

UNITED STATES PATENT AND TRADEMARK OFFICE

BEFORE THE PATENT TRIAL AND APPEAL BOARD

DENTAL IMAGING TECHNOLOGIES CORPORATION

Petitioner

v.

3SHAPE A/S

Patent Owner

U.S. Patent No. 11,076,146 to Fisker *et al.*

Issue Date: July 27, 2021

Title: FOCUS SCANNING APPARATUS

DECLARATION OF JAMES L. MULLINS, Ph.D.

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I. INTRODUCTION

1. I, James L. Mullins, Ph.D., hereby declare as follows:

2. I have been retained by Foley & Lardner LLP on behalf of Dental Imaging Technologies Corporation to authenticate and establish the dates of public accessibility of certain documents for use in *inter partes* review proceedings. For this service, I am being paid my usual hourly fee of \$275/hour. My compensation in no way depends on the substance of my testimony or the outcome of the proceedings.

3. I have personal knowledge of the facts and opinions set forth in this declaration. I believe them to be true, and if called upon to do so, I would testify competently to them. I have been warned that willful false statements and the like are punishable by fine or imprisonment, or both.

II. BACKGROUND AND QUALIFICATIONS

4. I am a retired academic librarian working as the Founder and Owner of the firm Prior Art Documentation Librarian Services, LLC at 205 Saint Cuthbert, Williamsburg, VA 23188. Attached as Appendix D is a true and correct copy of my Curriculum Vitae (“CV”) describing my background and experience. Further information about my firm, Prior Art Documentation Librarian Services, LLC (PADLS), is available at www.priorartdoclib.com.

5. In forming the opinions expressed in this Declaration, I have considered and relied upon my background and experience. In addition, I have reviewed and relied upon additional materials in preparation of this Declaration, as described below and provided in the Appendixes to this Declaration.

6. I am presently Dean Emeritus of Libraries and Esther Ellis Norton Professor Emeritus, Purdue University, 2018 – present.

7. I was previously employed as follows:

- Dean of Libraries and Professor & Esther Ellis Norton Professor, Purdue University, West Lafayette, IN, 2004-2017.
- Assistant/Associate Director for Administration, Massachusetts Institute of Technology (MIT), Cambridge, MA, 2000-2004.
- University Librarian and Director, Falvey Memorial Library, Villanova University, Villanova, PA, 1996-2000.
- Director of Library Services, Indiana University South Bend, South Bend, IN, 1978-1996.
- Part-time instructor, School of Library and Information Science, Indiana University, Bloomington, IN, 1979-1996.
- Associate Law Librarian, and associated titles, Indiana University School of Law, Bloomington, IN, 1974-1978.

- Catalog Librarian, Assistant Professor, Georgia Southern College (now University), Statesboro, GA, 1973-1974.

8. Over the course of my career as a librarian, instructor of library science, author of scholarly publications, and presenter at national and international conferences, I have had experience with catalog records and online library management systems built around Machine-Readable Cataloging (MARC) standards.

9. In the course of more than forty-four years as an academic librarian and scholar, I have been an active researcher. In my years as a librarian, I have facilitated the research of faculty colleagues either directly or through the provision of and access to the requisite print and/or digital materials and services at the universities I worked. I have kept current on the professional library science literature and served on the editorial board of the most prominent library journal, *College and Research Libraries*. This followed service as the chair of the Research Committee of the Association of College and Research Libraries (ACRL), a division of the American Library Association (ALA). As an academic library administrator, I have had responsibility to ensure that students were educated to identify, locate, assess and integrate information garnered from library resources.

III. PRELIMINARIES

10. I am not a lawyer, and I am not rendering an opinion on the legal

question of whether a particular document is, or is not, a “printed publication” under the law.

11. I am, however, rendering my expert opinion on the authenticity of the documents referenced herein and on when and how these documents were disseminated or otherwise made available to the extent that persons interested and ordinarily skilled in the subject matter or art, exercising reasonable diligence, could have located the documents by at least June 17, 2008.

