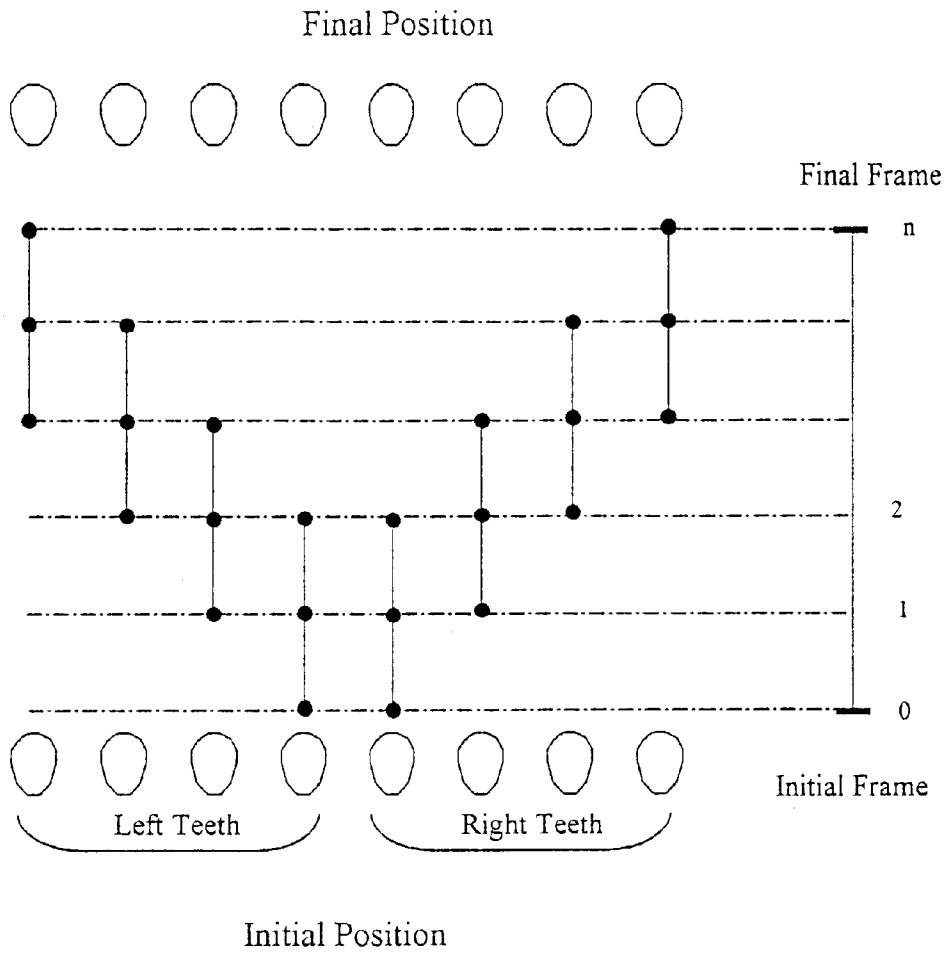
Final Position
Final Frame
n
2
1
0
Initial Frame
Left Teeth
Right Teeth
Initial Position

FIG. 11

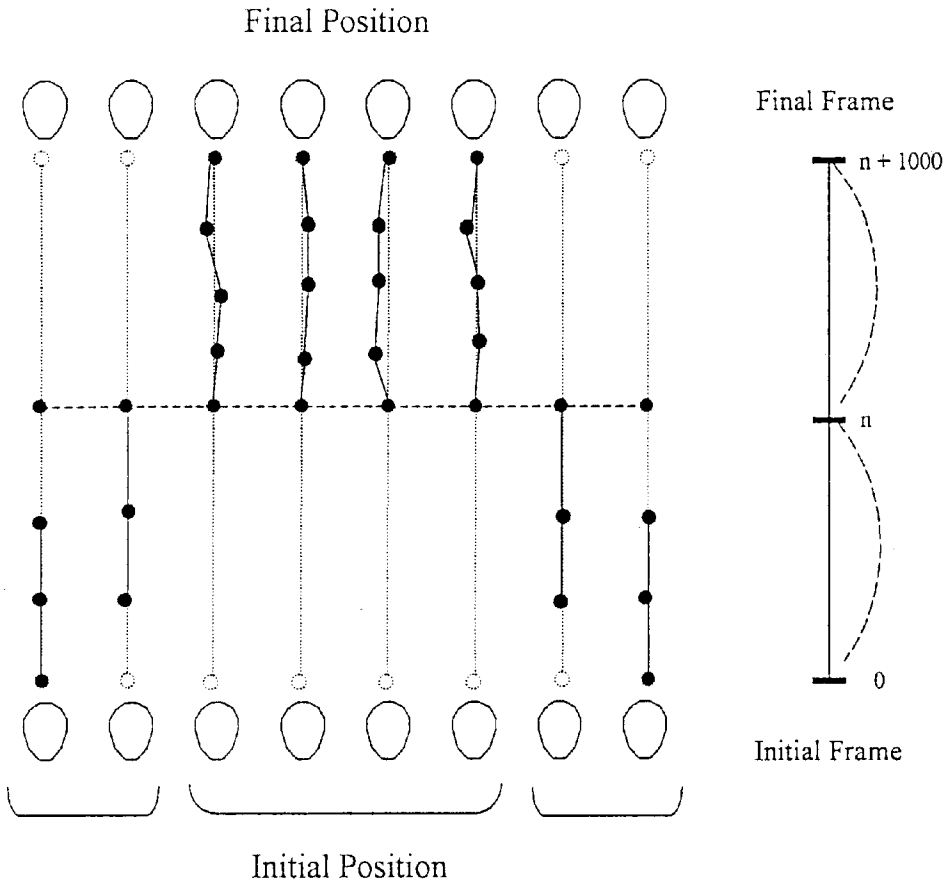
Final Position
Final Frame
n + 1000
n
0
Initial Frame
Initial Position

FIG. 12

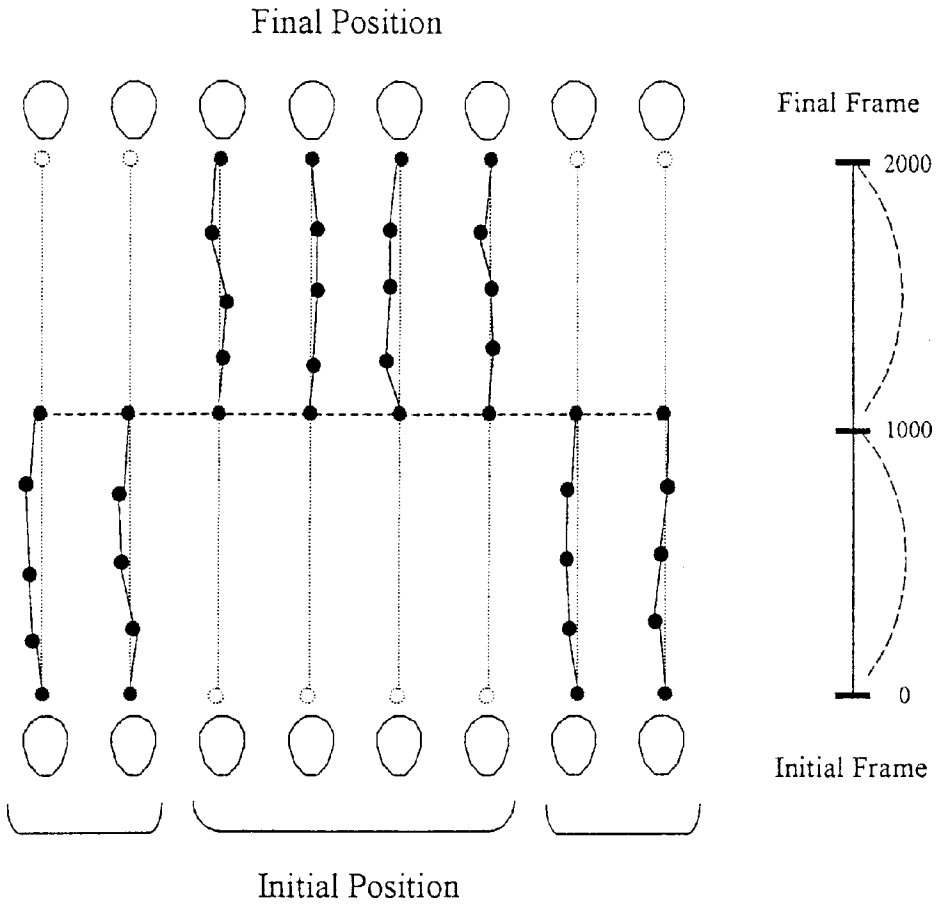
Final Position
Final Frame
2000
1000
0
Initial Frame
Initial Position

FIG. 13

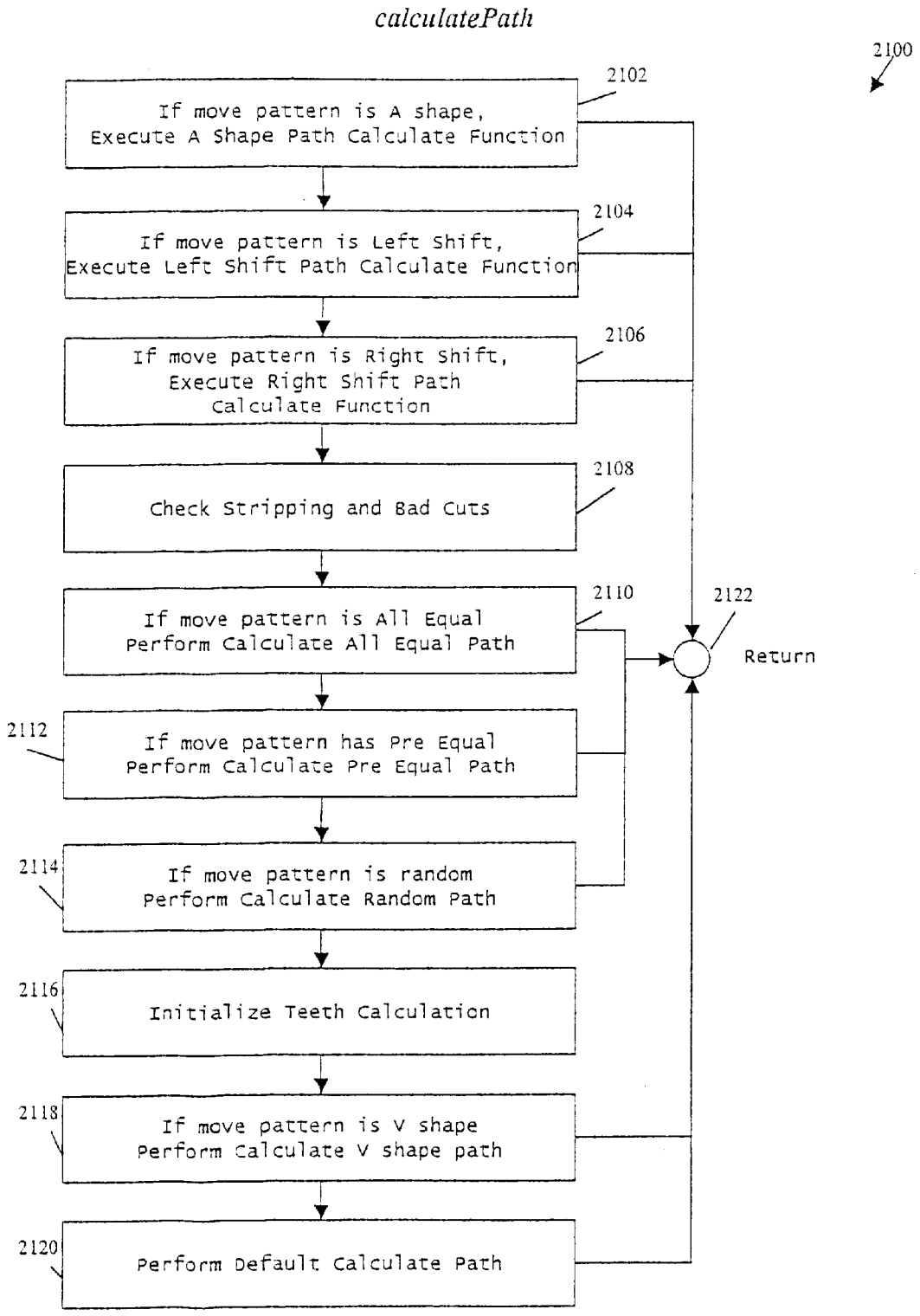
calculatePath
2100
2102
If move pattern is A shape,
Execute A Shape Path Calculate Function
2104
If move pattern is Left Shift,
Execute Left Shift Path Calculate Function
2106
If move pattern is Right Shift,
Execute Right Shift Path
Calculate Function
2108
Check Stripping and Bad Cuts
2110
If move pattern is All Equal
Perform Calculate All Equal Path
2122
Return
2112
If move pattern has Pre Equal
Perform Calculate Pre Equal Path
2114
If move pattern is random
Perform Calculate Random Path
2116
Initialize Teeth Calculation
2118
If move pattern is V shape
Perform Calculate V shape path
2120
Perform Default Calculate Path

FIG. 14

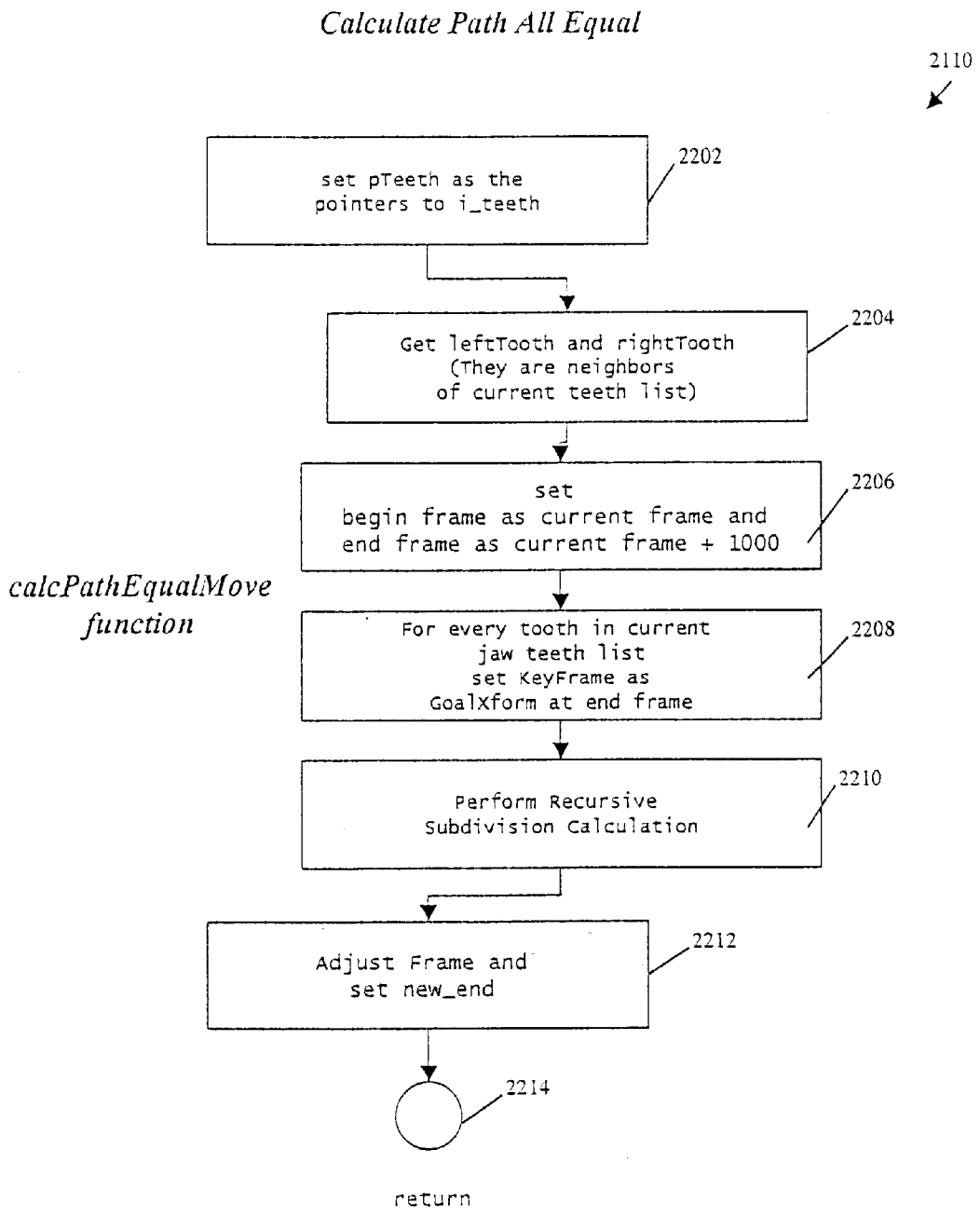
Calculate Path All Equal
2110
set pTeeth as the pointers to i_teeth
2202
Get leftTooth and rightTooth (They are neighbors of current teeth list)
2204
set begin frame as current frame and end frame as current frame + 1000
2206
calcPathEqualMove function
For every tooth in current jaw teeth list set KeyFrame as GoalXform at end frame
2208
Perform Recursive Subdivision Calculation
2210
Adjust Frame and set new_end
2212
2214
return

FIG. 15

Recursive Subdivision Calculation

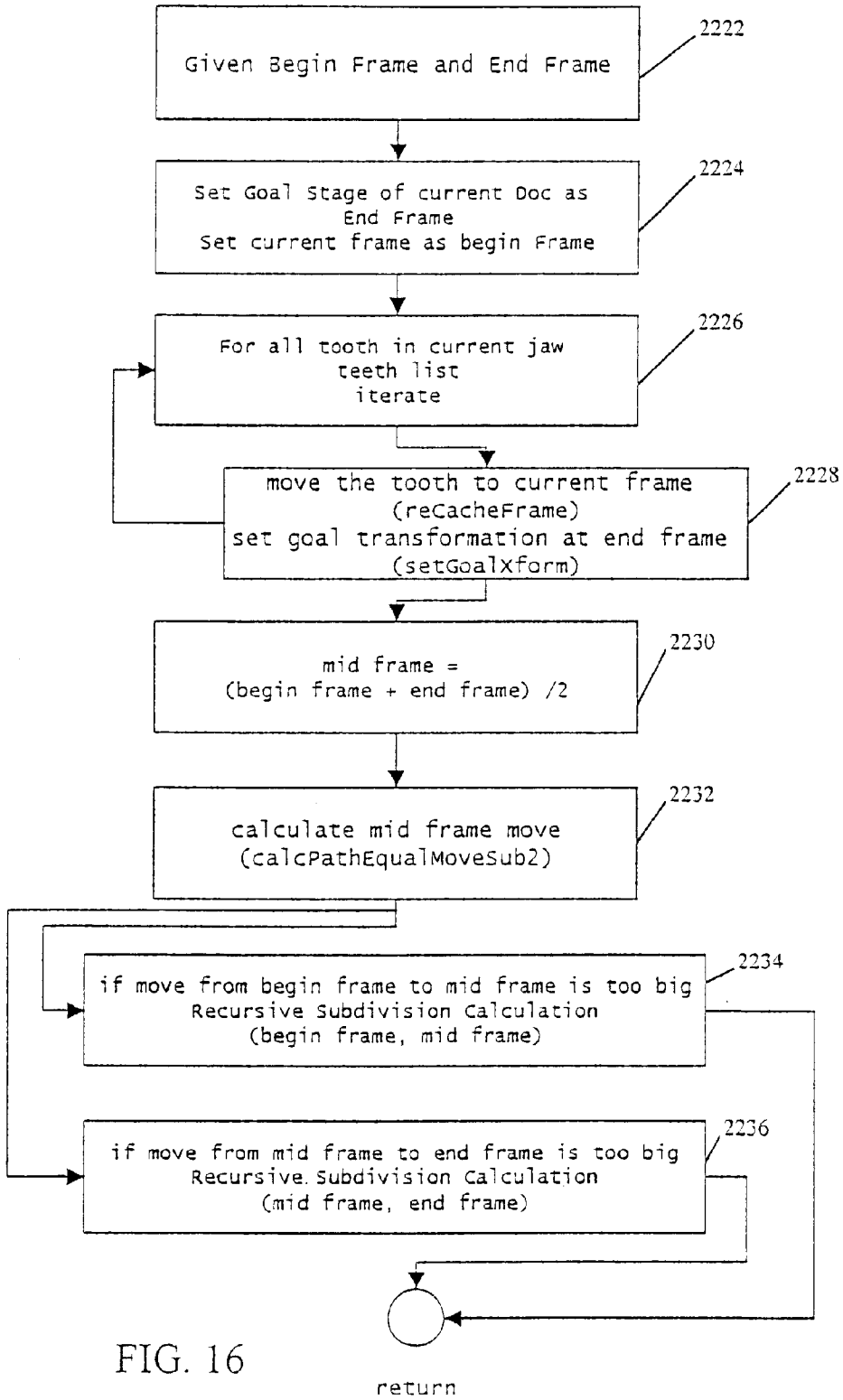

FIG. 16

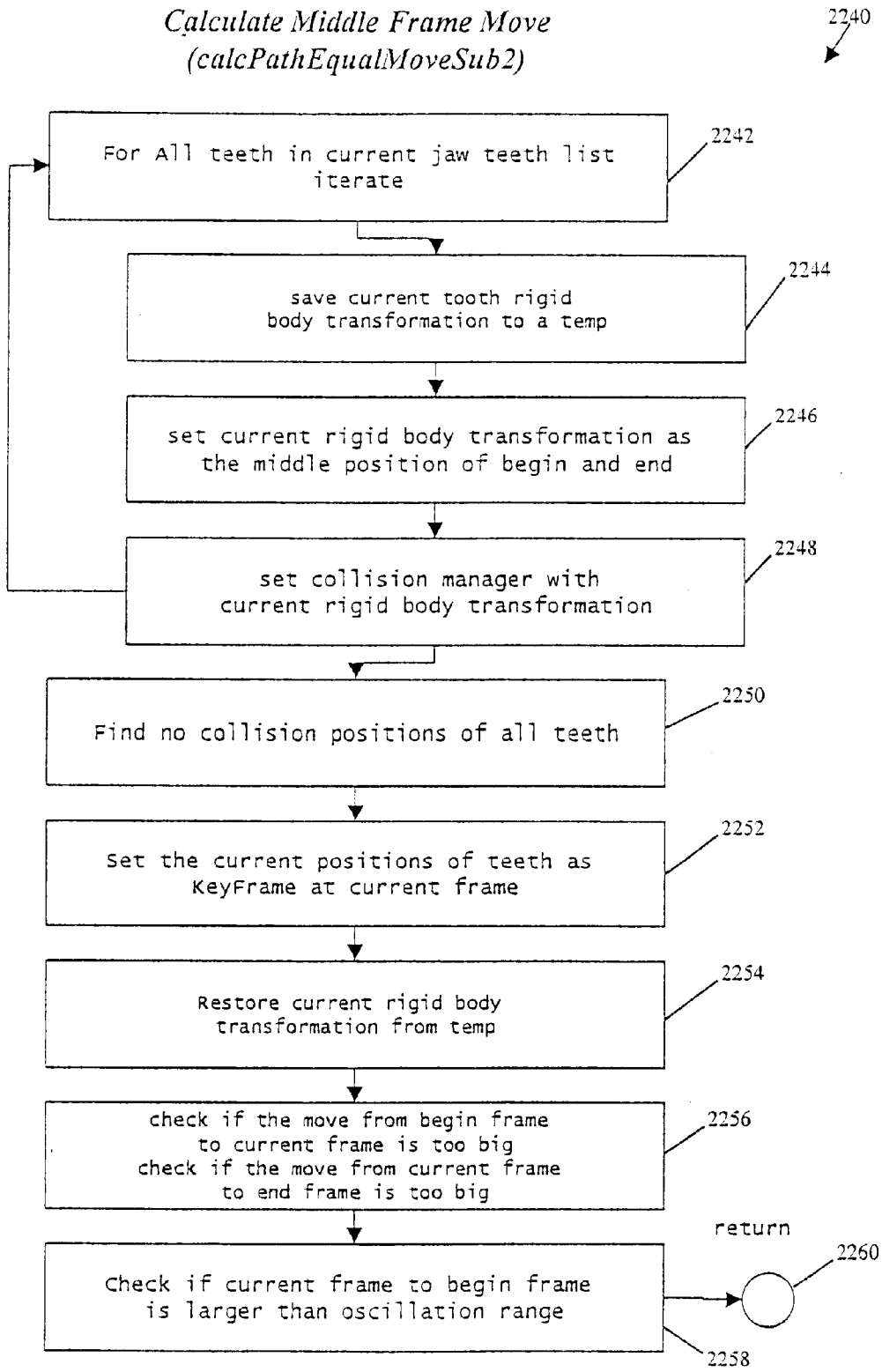
Calculate Middle Frame Move
(calcPathEqualMoveSub2)
2240
For All teeth in current jaw teeth list iterate
2242
save current tooth rigid body transformation to a temp
2244
set current rigid body transformation as the middle position of begin and end
2246
set collision manager with current rigid body transformation
2248
Find no collision positions of all teeth
2250
Set the current positions of teeth as KeyFrame at current frame
2252
Restore current rigid body transformation from temp
2254
check if the move from begin frame to current frame is too big
check if the move from current frame to end frame is too big
2256
Check if current frame to begin frame is larger than oscillation range
2258
return
2260

FIG. 17

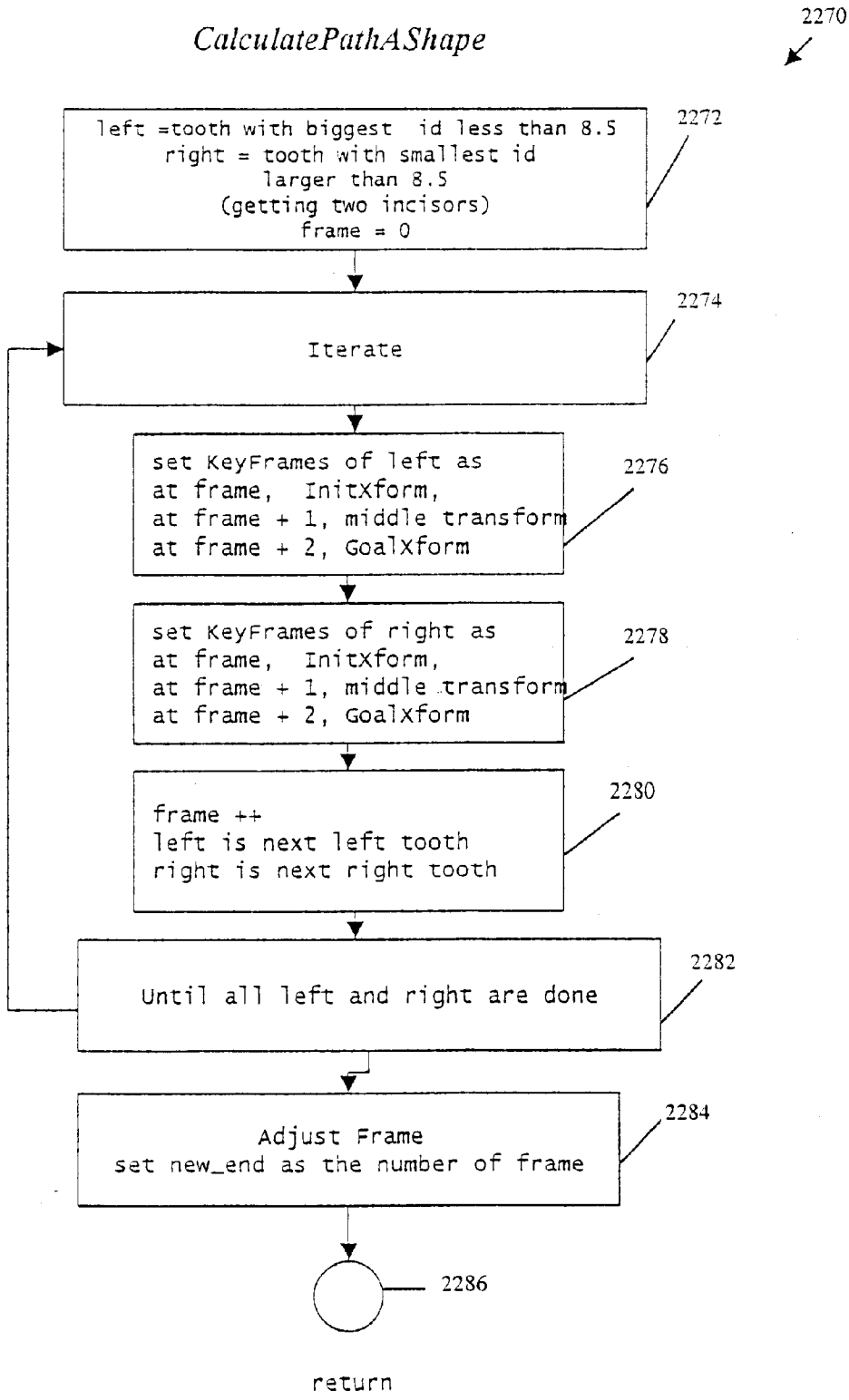
CalculatePathAShape
2270
left =tooth with biggest id less than 8.5
right = tooth with smallest id
larger than 8.5
(getting two incisors)
frame = 0
2272
Iterate
2274
set KeyFrames of left as
at frame, InitXform,
at frame + 1, middle transform
at frame + 2, GoalXform
2276
set KeyFrames of right as
at frame, InitXform,
at frame + 1, middle transform
at frame + 2, GoalXform
2278
frame ++
left is next left tooth
right is next right tooth
2280
Until all left and right are done
2282
Adjust Frame
set new_end as the number of frame
2284
2286
return