12. I am informed by counsel that an item is considered authentic if there is sufficient evidence to support a finding that the item is what it is claimed to be. I am also informed that authenticity can be established based on the contents of the documents themselves, such as the appearance, content, substance, internal patterns, or other distinctive characteristics of the item, taken together with all of the circumstances.

13. I am informed by counsel that a given reference is publicly accessible upon a satisfactory showing that such a document has been disseminated or otherwise made available to the extent that persons interested and ordinarily skilled in the subject matter or art exercising reasonable diligence, can locate it. I have also been informed by counsel that materials available in a library constitute printed publications if they are cataloged and indexed according to general library practices that make the references available to members of the interested public.

14. In forming the opinions expressed in this declaration, I have reviewed the documents and appendices referenced herein. These materials are records created in the ordinary course of business by publishers, libraries, indexing services, and others. From my years of experience, I am familiar with the process for creating many of these records, and I know these records are created by people with knowledge of the information in the record. Further, these records are created with the expectation that researchers and other members of the public will use them. All materials cited in this declaration and its appendices are of a type that experts in my field would reasonably rely upon and refer to in forming their opinions.

15. I am told by counsel that the subject matter of this proceeding relates to a scanner for scanning three-dimensional objects.

16. I have been informed by counsel that a person of ordinary skill in the art at the time of the purported inventions is a hypothetical person who is presumed to be familiar with the relevant field and its literature at the time of the purported inventions. This hypothetical person is also a person of ordinary creativity, capable of understanding the scientific principles applicable to the pertinent field.

17. I am told by counsel that a person of ordinary skill in the art ("POSA") would have had a bachelor's degree in Computer Engineering, Computer Science, Electrical Engineering, Physics, or an equivalent field, as well

as at least one or two years of design experience, or alternatively, at least five years of comparable industry experience. In particular, I am informed that a POSA would have had experience with and knowledge of three-dimensional (“3D”) imaging systems and 3D modeling techniques.

18. It is my opinion that such a person would have been engaged in academic research, learning through study and practice in the field and possibly through formal instruction the bibliographic resources relevant to that person’s research. Such a person would have had access to a vast array of print resources in 3D scanner design.

A. Library Records

19. Some background on MARC formatted records, OCLC, *WorldCat*, and OCLC’s Connexion is needed to understand the library catalog records discussed in this declaration.

20. Libraries world-wide use the MARC format for catalog records; this machine-readable format was developed by the Library of Congress in the 1960s.

21. MARC formatted records provide a variety of subject access points based on the content of the document being cataloged. All subject headings may be found in the MARC fields 6XX. For example, MARC Field 600 identifies personal names used as subjects and the MARC Field 650 identifies topical terms. A researcher might discover material relevant to his or her topic by a search using the

terms employed in the MARC Fields 6XX.

22. The MARC Field 040, subfield a, identifies the library or other entity that created the original catalog record for a given document and transcribed it into machine readable form. The MARC Field 008 identifies the date when this first catalog record was entered on the file. This date persists in all subsequent uses of the first catalog record, although newly-created records for the same document, separate from the original record will show a new date. It is not unusual to find multiple catalog records for the same document.

23. *WorldCat* is the world's largest public online catalog, maintained by the Online Computer Library Center, Inc., or OCLC, and built with the records created by the thousands of libraries that are members of OCLC. *WorldCat* provides a user-friendly interface for the public to use MARC records; it requires no knowledge of MARC tags and codes. *WorldCat* is easily accessible through the World Wide Web to all who wish to search it; there are no restrictions to be a member of a particular community, etc. The date a given catalog record was created (corresponding to the MARC Field 008) appears in some detailed *WorldCat* records as the Date of Entry but not necessarily all.

24. Whereas *WorldCat* records are widely available, the availability of MARC formatted records varies from library to library.

25. When an OCLC participating institution acquires a document for

which it finds no previously created record in OCLC, or when the institution chooses not to use an existing record, it creates a record for the document using OCLC's Connexion, the bibliographic system used by catalogers to create MARC records. Connexion automatically supplies the date of record creation in the MARC Field 008.