FIG. 18

Calculate Pre Equal Path

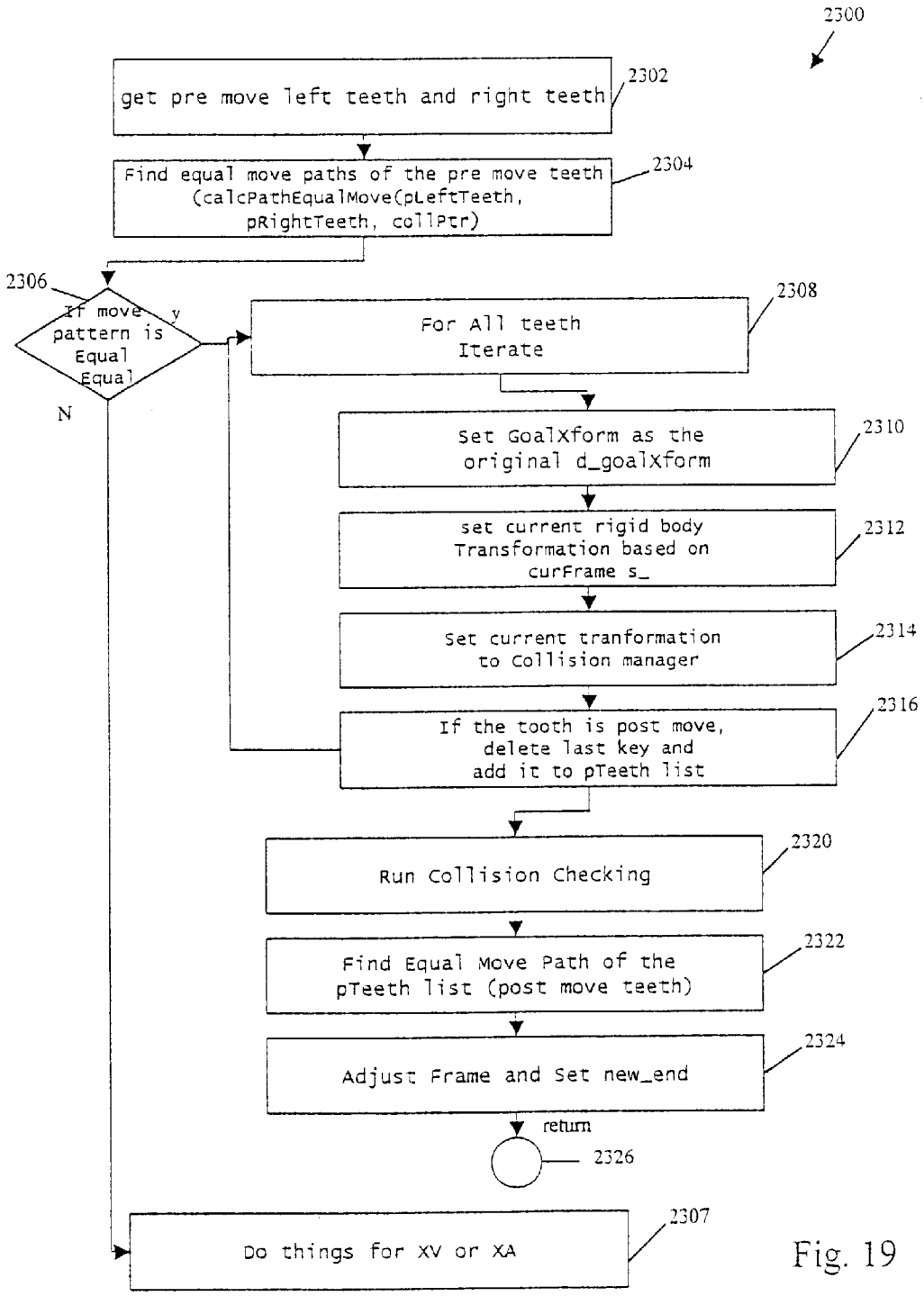

Fig. 19

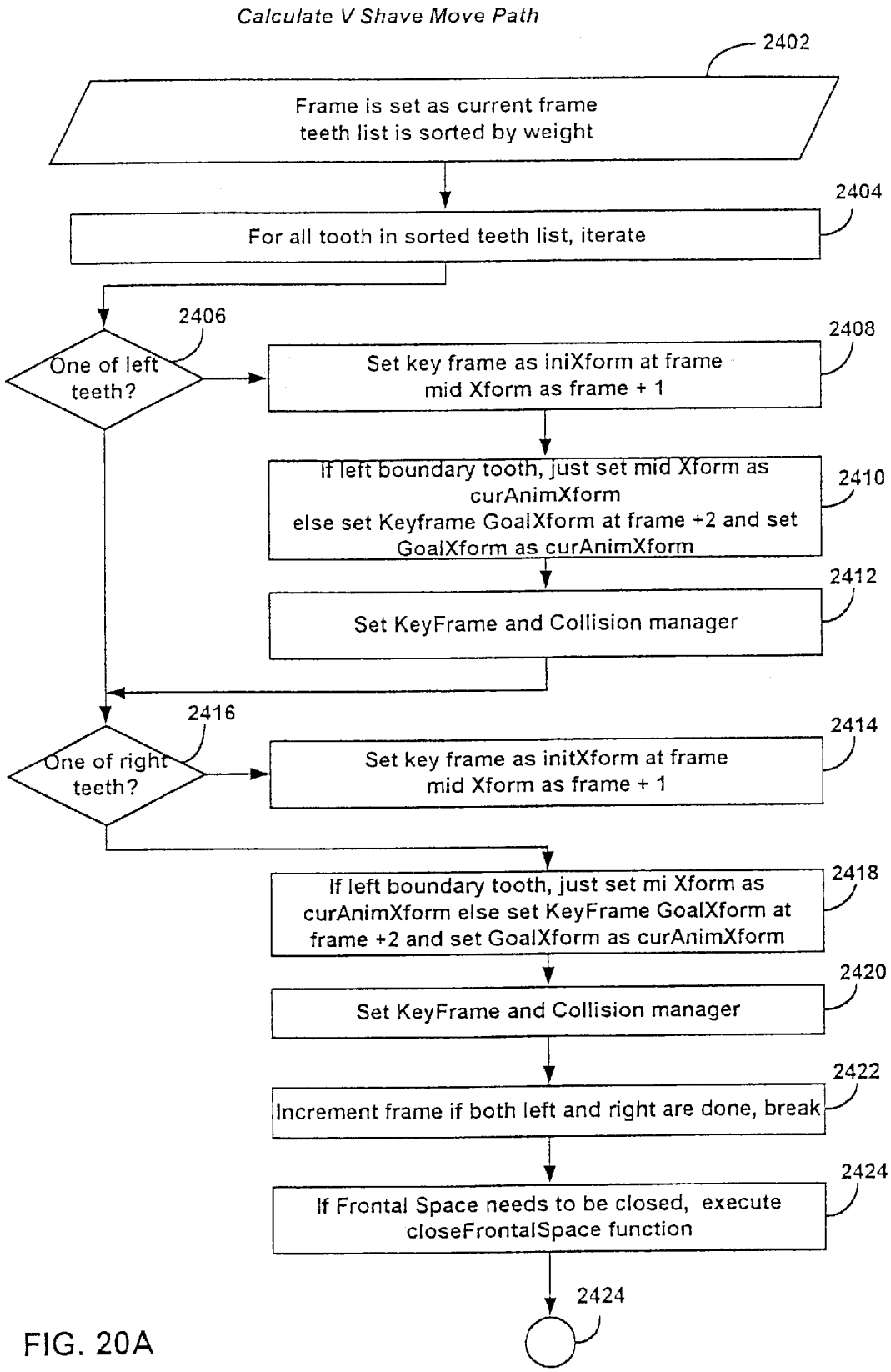
Calculate V Shave Move Path
2402
Frame is set as current frame
teeth list is sorted by weight
2404
For all tooth in sorted teeth list, iterate
2406
One of left teeth?
2408
Set key frame as iniXform at frame
mid Xform as frame + 1
2410
If left boundary tooth, just set mid Xform as curAnimXform
else set Keyframe GoalXform at frame +2 and set GoalXform as curAnimXform
2412
Set KeyFrame and Collision manager
2416
One of right teeth?
2414
Set key frame as initXform at frame
mid Xform as frame + 1
2418
If left boundary tooth, just set mi Xform as curAnimXform else set KeyFrame GoalXform at frame +2 and set GoalXform as curAnimXform
2420
Set KeyFrame and Collision manager
2422
Increment frame if both left and right are done, break
2424
If Frontal Space needs to be closed, execute closeFrontalSpace function
2424

FIG. 20A

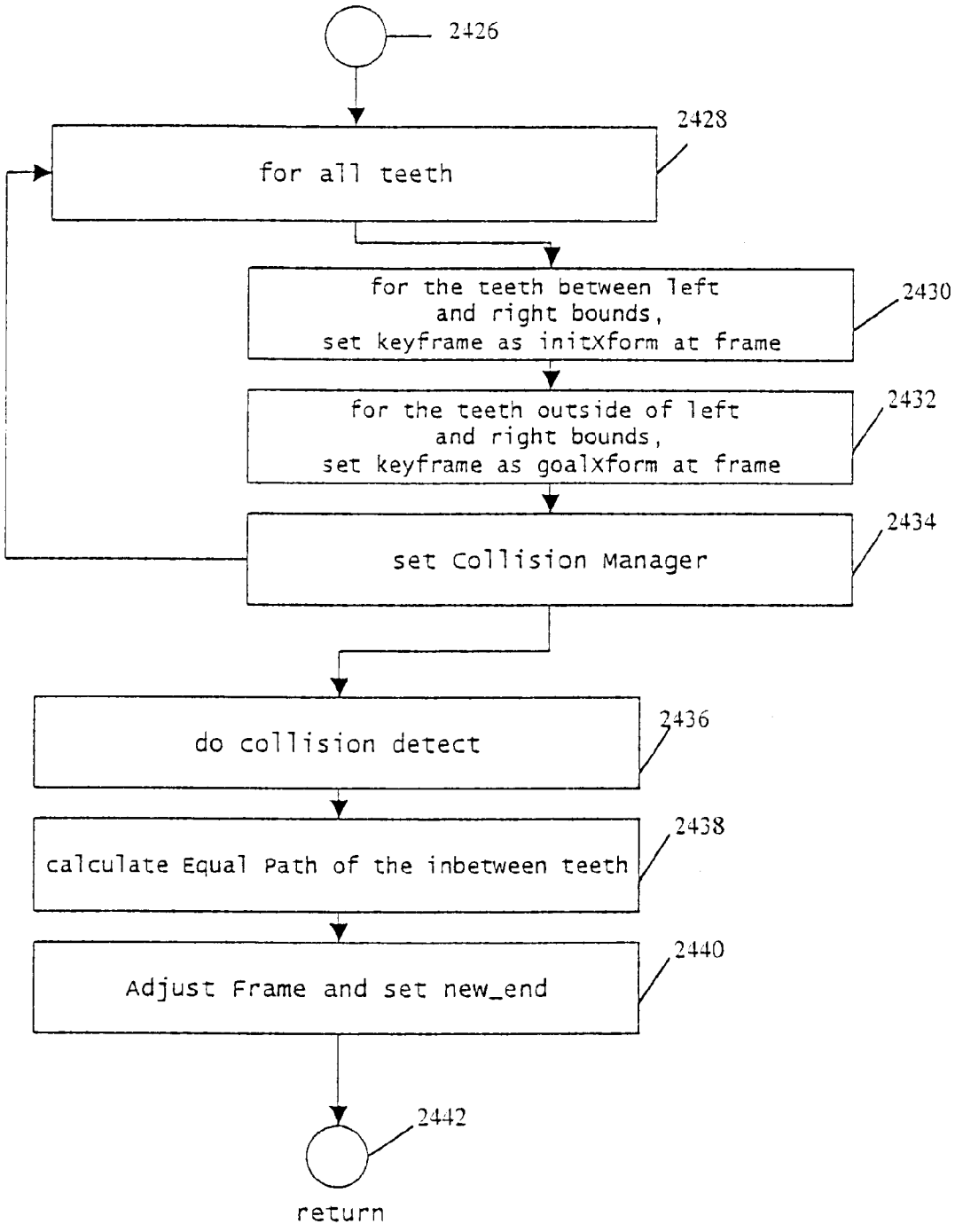
2426
2428
for all teeth
for the teeth between left
and right bounds,
set keyframe as initXform at frame
2430
for the teeth outside of left
and right bounds,
set keyframe as goalXform at frame
2432
set Collision Manager
2434
do collision detect
2436
calculate Equal Path of the inbetween teeth
2438
Adjust Frame and set new_end
2440
2442
return

FIG. 20B

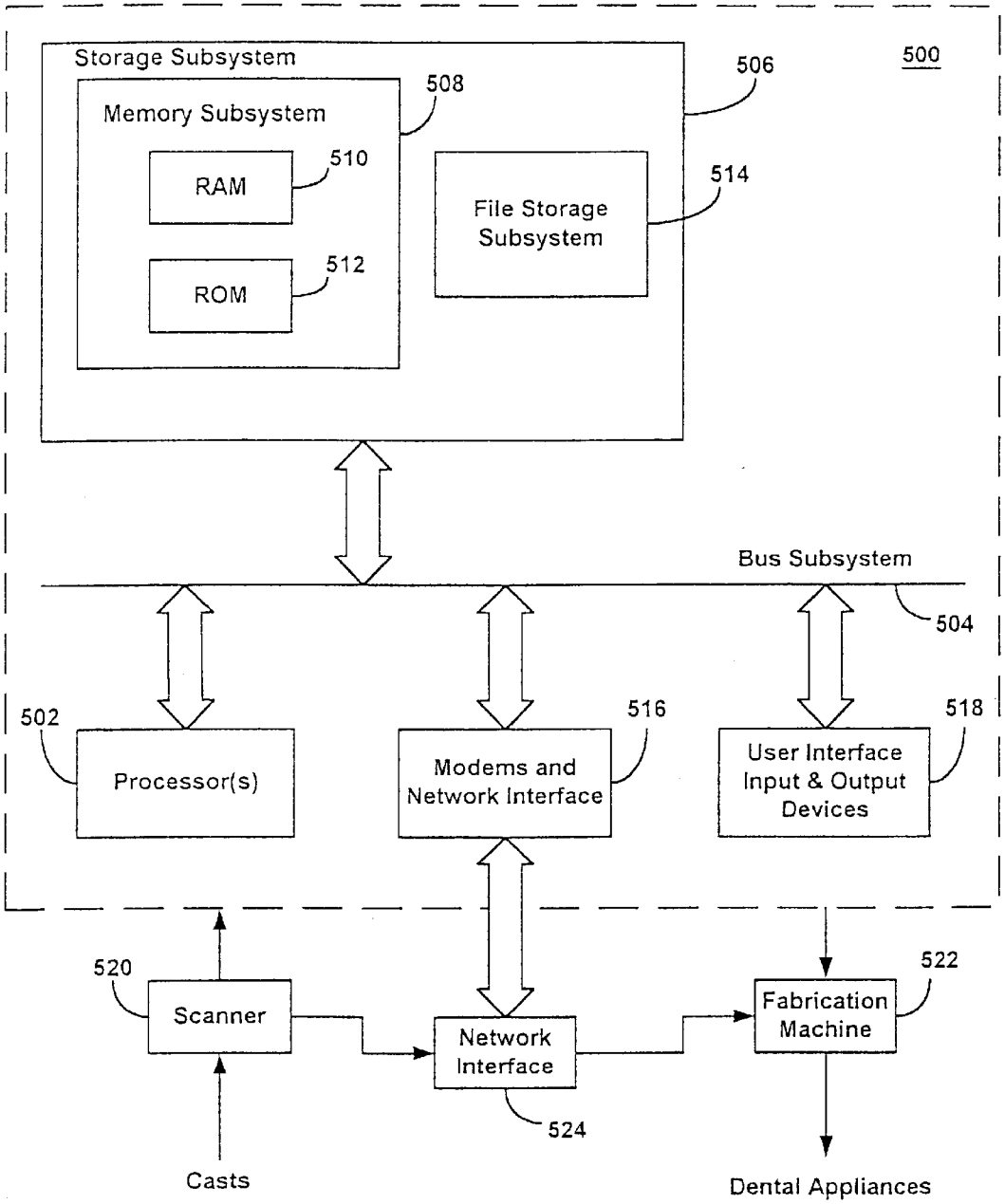
Storage Subsystem
Memory Subsystem
RAM
ROM
File Storage Subsystem
500
506
508
510
512
514
Bus Subsystem
504
502
Processor(s)
516
Modems and Network Interface
518
User Interface Input & Output Devices
520
Scanner
Network Interface
524
522
Fabrication Machine
Casts
Dental Appliances

FIG. 21

TOOTH PATH TREATMENT PLAN

This application a continuation-in-part of application Ser. No. 09/313,289, filed on May 13, 1999, now U.S. Pat. No. 6,318,994 the full disclosure of which is incorporated herein by reference and is related to two U.S. patent applications which are: Ser. No. 09/169,036, now U.S. Pat. No. 6,450,807 entitled "System and Method for Repositioning Teeth;" and Ser. No. 09/169,034, now U.S. Pat. No. 6,471,511 entitled "Defining Tooth-Moving Appliances Computationally." Both of these applications were filed Oct. 8, 1998, and the full disclosures of which are incorporated herein by reference.

BACKGROUND

1. Field of the Invention

The invention relates generally to the field of orthodontics and, more particularly, to computer-automated development of an orthodontic treatment plan and appliance.

2. Description of the Background Art

Repositioning teeth for aesthetic or other reasons is accomplished conventionally by wearing what are commonly referred to as "braces." Braces comprise a variety of appliances such as brackets, archwires, ligatures, and O-rings. Attaching the appliances to a patient's teeth is a tedious and time-consuming enterprise requiring many meetings with the treating orthodontist. Consequently, conventional orthodontic treatment limits an orthodontist's patient capacity and makes orthodontic treatment quite expensive. As such, the use of conventional braces is a tedious and time consuming process and requires many visits to the orthodontist's office. Moreover, from the patient's perspective, the use of braces is unsightly, uncomfortable, presents a risk of infection, and makes brushing, flossing, and other dental hygiene procedures difficult.

Tooth positioners for finishing orthodontic treatment are described by Kesling in the *Am. J. Orthod. Oral. Surg.* 31:297–304 (1945) and 32:285–293 (1946). The use of silicone positioners for the comprehensive orthodontic realignment of a patient's teeth is described in Warunek et al. (1989) *J. Clin. Orthod.* 23:694–700. Clear plastic retainers for finishing and maintaining tooth positions are commercially available from Raintree Essix, Inc., New Orleans, La. 70125, and Tru-Tain Plastics, Rochester, Minn. 55902. The manufacture of orthodontic positioners is described in U.S. Pat. Nos. 5,186,623; 5,059,118; 5,055,039; 5,035,613; 4,856,991; 4,798,534; and 4,755,139.

Other publications describing the fabrication and use of dental positioners include Kleemann and Janssen (1996) *J. Clin. Orthodon.* 30:673–680; Cureton (1996) *J. Clin. Orthodon.* 30:390–395; Chiappone (1980) *J. Clin. Orthodon.* 14:121–133; Shilliday (1971) *Am. J. Orthodontics* 59:596–599; Wells (1970) *Am. J. Orthodontics* 58:351–366; and Cottingham (1969) *Am. J. Orthodontics* 55:23–31.

Kuroda et al. (1996) *Am. J. Orthodontics* 110:365–369 describes a method for laser scanning a plaster dental cast to produce a digital image of the cast. See also U.S. Pat. No. 5,605,459.

U.S. Pat. Nos. 5,533,895; 5,474,448; 5,454,717; 5,447,432; 5,431,562; 5,395,238; 5,368,478; and 5,139,419, assigned to Ormco Corporation, describe methods for manipulating digital images of teeth for designing orthodontic appliances.

U.S. Pat. No. 5,011,405 describes a method for digitally imaging a tooth and determining optimum bracket positioning for orthodontic treatment. Laser scanning of a molded tooth to produce a three-dimensional model is described in U.S. Pat. No. 5,338,198. U.S. Pat. No. 5,452,219 describes a method for laser scanning a tooth model and milling a tooth mold. Digital computer manipulation of tooth contours is described in U.S. Pat. Nos. 5,607,305 and 5,587,912. Computerized digital imaging of the jaw is described in U.S. Pat. Nos. 5,342,202 and 5,340,309. Other patents of interest include U.S. Pat. Nos. 5,549,476; 5,382,164; 5,273,429; 4,936,862; 3,860,803; 3,660,900; 5,645,421; 5,055,039; 4,798,534; 4,856,991; 5,035,613; 5,059,118; 5,186,623; and 4,755,139.

SUMMARY

In one aspect, a computer-implemented method to prepare a malocclusion treatment plan includes selecting a tooth treatment pattern from a library of predetermined tooth treatment patterns; and generating the malocclusion treatment plan implementing the selected tooth treatment pattern.

Implementations of the above aspect may include one or more of the following. The generating the malocclusion treatment plan includes determining one or more tooth paths based on the selected tooth treatment pattern. The treatment pattern can be selected from one or more clinical treatment prescriptions. The clinical treatment prescription includes at least one of the following: space closure, reproximation, dental expansion, flaring, distalization, and lower incisor extraction. The determining a tooth path includes finding a collision free shortest path between an initial position and a final position for one or more teeth. The generating the malocclusion treatment plan includes specifying a series of treatment stages for one or more teeth. The method can include dividing a path for one or more teeth into the series of stages while keeping the movement of teeth in each stage below a predetermined range. The method can include generating an appliance for each treatment stage. The appliance can be either a removable appliance or a fixed appliance. The method can include generating a three-dimensional model for the teeth for each treatment stage. The method also can include generating dental diagnostic information from the three-dimensional model. Interproximal reduction, tooth size discrepancy information, and Bolton information, among others can be generated from the 3D model. The library of treatment patterns includes at least one or more of the following: all equal movement pattern, A-shaped movement pattern, V-shaped movement pattern, M-shaped movement pattern, W-shaped movement pattern, symmetric staircase pattern, asymmetric staircase pattern, and equal equal movement pattern. For the all equal movement pattern, the method includes subdividing paths while satisfying one or more constraints. The constraint can be minimizing tooth oscillation and tooth movement distance. For the equal equal pattern, the method includes dividing the teeth into a prestage movement group and a post stage movement group; and applying the all equal movement to the prestage movement group and subsequently applying the all equal movement to the prestage movement group. For the A-shaped movement pattern, the method includes sequentially moving each tooth from an incisor tooth toward a molar tooth. For the V-shaped movement pattern, the method includes sequentially moving each tooth from a molar tooth toward an incisor tooth.

In another aspect, a computer-implemented method prepares a malocclusion treatment plan by: selecting one tooth treatment pattern from a library of predetermined tooth treatment patterns; generating the malocclusion treatment plan in accordance with the selected treatment pattern; and

producing a plurality of data sets representing a series of successive tooth arrangements progressing from a first tooth arrangement to a second tooth arrangement. Implementations of this aspect may include generating an appliance for each tooth arrangement.

In another aspect, a computer-readable medium executable by a computer to prepare a malocclusion treatment plan includes code to select one tooth treatment pattern from a library of predetermined tooth treatment patterns; and code to generate the malocclusion treatment plan in accordance with the selected treatment pattern.

Implementation of this aspect may include one or more of the following. The medium can include code to fabricate an appliance for each tooth arrangement. The code to fabricate appliances can include code to control a fabrication machine to produce successive positive models of the tooth arrangements; and code to produce the appliance as a negative of the tooth model. The code to control a fabrication machine includes code to provide a volume of non-hardened polymeric resin; and code to scan a laser to selectively harden a resin to produce the positive model. The medium can include code to control a fabrication machine to produce successive appliances for the tooth arrangements.

In yet another aspect, a computer-implemented method to automatically stage a series of tooth movements, by selecting one teeth treatment pattern from a plurality of predetermined teeth treatment patterns; generating a treatment plan for the teeth in accordance with the selected move pattern by: generating a treatment plan with a tooth path for each tooth; and determining a series of treatment stages for the teeth; and controlling a fabrication machine to produce successive appliances for the tooth arrangements.

Implementations of this aspect may include generating an appliance as a negative or a positive of a dental model.

In another aspect, an appliance to correct malocclusion, the appliance formed using computer readable code controlling a fabrication machine, the code comprising instructions to: select one teeth treatment pattern from a plurality of predetermined teeth treatment patterns; generate a treatment plan for the teeth in accordance with the selected move pattern by: generate a treatment plan with a tooth path for each tooth; and determine a series of treatment stages for the teeth; and control the fabrication machine to produce successive appliances for the tooth arrangements.

In another aspect, a computer system to prepare a malocclusion treatment plan includes a processor; a display coupled to the processor; and a data storage device coupled to the processor and containing code to select a tooth treatment pattern from a library of predetermined tooth treatment patterns; and code to generate the malocclusion treatment plan implementing the selected tooth treatment pattern.

In yet another aspect, a computer system to prepare a malocclusion treatment plan includes means for selecting a tooth treatment pattern from a library of predetermined tooth treatment patterns; and means for generating the malocclusion treatment plan implementing the selected tooth treatment pattern.

Yet other implementations of the above aspects can include one or more of the following. The constraints relates to teeth crowding, teeth spacing, teeth extraction, teeth stripping, teeth rotation, and teeth movement. The teeth can be rotated approximately five and ten degrees (per stage) and can be incrementally moved in one or more stages (per stage), each stage moving each tooth approximately 0.2 mm to approximately 0.4 mm. The constraints can be stored in an array with one dimension of the array identifying each stage in the teeth movement. The treatment paths can include determining the minimum amount of transformation required to move each tooth from the initial position to the final position and creating each treatment path to require only the minimum amount of movement. Additionally, intermediate positions can be generated for at least one tooth between which the tooth undergoes translational movements of equal sizes. Further, intermediate positions can be generated for at least one tooth between which the tooth undergoes translational movements of unequal sizes. A set of rules can be applied to detect any collisions that will occur as the patient's teeth move along the treatment paths. Collisions can be detected by calculating distances between a first tooth and a second tooth by establishing a neutral projection plane between the first tooth and the second tooth, establishing a z-axis that is normal to the plane and that has a positive direction and a negative direction from each of a set of base points on the projection plane, computing a pair of signed distances comprising a first signed distance to the first tooth and a second signed distance to the second tooth, the signed distances being measured on a line through the base points and parallel to the z-axis, and determining that a collision occurs if any of the pair of signed distances indicates a collision. Where the positive direction for the first distance is opposite the positive direction for the second distance, a collision is detected if the sum of any pair of signed distances is less than or equal to zero. Information indicating whether the patient's teeth are following the treatment paths can be used to revise the treatment paths. More than one candidate treatment path for each tooth can be generated and graphically displayed for each candidate treatment path to a human user for selection. A set of rules can be applied to detect any collisions that will occur as the patient's teeth move along the treatment paths. Collisions can be detected by calculating distances between a first tooth and a second tooth by: establishing a neutral projection plane between the first tooth and the second tooth, establishing a z-axis that is normal to the plane and that has a positive direction and a negative direction from each of a set of base points on the projection plane, computing a pair of signed distances comprising a first signed distance to the first tooth and a second signed distance to the second tooth, the signed distances being measured on a line through the base points and parallel to the z-axis, and determining that a collision occurs if any of the pair of signed distances indicates a collision. A collision can also be detected if the sum of any pair of signed distances is less than or equal to zero. A set of rules can be applied to detect any improper bite occlusions that will occur as the patient's teeth move along the treatment paths. A value for a malocclusion index can be computed and the value displayed to a human user. The treatment paths can be generated by receiving data indicating restraints on movement of the patient's teeth and applying the data to generate the treatment paths. A three-dimensional (3D) graphical representation of the teeth at the positions corresponding to a selected data set can be rendered. The graphical representation of the teeth to provide a visual display of the movement of the teeth along the treatment paths can be generated. A graphical interface, with components representing the control buttons on a videocassette recorder, which a human user can manipulate to control the animation, can be generated. A portion of the data in the selected data set may be used to render the graphical representation of the teeth. A level-of-detail compression can be applied to the data set to render the graphical representation of the teeth. A human user can modify the

graphical representation of the teeth and the selected data set can be modified in response to the user's request. A human user can select a tooth in the graphical representation and, in response, information about the tooth can be displayed. The information can relate to the motion that the tooth will experience while moving along the treatment path. The information can also indicate a linear distance between the tooth and another tooth selected in the graphical representation. The teeth can be rendered at a selected one of multiple viewing orthodontic-specific viewing angles. A user interface through which a human user can provide text-based comments after viewing the graphical representation of the patient's teeth can be provided. The graphical representation data can be downloaded to a remote computer at which a human view wishes to view the graphical representation. An input signal from a 3D gyroscopic input device controlled by a human user can be applied to alter the orientation of the teeth in the graphical representation.