26. Once the MARC record is created by a cataloger at an OCLC participating member institution, it becomes available to other OCLC participating members in Connexion and also in *WorldCat*, where persons interested and ordinarily skilled in the subject matter or art, exercising reasonable diligence, can locate it.

B. Periodicals

27. A library typically creates a catalog record for a periodical publication when the library receives its first issue. When the institution receives subsequent issues/volumes of the periodical, the issues/volumes are checked in (often using a date stamp), added to the institution's holding records, and made available very soon thereafter – normally within a few days of receipt or (at most) within a few weeks of receipt.

28. The initial periodicals record will sometimes not reflect all subsequent changes in publication details (including minor variations in title, frequency, etc.).

C. Cataloging/Indexing

29. A researcher may discover material relevant to their topic in a variety of ways. One common means of discovery is to search for relevant information in an index of periodicals and other publications. Having found relevant material, the researcher will then normally obtain it online, look for it in libraries, or purchase it from the publisher, a bookstore, a document delivery service, or other provider. Sometimes, the date of a document's public accessibility will involve both indexing and library date information. Date information for indexing entries is, however, often unavailable. This is especially true for online indices.

30. Indexing services use a wide variety of controlled vocabularies to provide subject access and other means of discovering the content of documents. The formats in which these access terms are presented vary from service to service.

31. Online indexing services commonly provide bibliographic information, abstracts, and full-text copies of the indexed publications, along with a list of the documents cited in the indexed publication. These services also often provide lists of publications that cite a given document. A citation of a document is evidence that the document was publicly available and in use by researchers no later than the publication date of the citing document.

32. ***ACM Digital Library*** - Association for Computing Machinery. The ACM was founded in 1947 and is a scientific and educational computing society.

The portal has two main sections: the ACM Digital Library and the ACM Guide to Computing Literature. The ACM Digital Library provides access to the journals, newsletters and conference proceedings of the organization. The Guide to Computing Literature is a bibliography of computing literature beginning in the 1950s with more than a million entries. <https://dl.acm.org>.

33. All metadata in the ACM database are freely available on the web. This includes abstracts, linked references, citing work, and usage statistics. Full text of articles are available with subscription.

34. **Wiley Online Library** has a full range of journals, books, major reference works, and databases. It is a multidisciplinary collection of online resources covering life, health, and physical sciences; social science; and the humanities with 850 scientific and scholarly societies around the world, and access to over 7.5 million articles from over 1,600 journals, over 21,000 online books, and hundreds of multi-volume reference works, databases, and other resources online. <https://onlinelibrary.wiley.com/researchers>.

35. **Wisconsin TechSearch (WTS)** - WTS offers an array of article delivery and research services to individuals and organizations not affiliated with the University of Wisconsin or who need the specialized skills of WTS staff in locating and retrieving information. It is the policy of WTS to keep confidential all material submitted by clients with respect to searches as well as search results.

<https://wts.wisc.edu/>.

IV. OPINION REGARDING INDIVIDUAL DOCUMENTS

A. Wilson

36. I have been asked to opine on the authenticity and public access of an article authored by T. Wilson *et al.*, “Real-time Three-dimensional Imaging of Macroscopic Structures,” published in the *Journal of Microscopy*, Vol. 191, Pt. 2, August 1998, pp. 116-118 (“Wilson”).

37. For consistency and clarification, Wilson, when used in this declaration, refers not only to the Wilson article but also the journal volume and issue in which it was published: *Journal of Microscopy*, Vol. 191, Pt. 2, the August 1998 issue.

1. Authentication

38. I have evaluated the Wilson reference in three ways: (1) by assessing a scan of a copy of Wilson (EX1006 to the Petition for *Inter Partes* Review) provided to me by counsel; (2) assessing a scan of Wilson, Attachment A-1, that I obtained through Document Services of the Linda Hall Library from the print copy of Wilson owned by the Linda Hall Library, Kansas City, Missouri, a pre-eminent research library in the areas of science, engineering and technology on September 1, 2022; and (3) by retrieving and reviewing a download, Attachment A-2, I made on September 7, 2022 through Purdue University Libraries by my emeritus faculty

status from *Wiley Online Library*, a proprietary database through this URL:
<https://onlinelibrary-wiley-com.ezproxy.lib.purdue.edu/doi/pdfdirect/10.1046/j.1365-2818.1998.00403.x>.