Advantages of the system may include one or more of the following. The system facilitates automated staging after final setup. The system eliminates manual staging, saves time and is convenient to use. An easy to use graphical user interface supports the entry of treatment planning requirements such as particular staging pattern(s), anchorage requirement(s) (low, mid, high), and the minimum allowable tooth movements.

DESCRIPTION OF THE DRAWINGS

FIG. **1** is an elevational diagram showing the anatomical relationship of the jaws of a patient.

FIG. **2**A illustrates in more detail the patient's lower jaw and provides a general indication of how teeth may be moved by the methods and apparatus of the present invention.

FIG. **2**B illustrates a single tooth from FIG. **2**A and defines how tooth movement distances are determined.

FIG. **2**C illustrates the jaw of FIG. **2**A together with an incremental position adjustment appliance which has been configured according to the methods and apparatus of the present invention.

FIG. **3** is a block diagram illustrating a process for producing incremental position adjustment appliances.

FIG. **4** is a flow chart illustrating a process for optimizing a final placement of the patient's teeth.

FIG. **5** is a flow chart illustrating the positioning of teeth at various steps of an orthodontic treatment plan.

FIG. **6** is a flow chart of a process for determining a tooth's path among intermediate positions during an orthodontic treatment plan.

FIG. **7** is a flow chart of a process for optimizing the path of a tooth from an initial position to a final position during an orthodontic treatment plan.

FIG. **8** is a diagram illustrating a buffering technique for use in a collision detection algorithm.

FIG. **9** is a flow chart for a collision detection technique.

FIG. **10** shows an exemplary X-type movement.

FIG. **11** shows an exemplary A-type movement.

FIG. **12** shows an exemplary V-type movement.

FIG. **13** shows an exemplary XX-type movement.

FIG. **14** shows an exemplary process to determine tooth path.

FIG. **15** shows an exemplary process to determine an all-equal path.

FIG. **16** shows an exemplary process to recursively determine frame movement as used in FIG. **15**.

FIG. **17** shows an exemplary process to determine mid-frame movements as used in FIG. **16**.

FIG. **18** shows an exemplary process to determine an A-shape path.

FIG. **19** shows an exemplary process to determine an equal path.

FIGS. **20**A-**20**B show an exemplary process to determine a V-shape path.

FIG. **21** is a block diagram illustrating a system for generating appliances in accordance with the present invention.

DESCRIPTION

FIG. **1** shows a skull **10** with an upper jaw bone **22** and a lower jaw bone **20**. The lower jaw bone **20** hinges at a joint **30** to the skull **10**. The joint **30** is called a temporomandibular joint (TMJ). The upper jaw bone **22** is associated with an upper jaw **101**, while the lower jaw bone **20** is associated with a lower jaw **100**.

A computer model of the jaws **100** and **101** is generated, and a computer simulation models interactions among the teeth on the jaws **100** and **101**. The computer simulation allows the system to focus on motions involving contacts between teeth mounted on the jaws. The computer simulation allows the system to render realistic jaw movements which are physically correct when the jaws **100** and **101** contact each other. The model of the jaw places the individual teeth in a treated position. Further, the model can be used to simulate jaw movements including protrusive motions, lateral motions, and "tooth guided" motions where the path of the lower jaw **100** is guided by teeth contacts rather than by anatomical limits of the jaws **100** and **101**. Motions are applied to one jaw, but may also be applied to both jaws. Based on the occlusion determination, the final position of the teeth can be ascertained.

Referring now to FIG. **2**A, the lower jaw **100** includes a plurality of teeth **102**, for example. At least some of these teeth may be moved from an initial tooth arrangement to a final tooth arrangement. As a frame of reference describing how a tooth may be moved, an arbitrary centerline (CL) may be drawn through the tooth **102**. With reference to this centerline (CL), each tooth may be moved in orthogonal directions represented by axes **104**, **106**, and **108** (where **104** is the centerline). The centerline may be rotated about the axis **108** (root angulation) and the axis **104** (torque) as indicated by arrows **10** and **112**, respectively. Additionally, the tooth may be rotated about the centerline, as represented by an arrow **114**. Thus, all possible free-form motions of the tooth can be performed.

FIG. **2**B shows how the magnitude of any tooth movement may be defined in terms of a maximum linear translation of any point P on a tooth **102**. Each point P_1 will undergo a cumulative translation as that tooth is moved in any of the orthogonal or rotational directions defined in FIG. **2**A. That is, while the point will usually follow a nonlinear path, there is a linear distance between any point in the tooth when determined at any two times during the treatment. Thus, an arbitrary point P_1 may in fact undergo a true side-to-side translation as indicated by arrow d_1, while a second arbitration point P_2 may travel along an arcuate path, resulting in a final translation d_2. Many aspects of the present invention are defined in terms of the maximum permissible movement of a point P_1 induced on any particular tooth. Such maximum tooth movement, in turn, is defined as the maximum linear translation of that point P_1 on the tooth which undergoes the maximum movement for that tooth in any treatment step.

FIG. 2C shows one adjustment appliance **111** which is worn by the patient in order to achieve an incremental repositioning of individual teeth in the jaw as described generally above. The appliance is a polymeric shell having a teeth receiving cavity. This is described in U.S. application Ser. No. 09/169,036, filed Oct. 8, 1998, now U.S. Pat. No. 6,450,807 which claims priority from U.S. application Ser. No. 08/947,080, filed Oct. 8, 1997, now U.S. Pat. No. 5,975,893 which in turn claims priority from provisional application No. 06/050,352, filed Jun. 20, 1997 (collectively the "prior applications"), the full disclosures of which are incorporated by reference.

As set forth in the prior applications, each polymeric shell may be configured so that its tooth receiving cavity has a geometry corresponding to an intermediate or final tooth arrangement intended for the appliance. The patient's teeth are repositioned from their initial tooth arrangement to a final tooth arrangement by placing a series of incremental position adjustment appliances over the patient's teeth. The adjustment appliances are generated at the beginning of the treatment, and the patient wears each appliance until the pressure of each appliance on the teeth can no longer be felt. At that point, the patient replaces the current adjustment appliance with the next adjustment appliance in the series until no more appliance remains. Conveniently, the appliances are generally not affixed to the teeth and the patient may place and replace the appliances at any time during the procedure. The final appliance or several appliances in the series may have a geometry or geometries selected to overcorrect the tooth arrangement, i.e., have a geometry which would (if fully achieved) move individual teeth beyond the tooth arrangement which has been selected as the "final." Such overcorrection may be desirable in order to offset potential relapse after the repositioning method has been terminated, i.e., to permit some movement of individual teeth back toward their precorrected positions. Overcorrection may also be beneficial to speed the rate of correction, i.e., by having an appliance with a geometry that is positioned beyond a desired intermediate or final position, the individual teeth will be shifted toward the position at a greater rate. In such cases, the use of an appliance can be terminated before the teeth reach the positions defined by the appliance.

The polymeric shell **111** can fit over all teeth present in the upper or lower jaw. Often, only certain one(s) of the teeth will be repositioned while others of the teeth will provide a base or an anchor region for holding the appliance **111** in place as the appliance **111** applies a resilient repositioning force against the tooth or teeth to be repositioned. In complex cases, however, multiple teeth may be repositioned at some point during the treatment. In such cases, the teeth which are moved can also serve as a base or anchor region for holding the repositioning appliance.

The polymeric appliance **111** of FIG. 2C may be formed from a thin sheet of a suitable elastomeric polymer, such as Tru-Tain 0.03 in, thermal forming dental material, available from Tru-Tain Plastics, Rochester, Minn. Usually, no wires or other means will be provided for holding the appliance in place over the teeth. In some cases, however, it will be desirable or necessary to provide individual anchors on teeth with corresponding receptacles or apertures in the appliance **100** so that the appliance can apply an upward force on the tooth which would not be possible in the absence of such an anchor.

FIG. **3** shows a process **200** for producing the incremental position adjustment appliances for subsequent use by a patient to reposition the patient's teeth. As a first step, an initial digital data set (IDDS) representing an initial tooth arrangement is obtained (step **202**).

In some implementations, the IDDS includes data obtained by scanning a physical model of the patient's teeth, such as by scanning a positive impression or a negative impression of the patient's teeth with a laser scanner or a destructive scanner. The positive and negative impression may be scanned while interlocked with each other to provide more accurate data. The initial digital data set also may include volume image data of the patient's teeth, which the computer can convert into a 3D geometric model of the tooth surfaces, for example using a conventional marching cubes technique. In some embodiments, the individual tooth models include data representing hidden tooth surfaces, such as roots imaged through x-ray, CT scan, or MRI techniques. Tooth roots and hidden surfaces also can be extrapolated from the visible surfaces of the patient's teeth. The IDDS is then manipulated using a computer having a suitable graphical user interface (GUI) and software appropriate for viewing and modifying the images. More specific aspects of this process will be described in detail below.

Individual tooth and other components may be segmented or isolated in the model to permit their individual repositioning or removal from the digital model. After segmenting or isolating the components, the user will often reposition the tooth in the model by following a prescription or other written specification provided by the treating professional. Alternatively, the user may reposition one or more teeth based on a visual appearance or based on rules and algorithms programmed into the computer. Once the user is satisfied, the final teeth arrangement is incorporated into a final digital data set (FDDS) (step **204**).

In step **204**, final positions for the upper and lower teeth in a masticatory system of a patient are determined by generating a computer representation of the masticatory system. An occlusion of the upper and lower teeth is computed from the computer representation; and a functional occlusion is computed based on interactions in the computer representation of the masticatory system. The occlusion may be determined by generating a set of ideal models of the teeth. Each ideal model in the set of ideal models is an abstract model of if idealized teeth placement which is customized to the patient's teeth, as discussed below. After applying the ideal model to the computer representation, and the position of the teeth is optimized to fit the ideal model. The ideal model may be specified by one or more arch forms, or may be specified using various features associated with the teeth.

The FDDS is created by following the orthodontists' prescription to move the teeth in the model to their final positions. In one embodiment, the prescription is entered into a computer, which automatically computes the final positions of the teeth. In alternative other embodiments, a user moves the teeth into their final positions by independently manipulating one or more teeth while satisfying the constraints of the prescription. Various combinations of the above described techniques may also be used to arrive at the final tooth positions.

One method for creating the FDDS involves moving the teeth in a specified sequence. First, the centers of each tooth model may be aligned using a number of methods. One method is a standard arch. Then, the teeth models are rotated until their roots are in the proper vertical position. Next, the teeth models are rotated around their vertical axis into the proper orientation. The teeth models are then observed from the side, and translated vertically into their proper vertical

position. Finally, the two arches are placed together, and the teeth models moved slightly to ensure that the upper and lower arches properly mesh together. The meshing of the upper and lower arches together is visualized using a collision detection process to highlight the contacting points of the teeth.

Based on both the IDDS and the FDDS, a plurality of intermediate digital data sets (INTDDSs) are defined to correspond to incrementally adjusted appliances (step **206**). Finally, a set of incremental position adjustment appliances are produced based on the INTDDs and the FDDS (step **208**).

After the teeth and other components have been placed or removed to produce a model of the final tooth arrangement, it is necessary to generate a treatment plan which produces a series of INTDDS's and FDDS as described previously. To produce these data sets, it is necessary to define or map the movement of selected individual teeth from the initial position to the final position over a series of successive steps. In addition, it may be necessary to add other features to the data sets in order to produce desired features in the treatment appliances. For example, it may be desirable to add wax patches to the image in order to define cavities or recesses for particular purposes, such as to maintain a space between the appliance and particular regions of the teeth or jaw in order to reduce soreness of the gums, avoid periodontal problems, allow for a cap, and the like. Additionally, it will often be necessary to provide a receptacle or aperture intended to accommodate an anchor which is to be placed on a tooth in order to permit the tooth to be manipulated in a manner that requires the anchor, e.g., to be lifted relative to the jaw.

In the manner discussed above, information on how the patient's teeth should move from an initial, untreated state to a final, treated state is used to generate a prescription, or treatment plan. The prescription takes into consideration the following:

1. Initial Position: a detailed description of the initial maloclussion.
2. Final Position: a detailed description of treatment goals for the patient.
3. Movement: a detailed, sequential description of how the patient's teeth should be moved in order to accomplish the desired goals for final placement.

1. Initial Position

The initial position section describes in detail the patient's malocclusion. Considerations include:

1. Crowding
2. Spacing
3. Extraction
4. Stripping

Additionally, considerations for the Final Position discussed below may also be used.