39. Wilson is available for a fee at this URL:
<https://onlinelibrary.wiley.com/doi/full/10.1046/j.1365-2818.1998.00403.x>.

40. Attachment A-1 is a scan of Wilson that includes the issue cover of *Journal of Microscopy*, volume 191, part 2, August 1998; journal description; contents page that has a stamp that reads: “Linda Hall Library Aug 27 1998” (as shown below) that indicates ownership and date of receipt by the Linda Hall Library, Kansas City, Missouri. The date indicates it was received and “checked-in” to the collections of the Linda Hall Library, on August 27, 1998; and also includes the Wilson article, pages 116-118.



41. All identifying characteristics, such as the stamp on Attachment A-1 are consistent with library practice and procedure that I have observed during my career as a professional librarian. I have no cause for concern about the authenticity or accuracy of these identifying attributes. Attachment A-1 was found

within the custody of a library, the Linda Hall Library, one of the most likely locations for an authentic publication.

42. Attachment A-2 is a copy of Wilson that I retrieved on September 7, 2022, from *Wilson Online Library* through the Purdue University Libraries by my emeritus faculty status:

<https://onlinelibrary-wiley-com.ezproxy.lib.purdue.edu/doi/pdfdirect/10.1046/j.1365-2818.1998.00403.x>.

43. Wilson is available for a fee at this URL:

<https://onlinelibrary.wiley.com/doi/full/10.1046/j.1365-2818.1998.00403.x>.

44. After comparing Wilson as it appeared in Attachment A-1 and Attachment A-2, I conclude, based on finding Wilson in print in a library – Linda Hall – and online through a reputable, publisher database, *Wilson Online Library*, that Wilson is an authentic document, and that Attachment A-1 and Attachment A-2 are authentic and accurate copies of Wilson. I then compared Attachment A-1 and Attachment A-2 with EX1006, provided by counsel, and I found no difference.

45. Therefore, I conclude and affirm Wilson is an authentic document.

2. Public Accessibility

46. Attachment A-3 is a true and correct copy of the *WorldCat* entry for Wilson, *Journal of Microscopy*. Wilson was included among the articles published in *Journal of Microscopy*, volume 191, part 2, August 1998, on pages 116-118. I

obtained Attachment A-3 by completing a search on *WorldCat* on September 7, 2022. The document cataloged in this record is a periodical record for *Journal of Microscopy* as verified by title: *Journal of Microscopy*; publisher and publication date: Blackwell Publishing, 1969 -. The 1969- indicates an ‘open entry’, that is, a serial that will continue that started in 1969.

47. When undertaking the search of *WorldCat* as described above using the geographical location of Missouri, the Linda Hall Library was among the 1668 libraries that hold *Journal of Microscopy* world-wide.

48. Attachment A-4 is a download I made from the Linda Hall Library OPAC (online catalog) on September 7, 2022. The document cataloged in this record is a periodical record for: *Journal of Microscopy*; publisher and publication date: Blackwell Publishing, 1969 -. The 1969- indicates an ‘open entry’, that is, a serial that will continue that started in 1969. Under “Holdings” “v.89 (1969)-v.254:iss.1(2014:Apr.) indicates that the Linda Hall Library holds the issue that includes the article by Wilson.

49. Wilson could have been located by searching on the Linda Hall Library OPAC (online catalog) for the title: *Journal of Microscopy*; or by searching the subject heading: *Microscopy-Periodicals*.

50. On Attachment A-1 is the ownership and date stamp on the contents page that reads “LINDA HALL AUG 27 1998 LIBRARY”, as shown below. The

date of August 27, 1998 would be when receipt and the processing began on *Journal of Microscopy*, volume 191, part 2, August 1998 by the Linda Hall Library.