2. Final Position

This section is a detailed description of final position objectives and treatment goals—both static and functional. These considerations include

1. Overjet
2. Overbite
3. Midlines
4. Functional Occlusion
5. Classification
6. Torque
7. Tip
8. Rotations
9. Lingual/Palatal
10. Buccal/Facial
11. Intercuspation
12. Initial Position of the Occlusion—CR/CO Considerations
13. Interarch Issues
14. Intra-arch Issues
15. Space

3. Movement

The movement section specifies an order in moving the patient's teeth in order to achieve the goals for final placement. In this process, the orthodontist has precise control over which teeth the orthodontist wants to move and which teeth to anchor (not move), thereby breaking the treatment down into discrete stages. The movement order information is captured for both the upper and the lower arches.

At each stage, major and minor tooth movements are analyzed. Major movements usually occur at the beginning of a tooth's movement. Minor movements usually occur as "detailing" movements that occur toward the end of treatment. On average, each aligner should be able to accomplish move about 0.25–0.33 mm and to rotate about 5–10 degrees within a 2-week period. However, biologic variability, patient and clinician preferences are also taken into consideration. Additionally, various movements such as distalization, tip, and torque can have separate parameters.

Based on these considerations, a plan is generated for moving teeth. FIG. **4** illustrates a process **300** for generating tooth movements while minimizing teeth indices, as discussed in copending U.S. application Ser. No. 09/169,034, now U.S. Pat. No. 6,471,511 the content of which is hereby incorporated by reference. First, the process **300** automatically or, with human assistance, identifies various features associated with each tooth to arrive at a model of the teeth (step **302**). An ideal model set of teeth is then generated either from casts of the patient's teeth or from patients with a known acceptable occlusion (step **303**).

From step **302**, the process **300** positions the model of the teeth in its approximate final position based on a correspondence of features to the ideal model (step **304**). In that step, each tooth model is moved so that its features are aligned to the features of a corresponding tooth in the ideal model. The features may be based on cusps, fossae, ridges, distance-based metrics, or shape-based metrics. Shape-based metrics may be expressed as a function of the patient's arches, among others.

Next, the process **300** computes an orthodontic/occlusion index (step **306**). One index which may be used is the PAR (Peer Assessment Rating) index. In addition to PAR, other metrics such as shape-based metrics or distance-based metrics may be used. The PAR index identifies how far a tooth is from a good occlusion. A score is assigned to various occlusal traits which make up a malocclusion. The individual scores are summed to obtain an overall total, representing the degree a case deviates from normal alignment and occlusion. Normal occlusion and alignment is defined as all anatomical contact points being adjacent, with a good intercuspal mesh between upper and lower buccal teeth, and with nonexcessive overjet and overbite.

In PAR, a score of zero would indicate good alignment, and higher scores would indicate increased levels of irregularity. The overall score is recorded on pre- and posttreatment dental casts. The difference between these scores represents the degree of improvement as a result of orthodontic intervention and active treatment. The eleven com-

ponents of the PAR Index are: upper right segment; upper anterior segment; upper left segment; lower right segment; lower anterior segment; lower left segment; right buccal occlusion; overjet; overbite; centerline; and left buccal occlusion. In addition to the PAR index, other indices may be based on distances of the features on the tooth from their ideal positions or ideal shapes.

From step **306**, the process **300** determines whether additional index-reducing movements are possible (step **308**). Here, all possible movements are attempted, including small movements along each major axis as well as small movements with minor rotations. An index value is computed after each small movement and the movement with the best result is selected. In this context, the best result is the result that minimizes one or more metrics such as PAR-based metrics, shape-based metrics or distance-based metrics. The optimization may use a number of techniques, including simulated annealing technique, hill climbing technique, best-first technique, Powell method, and heuristics technique, among others. Simulated annealing techniques may be used where the index is temporarily increased so that another path in the search space with a lower minimum may be found. However, by starting with the teeth in an almost ideal position, any decrease in the index should converge to the best result.

In step **308**, if the index can be optimized by moving the tooth, incremental indexreducing movement inputs are added (step **310**) and the process loops back to step **306** to continue computing the orthodontic/occlusion index. Alternatively, in the event that the index cannot be further optimized, the process **300** exits (step **312**).

In generating the index reducing movements of step **310**, the process considers a set of movement constraints which affect the tooth path movement plan. In one embodiment, movement information for about fifty discrete stages is specified. Each stage represents a single aligner, which is expected to be replaced about every two weeks. Thus, each stage represents about a two-week period. In one embodiment, a two-dimensional array is used to track specific movements for each tooth at a specific period of time. One dimension of this array relates to teeth identification, while the second dimension relates to the time periods or stages. Considerations on when a tooth may be moved include the following:

1. Mesial
2. Distal
3. Buccal/Facial
4. Lingual/Palatial
5. Expansion
6. Space
7. Teeth moving past each other
8. Intrusion
9. Extrusion
10. Rotations
11. Which teeth are moving when?
12. Which teeth move first?
13. Which teeth need to be moved before others are moved?
14. What movements are easily done?
15. Anchorage
16. The orthodontist user's philosophy on distalization of molars and minor expansion in adults

In one embodiment, the user can change the number of desired treatment stages from the initial to the target states of the teeth. Any component that is not moved is assumed to remain stationary, and thus its final position is assumed to be the same as the initial position (likewise for all intermediate positions, unless one or more key frames are defined for that component).

The user may also specify "key frames" by selecting an intermediate state and making changes to component position(s). In some embodiments, unless instructed otherwise, the software automatically linearly interpolates between all user-specified positions (including the initial position, all key frame positions, and the target position). For example, if only a final position is defined for a particular component, each subsequent stage after the initial stage will simply show the component an equal linear distance and rotation (specified by a quatemion) closer to the final position. If the user specifies two key frames for that component, the component will "move" linearly from the initial position through different stages to the position defined by the first key frame. It will then move, possibly in a different direction, linearly to the position defined by the second key frame. Finally, it will move, possibly in yet a different direction, linearly to the target position.

These operations may be done independently to each component, so that a key frame for one component will not affect another component, unless the other component is also moved by the user in that key frame. One component may accelerate along a curve between one pair of stages (e.g., stages 3 and 8 in a treatment plan having that many stages), while another moves linearly between another pair of stages (e.g., stages 1 to 5), and then changes direction suddenly and slows down along a linear path to a later stage (e.g., stage 10). This flexibility allows a great deal of freedom in planning a patient's treatment.

In some implementations, non-linear interpolation is used instead of or in addition to linear interpolation to construct a treatment path among key frames. In general, a non-linear path, such as a spline curve, created to fit among selected points is shorter than a path formed from straight line segments connecting the points. A "treatment path" describes the transformation curve applied to a particular tooth to move the tooth from its initial position to its final position. A typical treatment path includes some combination of rotational and translational movement of the corresponding tooth, as described above.

FIG. **5** shows step **310** in more detail. Initially, a first tooth is selected (step **311**). Next, constraints associated with the tooth is retrieved for the current stage or period (step **312**). Thus, for the embodiment which keeps a two-dimensional array to track specific movements for each tooth at a specific period of time, the tooth identification and the time period or stage information are used to index into the array to retrieve the constraints associated with the current tooth.

Next, a tooth movement plan which takes into consideration the constraints is generated (step **313**). The process of FIG. **5** then detects whether the planned movements would cause collisions with neighboring teeth (step **314**). The collision detection process determines if any of the geometries describing the tooth surfaces intersect. If there are no obstructions, the space is considered free; otherwise it is obstructed. Suitable collision detection algorithms are discussed in more detail below.

If a collision occurs, a "push" vector is created to shift the path of the planned movement (step **315**). Based on the push vector, the current tooth "bounces" from the collision and a new tooth movement is generated (step **316**). From step **314** or **316**, the movement of the current tooth is finalized.

Next, the process of FIG. **5** determines whether tooth movement plans have been generated for all teeth (step **317**),

and if so, the process exits. Alternatively, the next tooth in the treatment plan is selected (**318**), and the process of FIG. **5** loops back to step **312** to continue generating tooth movement plans.

The resulting final path consists of a series of vectors, each of which represents a group of values of the interpolation parameters of the translational and rotational components of the transformations of the moving teeth. Taken together, these constitute a schedule of tooth movement which avoids tooth-to-tooth interferences. Pseudo code for generating the tooth path in view of specified constraints is shown below:

```
For each tooth path model
  For each path increment
    Load constrains associated with each tooth
    Move the tooth in view of constraint
    Perform tooth collision detection
    If collision occurs, for associated colliding teeth
      create "push" vector
    and "bounce" back from collision to avoid collision
  end for
end tooth path model
```

FIG. **6** is a flow chart of a computer-implemented process for generating non-linear treatment paths along which a patient's teeth will travel during treatment. The non-linear paths usually are generated automatically by computer program, in some cases with human assistance. The program receives as input the initial and final positions of the patient's teeth and uses this information to select intermediate positions for each tooth to be moved (step **1600**). The program then applies a conventional spline curve calculation algorithm to create a spline curve connecting each tooth's initial position to the tooth's final position (step **1602**). In many situations, the curve is constrained to follow the shortest path between the intermediate positions. The program then samples each spline curve between the intermediate positions (step **1604**) and applies the collision detection algorithm to the samples (step **1606**). If any collisions are detected, the program alters the path of at least one tooth in each colliding pair by selecting a new position for one of the intermediate steps (step **1608**) and creating a new spline curve (**1602**). The program then samples the new path (**1604**) and again applies the collision detection algorithm (**1606**). The program continues in this manner until no collisions are detected. The routine then stores the paths, e.g., by saving the coordinates of each point in the tooth at each position on the path in an electronic storage device, such as a hard disk (step **1610**).

The path-generating program, whether using linear or non-linear interpolation, selects the treatment positions so that the tooth's treatment path has approximately equal lengths between each adjacent pair of treatment steps. The program also avoids treatment positions that force portions of a tooth to move with more than a given maximum velocity.

Orthodontic constraints that may be applied by the path-generating program include the minimum and maximum distances allowed between adjacent teeth at any given time, the maximum linear or rotational velocity at which a tooth should move, the maximum distance over which a tooth should move between treatment steps, the shapes of the teeth, the characteristics of the tissue and bone surrounding the teeth (e.g., ankylose teeth cannot move at all), and the characteristics of the aligner material (e.g., the maximum distance that the aligner can move a given tooth over a given period of time). For example, the patient's age and jaw bone density may dictate certain "safe limits" beyond which the patient's teeth should not forced to move. In general, a gap between two adjacent, relatively vertical and non-tipped central and lateral teeth should not close by more than about 1 mm every seven weeks. The material properties of the orthodontic appliance also limit the amount by which the appliance can move a tooth. For example, conventional retainer materials usually limit individual tooth movement to approximately 0.5 mm between treatment steps. The constraints have default values that apply unless patient-specific values are calculated or provided by a user. Constraint information is available from a variety of sources, including text books and treating clinicians.

In selecting the intermediate positions for each tooth, the path-generating program invokes the collision detection program to determine whether collisions will occur along the chosen paths. The program also inspects the patient's occlusion at each treatment step along the path to ensure that the teeth align to form an acceptable bite throughout the course of treatment. If collisions or an unacceptable bite will occur, or if a required constraint cannot be satisfied, the program iteratively alters the offending tooth path until all conditions are met. The virtual articulator described above is one tool for testing bite occlusion of the intermediate treatment positions.

As shown in FIG. **7**, once the path-generating program has established collision-free paths for each tooth to be moved, the program calls an optimization routine that attempts to make the transformation curve for each tooth between the initial and final positions more linear. The routine begins by sampling each treatment path at points between treatment steps (step **1702**), e.g., by placing two sample points between each treatment step, and calculating for each tooth a more linear treatment path that fits among the sample points (step **1704**). The routine then applies the collision detection algorithm to determine whether collisions result from the altered paths (step **1706**). If so, the routine resamples the altered paths (step **1708**) and then constructs for each tooth an alternative path among the samples (step **1710**). The routine continues in this manner until no collisions occur (step **1712**).

In some embodiments, as alluded to above, the software automatically computes the treatment path, based upon the IDDS and the FDDS. This is accomplished using a path scheduling algorithm which determines the rate at which each component, i.e., each tooth, moves along the path from the initial position to the final position. The path scheduling algorithm determines the treatment path while avoiding "round-tripping," i.e., while avoiding moving a tooth along a distance greater than absolutely necessary to straighten the teeth. Such motion is highly undesirable, and has potential negative effects on the patient.

One implementation of the path scheduling algorithm attempts first to schedule or stage the movements of the teeth by constraining each tooth to the most linear treatment path between the initial and final positions. The algorithm then resorts to less direct routes to the final positions only if collisions will occur between teeth along the linear paths or if mandatory constraints will be violated. The algorithm applies one of the path-generation processes described above, if necessary, to construct a path for which the intermediate treatment steps do not lie along a linear transformation curve between the initial and final positions. Alternatively, the algorithm schedules treatment paths by drawing upon a database of preferred treatments for exemplary tooth arrangements. This database can be constructed over time by observing various courses of treatment and identifying the treatment plans that prove most successful

with each general class of initial tooth arrangements. The path scheduling algorithm can create several alternative paths and present each path graphically to the user. The algorithm provides as output the path selected by the user.

In other implementations, the path scheduling algorithm utilizes a stochastic search technique to find an unobstructed path through a configuration space which describes possible treatment plans. One approach to scheduling motion between two user defined global key frames is described below. Scheduling over a time interval which includes intermediate key frames is accomplished by dividing the time interval into subintervals which do not include intermediate key frames, scheduling each of these intervals independently, and then concatenating the resulting schedules.

A collision or interference detection algorithm employed in one embodiment is based on the algorithm described in SIGGRAPH article, Stefan Gottschalk et al. (1996): "*OBBTree: A Hierarchical Structure for Rapid Interference Detection.*" The contents of the SIGGRAPH article are herein incorporated by reference.

The algorithm is centered around a recursive subdivision of the space occupied by an object, which is organized in a binary-tree like fashion. Triangles are used to represent the teeth in the DDS. Each node of the tree is referred to as an oriented bounding box (OBB) and contains a subset of triangles appearing in the node's parent. The children of a parent node contain between them all of the triangle data stored in the parent node.