51. Consistent with standard library policy and practice, this issue would have been accessible on the shelf in the Linda Hall Library within a week to ten days after receipt by the library, that is, no later than September 7, 1998.

3. Conclusion Regarding Wilson

52. I conclude that Wilson is an authentic document and would have been publicly accessible through the Linda Hall Library no later than September 7, 1998.

B. Neil

53. I have been asked to opine on an article by M. A. A. Neil, *et al.*, "Method of Obtaining Optical Sectioning by Using Structured Light in a Conventional Microscope," *Optics Letters*, Vol. 22, No. 24, December 15, 1997, pp. 1905-1907 ("Neil").

54. For consistency and clarification, Neil, when used in this declaration,

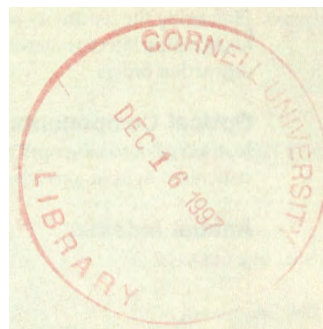
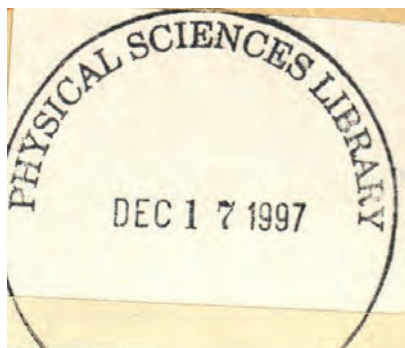
refers not only to the Neil article but also the journal volume and issue in which it was published: *Optics Letters*, Vol. 22, No. 24, December 15, 1997.

1. Authentication

55. I have evaluated the authenticity of the Neil reference in several ways: (1) by assessing and reviewing the version of Neil provided to me by counsel (EX1010 to the Petition for *Inter Partes* Review); (2) by assessing scans of a print copy of Neil provided to me at my request on September 19, 2022 by the Wisconsin TechSearch (WTS) of the print copy of Neil owned by the Cornell University Libraries University, Attachment B-1; and (3) by assessing a download I made of Neil from the Optima Publishing Group database through Purdue University Libraries.

56. Attachment B-1 was provided to me at my request on September 19, 2022, by Wisconsin TechSearch of the print copy of Neil owned by the Cornell University Libraries. Attachment B-1 includes scans of Neil: issue cover, *Optics Letters*, volume 22, issue number 24, December 15, 1997 with a stamp that reads “Physical Sciences Library DEC 17 1997”, as shown below; journal information page; contents of the issue; back cover with a stamp that reads “Cornell University Libraries DEC 16 1997”, as shown below; and the Neil article on pages 1905-1907. The one day difference between the two dates probably indicates initial receipt (December 16, 1997) and when it was checked-in onto the record

(December 17, 1997).



57. All identifying characteristics, such as stamps and notations on Attachment B-1 are consistent with library practice and procedure that I have observed during my career as a professional librarian, specifically when reviewing scans from the collections of the Cornell University Libraries made by WTS. Also, since this was provided to me by the Wisconsin TechSearch (WTS), a service offered through the University of Wisconsin – Madison Libraries, I have no doubt about its authenticity or concern about accuracy of these identifying attributes. Attachment B-1 was found within the custody of a library, the Cornell University Libraries, one of the most likely locations for an authentic document to be publicly accessible.

58. I accessed and downloaded Attachment B-2 from the *Optica Publishing Group* database by my emeritus faculty status through Purdue University Libraries at this URL: https://opg-optica-org.ezproxy.lib.purdue.edu/view_article.cfm?gotourl=https%3A%2F%2Fopg%2E

[optica%2Eorg%2FDirectPDFAccess%2F819B73AE%2D5F17%2D46F6%2D89684AC2C8AB9FAB%5F36487%2Fol%2D22%2D24%2D1905%2Epdf%3Fda%3D1%26id%3D36487%26seq%3D0%26mobile%3Dno&org=Purdue%20University.](https://opg.optica.org/ol/viewmedia.cfm?uri=ol-22-24-1905&seq=0)

It is available for a fee at this URL:
[https://opg.optica.org/ol/viewmedia.cfm?uri=ol-22-24-1905&seq=0.](https://opg.optica.org/ol/viewmedia.cfm?uri=ol-22-24-1905&seq=0)

59. I conclude, based on finding a print copy of Neil in a research library (Cornell University Libraries) and online through a reputable, publisher database (Optica Publishing) through Purdue University Libraries, that Attachment B-1 and Attachment B-2 , are each authentic, true, and correct copies of Neil. EX1010 matches exactly with Attachment B-1 and Attachment B-2; therefore, I conclude that EX1010 is an authentic, true and accurate copy of Neil.

2. Public Accessibility

60. Attachment B-3 is a true and correct copy of the *WorldCat* entry for Neil, *Optics Letters*, as a serial publication. Neil was included among the papers published in *Optics Letters*, in its volume 22, issue number 24, December 15, 1997.

61. I obtained Attachment B-3 by completing a search on *WorldCat* on September 20, 2022, for *Optics Letters*. The document cataloged in this record is a periodical record for *Optics Letters* as verified by title: *Optics Letters*; and publisher: Optical Society of America.

62. When I searched this *WorldCat* record for holdings of *Optics Letters* in New York, Cornell University Libraries was on the list among the 700 libraries worldwide that held the *Optics Letters* (see Attachment B-3).

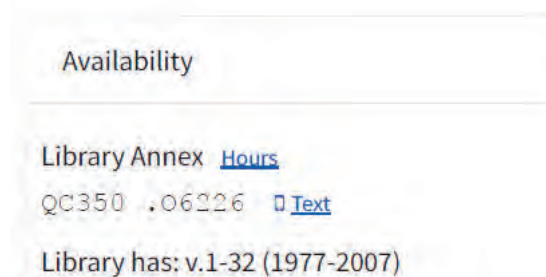
63. In the early 2000s, *WorldCat* had been made ‘open access’, and was easily searchable on the Internet, without an access code, etc. Therefore, *Optics Letters* could have been located in *WorldCat* from the early 2000s.

64. *Optics Letters* was accessible by a researcher by title: *Optics Letters*; and by subject headings: 33.38 modern optics; *Optica*; *Optics*; *Optics – Periodicals*; and/or *Optic and Photonics*. These searches could have been completed anywhere in the world by a researcher who had access to *WorldCat* and its predecessor database, *First Search*, through an OCLC member library from the late 1990s and early 2000s through 2007. As mentioned above, in the early 2000’s *WorldCat* became “open access”; therefore it was accessible to any person on the Internet without a required login.

65. During the timeframe of Neil, research libraries regularly maintained records in the course of library operation. One such regularly-maintained catalog and index record was an OPAC entry. The receipt of the print copy of a journal issue, such as *Optics Letters*, would have been recorded on a record accessible to a researcher.

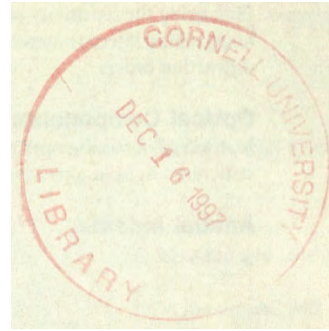
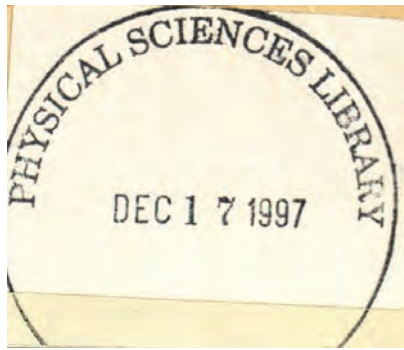
66. Attachment B-4 is a download I made from the Cornell University

Libraries' OPAC (online catalog) on September 20, 2022. The document cataloged in this OPAC periodical record is for *Optics Letters* as verified by title: *Optics Letters*; publisher and publication dates: Optical Society of America, "Publication Dates: Vol.1, no. 1 (July 1977) -". The hyphen after July 1977 indicates that *Optics Letters* is published to the present day. Proof that the Cornell University Libraries own this issue of *Optics Letters* is shown by the holdings statement, as shown below, in "Availability – Library has: v.1-32 (1977-2007) [in print]" inclusive of volume 22, no. 24, December 15, 1997.