The bounding box of a node is oriented so it tightly fits around all of the triangles in that node. Leaf nodes in the tree ideally contain a single triangle, but can possibly contain more than one triangle. Detecting collisions between two objects involves determining if the OBB trees of the objects intersect. If the OBBs of the root nodes of the trees overlap, the root's children are checked for overlap. The algorithm proceeds in a recursive fashion until the leaf nodes are reached. At this point, a robust triangle intersection routine is used to determine if the triangles at the leaves are involved in a collision.

The collision detection technique described here provides several enhancements to the collision detection algorithm described in the SIGGRAPH article. For example, OBB trees can be built in a lazy fashion to save memory and time. This approach stems from the observation that some parts of the model will never be involved in a collision, and consequently the OBB tree for such parts of the model need not be computed. The OBB trees are expanded by splitting the internal nodes of the tree as necessary during the recursive collision determination algorithm.

Moreover, the triangles in the model which are not required for collision data may also be specifically excluded from consideration when building an OBB tree. For instance, motion may be viewed at two levels. Objects may be conceptualized as "moving" in a global sense, or they may be conceptualized as "moving" relative to other objects. The additional information improves the time taken for the collision detection by avoiding recomputation of collision information between objects which are at rest relative to each other since the state of the collision between such objects does not change.

FIG. **8** illustrates an alternative collision detection scheme, one which calculates a "collision buffer" oriented along a z-axis **1802** along which two teeth **1804**, **1806** lie. The collision buffer is calculated for each treatment step or at each position along a treatment path for which collision detection is required. To create the buffer, an x,y plane **1808** is defined between the teeth **1804**, **1806**. The plane must be "neutral" with respect to the two teeth. Ideally, the neutral plane is positioned so that it does not intersect either tooth. If intersection with one or both teeth is inevitable, the neutral plane is oriented such that the teeth lie, as much as possible, on opposite sides of the plane. In other words, the neutral plane minimizes the amount of each tooth's surface area that lies on the same side of the plane as the other tooth.

In the plane **1808** is a grid of discrete points, the resolution of which depends upon the required resolution for the collision detection routine. A typical high-resolution collision buffer includes a 400×400 grid; a typical low-resolution buffer includes a 20×20 grid. The z-axis **1802** is defined by a line normal to the plane **1808**.

The relative positions of the teeth **1804**, **1806** are determined by calculating, for each of the points in the grid, the linear distance parallel to the z-axis **1802** between the plane **1808** and the nearest surface of each tooth **1804**, **1806**. For example, at any given grid point (M,N), the plane **1808** and the nearest surface of the rear tooth **1804** are separated by a distance represented by the value $Z_{1(M,N)}$, while the plane **1808** and the nearest surface of the front tooth **1806** are separated by a distance represented by the value $Z_{2(M,N)}$. If the collision buffer is defined such that the plane **1808** lies at z=0 and positive values of z lie toward the back tooth **1804**, then the teeth **1804**, **1806** collide when $Z_{1(M,N)} \leqq Z_{2(M,N)}$ at any grid point (M,N) on the plane **1808**.

FIG. **9** is a flow chart of a collision detection routine implementing this collision buffer scheme. The routine first receives data from one of the digital data sets indicating the positions of the surfaces of the teeth to be tested (step **1900**). The routine then defines the neutral x,y-plane (step **1902**) and creates the z-axis normal to the plane (step **1904**).

The routine then determines for the x,y-position of the first grid point on the plane the linear distance in the z-direction between the plane and the nearest surface of each tooth (step **1906**). To detect a collision at that x,y-position, the routine determines whether the z-position of the nearest surface of the rear tooth is less than or equal to the z-position of the nearest surface of the front tooth (step **1908**). If so, the routine creates an error message, for display to a user or for feedback to the path-generating program, indicating that a collision will occur (step **1910**). The routine then determines whether it has tested all x,y-positions associated with grid points on the plane (step **1912**) and, if not, repeats the steps above for each remaining grid point. The collision detection routine is performed for each pair of adjacent teeth in the patient's mouth at each treatment step.

In one embodiment, the system plans tooth path in accordance with a library of movements. For a given initial position of patient teeth and a final corrected position, the system generates in-between stages by finding the stage positions of each tooth in accordance with a selected movement. FIGS. **10**–**13** show exemplary movement patterns, namely an X-type movement, an A-type movement, a V-type movement, and an XX-type movement, among others. These exemplary movement patterns will be discussed next.

Turning now to FIG. **10**, an exemplary X-type movement is shown. The X-type movement is also known as an 'All Equal Movement'. In this movement, all teeth in a given group are moving at the same time. The tooth path is determined by dividing a starting frame containing the teeth into half frames and recursively determines intermediate paths in each half. The recursion stops when the moving distance in each frame meets a given criterion. Once the movements are done, the system adjusts teeth movements so that each frame does not exceed one or more distance constraints.

Next, the A-type movement is discussed. In this type of movement, the anterior tooth moves first, followed by the posterior teeth. The movement looks like an A character as the front tooth is moving ahead of the next tooth. In each tooth, the next tooth starts to move when the current tooth reaches midway to the current tooth's goal position. The diagram of the A type movement is shown in FIG. **11**.

The V-type movement is shown in FIG. **12**. Conceptually, the V type movement is reverse of A type movement: the rear teeth move first then the next front teeth follow. In one implementation, a reverse A movement is done for posterior teeth, while the anterior teeth go through an X type movement.

FIG. **13** shows an XX type movement, which involves two all equal movement. Posterior teeth go through an all equal movement (X-type) first and the anterior teeth go through the all equal movement.

Referring now to FIG. **14**, a process **2100** is a top-level routing process that allows a user to select one move pattern from a plurality of move patterns. Before starting, the process **2100** checks various requirements, for example:

Does the jaw have more than one base?

Are the lower jaw teeth attached to upper jaw or vice versa?

Are there any duplicate teeth identifications in the same jaw?

Does each tooth have polygon shape?

Does teeth have high resolution polygon shape?

Does the Z Axis for all teeth point at the same direction?

Are all teeth in their proper order?

Is there any intra arch collision excluding the base at stage 0?

Is there any intra arch collision excluding the base at final stage?

If any of the above check fails, the process **2100** aborts. Otherwise, the process **2100** determines whether a user has requested an A shape move pattern, and if so, executes an A shaped path calculation (step **2102**) and exits (step **2122**). If not, the process **2100** further determines whether the user has requested a left shift move pattern and if so, executes a left shift path calculation (step **2104**) before exiting (step **2122**). From step **2104**, if the user had not specified a left shift move pattern, the process **2100** determines whether the user has requested a right shift move pattern and if so, executes a right shift path calculation (step **2106**) before exiting (step **2122**).

In step **2106**, if the move pattern is not a right shift move pattern, the process **2100** checks for stripping and bad cuts (step **2108**). The process **2100** also checks whether the user has requested an all equal move pattern, and if so, performs an All Equal path calculation (step **2110**) and exits (step **2122**). Alternatively, the process **2100** checks whether the user has specified a Pre Equal move pattern, and if so, performs a PreEqual path calculation (step **2112**) and then exits (step **2122**). Alternatively, if the user specifies a random move pattern, the process **2100** performs a random path calculation (step **2114**) and exits (step **2122**).

If the move pattern in step **2114** is not a random move pattern, variables used in teeth calculation are initialized (step **2116**). The process **2100** also checks whether the move pattern is V shaped pattern, and if so performs a V shaped path calculation (step **2118**) and exits (step **2122**). Alternatively, the process **2100** executes a default path calculation (step **2120**) and exits (step **2122**).

In summary, the process **2100** directs the procedure to an appropriate process depending on the move pattern that is specified by the user.

Referring now to FIG. **15**, the process **2110** for calculating the all equal path is shown. Steps **2202** to **2208** initialize the algorithm. First, the process **2110** sets a pointer to the teeth (step **2202**). Next the process **2110** obtains neighbors of the current teeth (step **2204**). Next, the process **2110** sets a variable begin_frame as the current frame and a variable end_frame as the current frame plus a predetermined value such as **1000** (step **2206**). For every tooth in the current jaw teeth list, the process **2110** sets a transformation goal, or the goal position in 3-D space, as the key frame at end_frame (step **2208**). Next, the process **2110** performs a recursive subdivision calculation (step **2210**), whose operation is shown in more detail in FIG. **16**. The process **2110** then adjusts the frame to refine the frame and set a new end frame (step **2212**) before exiting (step **2214**). Step **2212** is a finishing process that refines the frames to meet a staging protocol to sequence the tooth movement.

In summary, the process **2110** is the top level of the all equal movement calculation. All teeth move at their respective begin_frame to reach desired goal positions at end_frame. A recursive process calculates the middle frame positions. The all equal movement needs collision detection to find collision free path, which is done in the process **2240**, as described below.

Referring now to FIG. **16**, the recursive subdivision calculation process **2210** is shown in more detail. First, the process **2210** receives a begin frame and an end frame (step **2222**). Next, the process **2210** puts a goal stage as the end frame, and sets the current frame as the begin frame (step **2224**). Next, for all teeth in the current jaw teeth list, the process iterates (step **2226**) by moving the tooth to the current frame and setting the goal transformation at the end frame (step **2228**). Once all teeth have been processed, the process **2210** computes a mid-frame by averaging the beginning frame and the end frame values (step **2230**). Next, the process **2210** calculates the position of the middle frame (step **2232**). The process then determines whether the move from the begin frame to the mid-frame exceeds a predetermined size and if so, it recursively invokes the process **2210** (step **2234**). Additionally, the process **2210** also determines whether the move from the mid-frame to the end frame exceeds a predetermined limit and if so, recursively invokes itself (step **2236**) before exiting.

The process **2210** recursively divides each whole frame in half and calculates the position at the middle frame. The recursion proceeds until the moves of the each half part of the frames fall below a specified criterion. The actual calculation of the position at the middle frame is illustrated in process **2240** below. As the recursion propagates, the collision free positions are determined in the frames.

FIG. **17** shows in more detail the process **2240** that computes rigid body transforms for teeth positions at the middle frame. The process **2240** finds collision free positions for all teeth at a given middle frame, and then sets the position to the key frame. For all teeth in the current jaw teeth list, steps **2242–2248** are performed. First, the current tooth rigid body transformation is saved to a temporary variable (step **2244**). Next, the current rigid body transformation is set at the middle position for the beginning and the end of the transformation (step **2246**). Next, step **2248** sets the current rigid body transformation, the current position, to the collision manager for the process **2250**. Steps **2242–2248** are repeated for all teeth in the current jaw. Steps **2242** to **2248** set all teeth in their middle frame positions in a collision manager before triggering a collision detection analysis.

Then, step **2250** triggers the collision detection analysis and moves teeth to collision-free positions. Next, the process

2240 sets the current collision free position as the key frame (step 2252). Next, the process 2240 restores the current rigid body transformation from the temporary variable (step 2254). The process 2240 then checks whether to move from the begin frame to the current frame exceeds a predetermined limit and also checks if the move from the current frame to the end frame exceeds a second predetermined limit (step 2256). The process 2240 also checks whether the current frame to the begin frame exceeds an oscillation range (step 2258). After performing these checks, the process of FIG. 17 exits (step 2260).

In summary, process 2240 finds collision free positions of teeth at the middle of current begin and end frames and then checks the termination criteria.

FIG. 18 shows a process 2270 for calculating paths for an A-shaped movement. First, the process 2270 determines a left value as being the tooth with the biggest identifier that is below a predetermined value (in this case, 8.5). The right tooth is also selected as the tooth with the smallest identification value larger than the predetermined value. The net effect of this is to obtain two incisor teeth (step 2272).

Next, the process 2270 finds the frame moves iterating tooth by tooth from the incisors to the last molars 2274–2282. First, the process 2276 sets key frames for a left tooth. For the current frame, the key frame is set to an initial transform (initial position), and for the next frame (current frame +1), the key frame is set to the middle transform. For the subsequent frame (current frame +2), the key frame is set to the goal transform (step 2276). The same procedure is applied to a right tooth (step 2278). Next, the frame is incremented and the left tooth becomes the next left tooth and the right tooth becomes the next right tooth (step 2280).

In the above manner, all teeth will move in three frames, and the move will start from incisor teeth and propagates toward posterior teeth. Upon exiting the iterations of steps 2274–2282, the process 2270 adjusts the frames and sets the new end value as the number of the frame (step 2284) and exits (step 2286).

FIG. 19 illustrates an exemplary PreEqual path calculation process 2300. Some move patterns have two distinct phases. The process 2300 is for the move pattern that has an equal movement in the first phase of the movement. First, the process 2300 obtains a pre-move left teeth and right teeth (step 2302). Next, it runs calculating equal move paths with the pre-move teeth (step 2304). The process 2300 then checks whether the post move pattern is also an equal move (step 2306). If so, for all teeth the process iterates in step 2308–2316. In this loop, the process 2300 first sets the current goal transformation as the original goal transformation (step 2310). Next, it sets the current rigid body transformation based on the current frame (step 2312). The process then sets the current transformation to a collision manager (step 2314). Next, it checks whether the tooth should move and if so, it deletes the last key and adds it to the teeth pointer list (step 2316). This iteration sets the teeth at the position from the current transformation, then put the post move teeth into the collision manager.

Upon completing the iteration (step 2308–2316), the process 2300 executes a collision detection operation (step 2320). Next, it executes an equal move path with the post move teeth (step 2322). Finally, the process 2300 runs adjustframe to refine the frames and sets a new end (step 2324) before it exits (step 2326). From step 2306, if the move pattern is not equal to Equal path, the process performs operations for XV or XA pattern (step 2307).

In summary, the process 2300 calculates a tooth path that has an equal movement pattern in pre-move phase. It runs the calculate equal move for the pre-move teeth, and then if the move pattern is equal-equal, runs another calculate equal move for the post move teeth.

Referring now to FIG. 20A, a process 2400 for calculating a V shaped movement is shown. First, a frame variable is set as the current frame and the teeth list is sorted by its weight (step 2402). Next, for all teeth in the sorted teeth list, the process 2400 performs the following steps. The iteration starts from the leftmost and the rightmost teeth (step 2404). First, the process 2400 operates on a left tooth (step 2406). For the current tooth, the process sets the key frame as the initial transform at current frame and at middle transformation at the frame +1 (step 2408). The middle transformation is interpolated half way from the initial transformation to the goal transformation. Then, the process 2400 sets the key frame to goal transformation at frame +2 and sets the current transformation as the goal transformation. In this manner, each tooth is sequentially moved in three frames. For example, if the current tooth is the left boundary tooth (left canine tooth), the process skips the frame +2, and sets the middle transformation as the current transformation (step 2410). The process 2400 then sets the tooth in the collision manager (step 2412). This loop sets the three-frame move to the tooth, the initial transformation, middle transformation, and the goal transformation except for the boundary tooth. The iteration progresses toward the front teeth in each frame (step 2414).