67. Neil could have been located from the late 1990s to 2007 by searching on the Cornell University Libraries' OPAC (online catalog) for the title: *Optics Letters*; and/or by searching the subject heading: *Optics – Periodicals*.

68. The date stamps on Attachment B-1, as shown below, indicates receipt of Neil on December 16-17, 1997, by the Cornell University Libraries



69. From my experience, a typical amount of time to process a journal article such as the volume 22, number 24, December 15, 1997 issue of *Optics Letters*, and transfer it to the shelves and make it accessible to a researcher would be one week to 10 days. Therefore, Neil would have been publicly accessible no later than December 27, 1997 at the Cornell University Libraries.

3. Conclusion Regarding Neil

70. I conclude that the copy of Neil, Attachment B-1 is an authentic, true, and correct document and would have been publicly accessible by December 27, 1997 through the Cornell University Libraries. Attachment B-2 is a match to Attachment B-1. EX1010 is an exact match to Attachment B-1 and Attachment B-2, the download I made through Purdue University Libraries, therefore, I conclude that Neil, EX1010, is an authentic document and that it was publicly accessible no later than December 27, 1997.

C. Zhang

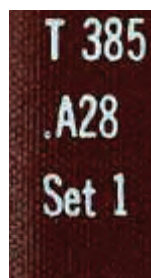
71. I have been asked to opine on an article authored by: L. Zhang *et al.*, titled: "Projection Defocus Analysis for Scene Capture and Image Display;"

published in ACM SIGGRAPH 2006, July 2006, on pages 907-915. (“Zhang”).

1. Authentication

72. I have evaluated the Zhang reference three ways: (1) by assessing the copy of Zhang (EX1011 to the Petition for *Inter Partes* Review) provided to me by counsel; (2) by assessing scans of a copy of Zhang owned by the Library of Congress, Attachment C-1; and (3) by accessing and assessing a download of Zhang I made on September 7, 2022.

73. Attachment C-1 is a scan of the print document held by the Library of Congress. It was provided to me at my request from the Wisconsin TechSearch from the print copy of Zhang owned by the Library of Congress on September 1, 2022. Attachment C-1 includes: bound front cover, spine and back cover with a stamp that reads “T 385.A28 Set 1”, as shown below; published cover; publication information page; title page; verso of the title page (copyright) with a stamp that reads “Library of Congress AUG 15 2006”, as shown below; Table of Contents; and Zhang article on pages 907-915.



74. All identifying characteristics, such as stamps and notations, on Attachment C-1, are consistent with library practice and procedure that I have observed during my career as a professional librarian, specifically with those items held by the Library of Congress. I have no cause for concern about the authenticity or accuracy of these identifying attributes. In addition, Zhang was found within the custody of a library, the Library of Congress, one of the most likely locations for an authentic publication to be located.

75. Evidence of the ownership of Zhang by the Library of Congress will further be explored and detailed in the section below on public access.

76. Attachment C-2 is a download I made on September 8, 2022. I accessed and downloaded Attachment C-2 from the *ACM Digital Library* database by my emeritus faculty status through Purdue University Libraries at this URL: <https://dl-acm-org.ezproxy.lib.purdue.edu/doi/pdf/10.1145/1141911.1141974>.

It is available for a fee at this URL:

<https://dl.acm.org/doi/abs/10.1145/1179352.1141974>.

77. After comparison of Zhang between Attachment C-1 and corresponding pages of Attachment C-2, I found no difference between the two. Therefore, upon finding Zhang in the Library of Congress and also in the *ACM Digital Library* database, I have determined that EX1011, Zhang, is an authentic

document.