The same operation is applied to the right teeth (steps 2416 to 2420). Starting from the rightmost tooth, the process sets the three-frame movement for each tooth until it reach the right boundary tooth (right canine). Then, it moves the boundary tooth only to the half way. Both left and right teeth are incrementally processed toward front until both of the boundary teeth are reached (step 2422).

After both the left and right teeth have been processed, the process 2400 further checks whether the frontal space need to be closed and if so, it executes a closed frontal space function (step 2424).

FIG. 20B is a continuation of FIG. 20A through a connector 2426. The process of FIG. 20B continues with another iteration in steps 2428–2434. For all teeth, the process 2400 sets the key frame as the initial transformation at the current frame for anterior teeth, or teeth between the left and the right boundaries (step 2430). For the posterior teeth, or teeth set outside of left and right boundaries, the key frame is set at the goal transform at the current frame (step 2432). All teeth are set to the collision manager to do the collision detection (step 2434).

Upon processing all teeth after step 2434, the process 2400 triggers a collision detection operation (step 2436). Next, it calculates an equal teeth for the anterior teeth (step 2438). Finally, the process 2400 adjusts the frame to refine the frames and sets a new end frame (step 2440) before exiting.

In summary, the V-shape move path is calculated in the opposite direction of the A shape move. It starts from leftmost and rightmost teeth, and sequentially the next ones move until the boundary teeth move. The difference from A-shape move is that the remaining anterior teeth go through an equal move calculations. Thus, V shape move is also a two-phase movement.

The system may also incorporate and the user may at any point use a "movie" feature to show an animation of the movement from initial to target states. This is helpful for visualizing overall component movement throughout the treatment process.

As described above, one suitable user interface for component identification is a three dimensional interactive

graphical user interface (GUI). A three-dimensional GUI is also advantageous for component manipulation. Such an interface provides the treating professional or user with instant and visual interaction with the digital model components. The three-dimensional GUI provides advantages over interfaces that permit only simple low-level commands for directing the computer to manipulate a particular segment. In other words, a GUI adapted for manipulation is better in many ways than an interface that accepts directives, for example, only of the sort: "translate this component by 0.1 mm to the right." Such low-level commands are useful for fine-tuning, but, if they were the sole interface, the processes of component manipulation would become a tiresome and time-consuming interaction.

Before or during the manipulation process, one or more tooth components may be augmented with template models of tooth roots. Manipulation of a tooth model augmented with a root template is useful, for example, in situations where impacting of teeth below the gumline is a concern. These template models could, for example, comprise a digitized representation of the patient's teeth x-rays.

The software also allows for adding annotations to the data sets which can comprise text and/or the sequence number of the apparatus. The annotation is added as recessed text (i.e., it is 3-D geometry), so that it will appear on the printed positive model. If the annotation can be placed on a part of the mouth that will be covered by a repositioning appliance, but is unimportant for the tooth motion, the annotation may appear on the delivered repositioning appliance(s).

The above-described component identification and component manipulation software is designed to operate at a sophistication commensurate with the operator's training level. For example, the component manipulation software can assist a computer operator, lacking orthodontic training, by providing feedback regarding permissible and forbidden manipulations of the teeth. On the other hand, an orthodontist, having greater skill in intraoral physiology and teeth-moving dynamics, can simply use the component identification and manipulation software as a tool and disable or otherwise ignore the advice.

FIG. **21** is a simplified block diagram of a data processing system **500**. Data processing system **500** typically includes at least one processor **502** which communicates with a number of peripheral devices over bus subsystem **504**. These peripheral devices typically include a storage subsystem **506** (memory subsystem **508** and file storage subsystem **514**), a set of user interface input and output devices **518**, and an interface to outside networks **516**, including the public switched telephone network. This interface is shown schematically as "Modems and Network Interface" block **516**, and is coupled to corresponding interface devices in other data processing systems over communication network interface **524**. Data processing system **500** may include a terminal or a low-end personal computer or a high-end personal computer, workstation or mainframe.

The user interface input devices typically include a keyboard and may further include a pointing device and a scanner. The pointing device may be an indirect pointing device such as a mouse, trackball, touchpad, or graphics tablet, or a direct pointing device such as a touchscreen incorporated into the display. Other types of user interface input devices, such as voice recognition systems, may be used.

User interface output devices may include a printer and a display subsystem, which includes a display controller and a display device coupled to the controller. The display device may be a cathode ray tube (CRT), a flat-panel device such as a liquid crystal display (LCD), or a projection device. The display subsystem may also provide nonvisual display such as audio output.

Storage subsystem **506** maintains the basic programming and data constructs that provide the functionality of the present invention. The software modules discussed above are typically stored in storage subsystem **506**. Storage subsystem **506** typically comprises memory subsystem **508** and file storage subsystem **514**.

Memory subsystem **508** typically includes a number of memories including a main random access memory (RAM) **510** for storage of instructions and data during program execution and a read only memory (ROM) **512** in which fixed instructions are stored. In the case of Macintosh-compatible personal computers the ROM would include portions of the operating system; in the case of IBM-compatible personal computers, this would include the BIOS (basic input/output system).

File storage subsystem **514** provides persistent (nonvolatile) storage for program and data files, and typically includes at least one hard disk drive and at least one floppy disk drive (with associated removable media). There may also be other devices such as a CD-ROM drive and optical drives (all with their associated removable media). Additionally, the system may include drives of the type with removable media cartridges. The removable media cartridges may, for example be hard disk cartridges, such as those marketed by Syquest and others, and flexible disk cartridges, such as those marketed by Iomega. One or more of the drives may be located at a remote location, such as in a server on a local area network or at a site on the Internet's World Wide Web.

In this context, the term "bus subsystem" is used generically so as to include any mechanism for letting the various components and subsystems communicate with each other as intended. With the exception of the input devices and the display, the other components need not be at the same physical location. Thus, for example, portions of the file storage system could be connected over various local-area or wide-area network media, including telephone lines. Similarly, the input devices and display need not be at the same location as the processor, although it is anticipated that the present invention will most often be implemented in the context of PCS and workstations.

Bus subsystem **504** is shown schematically as a single bus, but a typical system has a number of buses such as a local bus and one or more expansion buses (e.g., ADB, SCSI, ISA, EISA, MCA, NuBus, or PCI), as well as serial and parallel ports. Network connections are usually established through a device such as a network adapter on one of these expansion buses or a modem on a serial port. The client computer may be a desktop system or a portable system.

Scanner **520** is responsible for scanning casts of the patient's teeth obtained either from the patient or from an orthodontist and providing the scanned digital data set information to data processing system **500** for further processing. In a distributed environment, scanner **520** may be located at a remote location and communicate scanned digital data set information to data processing system **500** over network interface **524**.

Fabrication machine **522** fabricates dental appliances based on intermediate and final data set information received from data processing system **500**. In a distributed environment, fabrication machine **522** may be located at a remote location and receive data set information from data processing system **500** over network interface **524**.

Various alternatives, modifications, and equivalents may be used in lieu of the above components. Although the final position of the teeth may be determined using computer-aided techniques, a user may move the teeth into their final positions by independently manipulating one or more teeth while satisfying the constraints of the prescription.

Additionally, the techniques described here may be implemented in hardware or software, or a combination of the two. The techniques may be implemented in computer programs executing on programmable computers that each includes a processor, a storage medium readable by the processor (including volatile and nonvolatile memory and/or storage elements), and suitable input and output devices. Program code is applied to data entered using an input device to perform the functions described and to generate output information. The output information is applied to one or more output devices.

Each program can be implemented in a high level procedural or object-oriented programming language to operate in conjunction with a computer system. However, the programs can be implemented in assembly or machine language, if desired. In any case, the language may be a compiled or interpreted language.

Each such computer program can be stored on a storage medium or device (e.g., CD-ROM, hard disk or magnetic diskette) that is readable by a general or special purpose programmable computer for configuring and operating the computer when the storage medium or device is read by the computer to perform the procedures described. The system also may be implemented as a computer-readable storage medium, configured with a computer program, where the storage medium so configured causes a computer to operate in a specific and predefined manner.

The invention has been described in terms of particular embodiments. Other embodiments are within the scope of the following claims. For example, the three-dimensional scanning techniques described above may be used to analyze material characteristics, such as shrinkage and expansion, of the materials that form the tooth castings and the aligners. Also, the 3D tooth models and the graphical interface described above may be used to assist clinicians that treat patients with conventional braces or other conventional orthodontic appliances, in which case the constraints applied to tooth movement would be modified accordingly. Moreover, the tooth models may be posted on a hypertext transfer protocol (http) web site for limited access by the corresponding patients and treating clinicians.

Further, while the invention has been shown and described with reference to an embodiment thereof, those skilled in the art will understand that the above and other changes in form and detail may be made without departing from the spirit and scope of the following claims.

What is claimed is:

1. A computer-implemented method to prepare a malocclusion treatment plan, comprising:

selecting a tooth treatment pattern from a library of predetermined tooth treatment patterns;

generating the malocclusion treatment plan implementing the selected tooth treatment pattern; and

generating a series of successive tooth arrangements progressing from a first tooth arrangement to a second tooth arrangement.

2. The method of claim **1**, wherein generating the malocclusion treatment plan comprises determining one or more tooth paths based on the selected tooth treatment pattern.

3. The method of claim **2**, wherein determining a tooth path comprises finding a collision free shortest path between an initial position and a final position for one or more teeth.

4. The method of claim **1**, wherein the treatment pattern is selected from one or more clinical treatment prescriptions.

5. The method of claim **4**, wherein the clinical treatment prescription includes at least one of the following: space closure, reproximation, dental expansion, flaring, proclination, distalization, and lower incisor extraction.

6. The method of claim **1**, wherein generating the malocclusion treatment plan comprises specifying a series of treatment stages for one or more teeth.

7. The method of claim **6**, further comprising dividing a path for one or more teeth into the series of stages while keeping the movement of teeth in each stage below a predetermined range.

8. The method of claim **1**, further comprising generating an appliance for a treatment stage.

9. The method of claim **8**, wherein the appliance is either a removable appliance or a fixed appliance.

10. The method of claim **1**, further comprising generating a three-dimensional model for the teeth for a treatment stage.

11. The method of claim **10**, further comprising generating dental diagnostic information from the three-dimensional model.

12. The method of claim **10**, further comprising generating interproximal reduction information from the 3D model.

13. The method of claim **10**, further comprising generating tooth size discrepancy information from the 3D model.

14. The method of claim **10**, further comprising generating Bolton information from the 3D model.

15. The method of claim **1**, wherein the library of treatment patterns comprises at least one or more of the following: all equal movement pattern, A-shaped movement pattern, V-shaped movement pattern, M-shaped movement pattern, W-shaped movement pattern, symmetric staircase pattern, asymmetric staircase pattern, and equal equal movement pattern.

16. The method of claim **1**, wherein the selected pattern comprises an all equal movement pattern, further comprising subdividing paths while satisfying one or more constraints.

17. The method of claim **16**, wherein the constraint comprises minimizing tooth oscillation and tooth movement distance.

18. The method of claim **1**, wherein the selected pattern comprises an equal equal pattern, further comprising:

dividing the teeth into a prestage movement group and a post stage movement group; and

applying the all equal movement to the prestage movement group and subsequently applying the all equal movement to the prestage movement group.

19. The method of claim **1**, wherein the selected pattern is an A-shaped movement pattern, further comprising sequentially moving each tooth from an incisor tooth toward a molar tooth.

20. The method of claim **1**, wherein the selected pattern is a V-shaped movement pattern, further comprising sequentially moving each tooth from a molar tooth toward an incisor tooth.

21. A computer-implemented method to prepare a malocclusion treatment plan, comprising:

selecting one tooth treatment pattern from a library of predetermined tooth treatment patterns;

generating the malocclusion treatment plan in accordance with the selected treatment pattern; and

producing data representing a series of successive tooth arrangements progressing from a first tooth arrangement to a second tooth arrangement.

22. The method of claim 21, further comprising generating an appliance for each tooth arrangement.

23. A computer-readable medium executable by a computer to prepare a malocclusion treatment plan, comprising:

code to select one tooth treatment pattern from a library of predetermined tooth treatment patterns;

code to generate the malocclusion treatment plan in accordance with the selected treatment pattern; and

code to generate a series of successive tooth arrangements progressing from a first tooth arrangement to a second tooth arrangement.

24. The medium of claim 23, further comprising code to fabricate an appliance for a tooth arrangement.

25. The medium of claim 23, wherein the code to fabricate appliances further comprises:

a. code to control a fabrication machine to produce successive positive models of the tooth arrangements; and

code to produce the appliance as a negative of the tooth model.

26. The medium of claim 23, wherein the code to control a fabrication machine comprises:

code to provide a volume of non-hardened polymeric resin; and

code to scan a laser to selectively harden a resin to produce the positive model.

27. The medium of claim 23, further comprising code to control a fabrication machine to produce successive appliances for the tooth arrangements.

28. A computer-implemented method to automatically stage a series of tooth movements, comprising:

selecting one teeth treatment pattern from a plurality of predetermined teeth treatment patterns;

generating a treatment plan for the teeth in accordance with the selected move pattern by:

generating a treatment plan with a tooth path for each tooth; and

determining a series of treatment stages for the teeth; and

controlling a fabrication machine to produce successive appliances for the tooth arrangements.

29. The method of claim 28, wherein the controlling a fabrication machine comprises generating an appliance as a negative or a positive of a dental model.

30. A computer system to prepare a malocclusion treatment plan, comprising:

a processor;

a display coupled to the processor; and

a data storage device coupled to the processor and containing code to select a tooth treatment pattern from a library of predetermined tooth treatment patterns; and code to generate the malocclusion treatment plan implementing the selected tooth treatment pattern.

31. A computer system to prepare a malocclusion treatment plan for a digital model of a patient's teeth, comprising:

means for selecting a tooth treatment pattern from a library of predetermined tooth treatment patterns; and

means for generating the malocclusion treatment plan implementing the selected tooth treatment pattern on the digital model.

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