78. I conclude and affirm that Zhang, EX1011, is an authentic document.

2. Public Accessibility

79. Attachment C-3 is a true and correct copy of the *WorldCat* entry for Zhang. I obtained Attachment C-3 by completing a search on *WorldCat* on September 10, 2022 by searching geographical location, Washington, D.C. (Library of Congress). When I searched *WorldCat* for holdings of Zhang in Washington, D.C., the Library of Congress was third on the list among the 459 libraries shown as holding Zhang worldwide.

80. Attachment C-3 shows that Zhang is the document associated with this *WorldCat* entry, as verified by title and authors: *Proceedings. ACM SIGGRAPH Symposium on Interactive 3D Graphics and Games, SIGGRAPH, Association of Computing Machinery*; publication date: c2005-, which is an open entry indicating that it is an annual and each year would be added as received.

81. Zhang could have been located by searching for the author and title: *Proceedings. ACM SIGGRAPH Symposium on Interactive 3D Graphics and Games*; and/or by searching the subject headings: *Computer graphics; Computer graphics - Congresses; Three-dimensional display systems; and/or Three-dimensional display systems - Congresses*.

82. The search discussed above could have been performed anywhere in

the world by anyone who accessed *WorldCat* and its predecessor database through an OCLC member library, which have been available from the 1990s through today.

83. Attachment C-4 is a download I made from the Library of Congress OPAC (online catalog) on September 1, 2022. The document cataloged in this record is Zhang as verified by the OPAC record fields including meeting name: *ACM SIGGRAPH Symposium on Interactive 3D Graphics and Games*; main title: *Proceedings*; publisher and publication date; Association of Computing Machinery from 2005-.

84. Zhang could have been located in the Library of Congress OPAC by searching for meeting name and title: *Proceedings, ACM SIGGRAPH Symposium on Interactive 3D Graphics and Games*; or by searching the subject headings: *Computer graphics – Congresses*; *Three-dimensional – Congresses*; *Computer graphics*; and/or *Three dimensional display systems*.

85. The Library of Congress OPAC record documents that the *2006 Proceedings, ACM SIGGRAPH Symposium on Interactive 3D Graphics and Games* is held by the Library of Congress is listed in “Request in Jefferson or Adams Reading Rooms” Latest receipts 2009, 2008, 2007, **2006**, 2005, as shown below:

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86. The date stamped on Attachment C-1 of August 15, 2006, as shown below, indicates receipt of Zhang by the Library of Congress, after which it would have been sent for processing and labeling. From my extensive professional experience and my knowledge of the Library of Congress processing, it is my opinion that Zhang would have been available at the Library of Congress within a week to ten days, therefore, Zhang would have been available no later than August 25, 2006.



87. Once Zhang was entered into the general collection of the Library of Congress, members of the public could access the book by having it brought to either the Jefferson or Adams Reading Rooms. The collections of the Library of Congress are searchable by subject matter, author, or title such that a skilled researcher could find works in which they were interested. For example, a member of the public could have located a copy of Zhang by searching for the meeting name and title: *Proceedings, ACM SIGGRAPH Symposium on Interactive 3D Graphics and Games*; or by searching the subject headings: *Computer graphics* –

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88. Members of the public could read, study, and make notes about a selected work in the Library of Congress Reading Rooms. Further, members of the public were permitted to make photocopies of portions of the work while in the Reading Rooms. Accordingly, a copy of Zhang was accessible to the general public when it was available at the Library of Congress.

3. Conclusion Regarding Zhang

89. I conclude that Zhang, EX1011, is an authentic document and would have been publicly accessible through the Library of Congress no later than August 25, 2006.

V. CONCLUSION

90. I reserve the right to supplement my opinions in the future to respond to any arguments that Patent Owner or its expert(s) may raise and to take-into account new information as it becomes available to me.

I hereby declare under penalty of perjury under the laws of the United States of America that the foregoing is true and correct, and that all statements made of my own knowledge are true and that all statements made on information and belief are believed to be true. I understand that willful false statements and the like are punishable by fine or imprisonment, or both (18 U.S.C. § 1001).

Executed on October 21, 2022 in Williamsburg, Virginia.


JAMES L. MULLINS, Ph.D

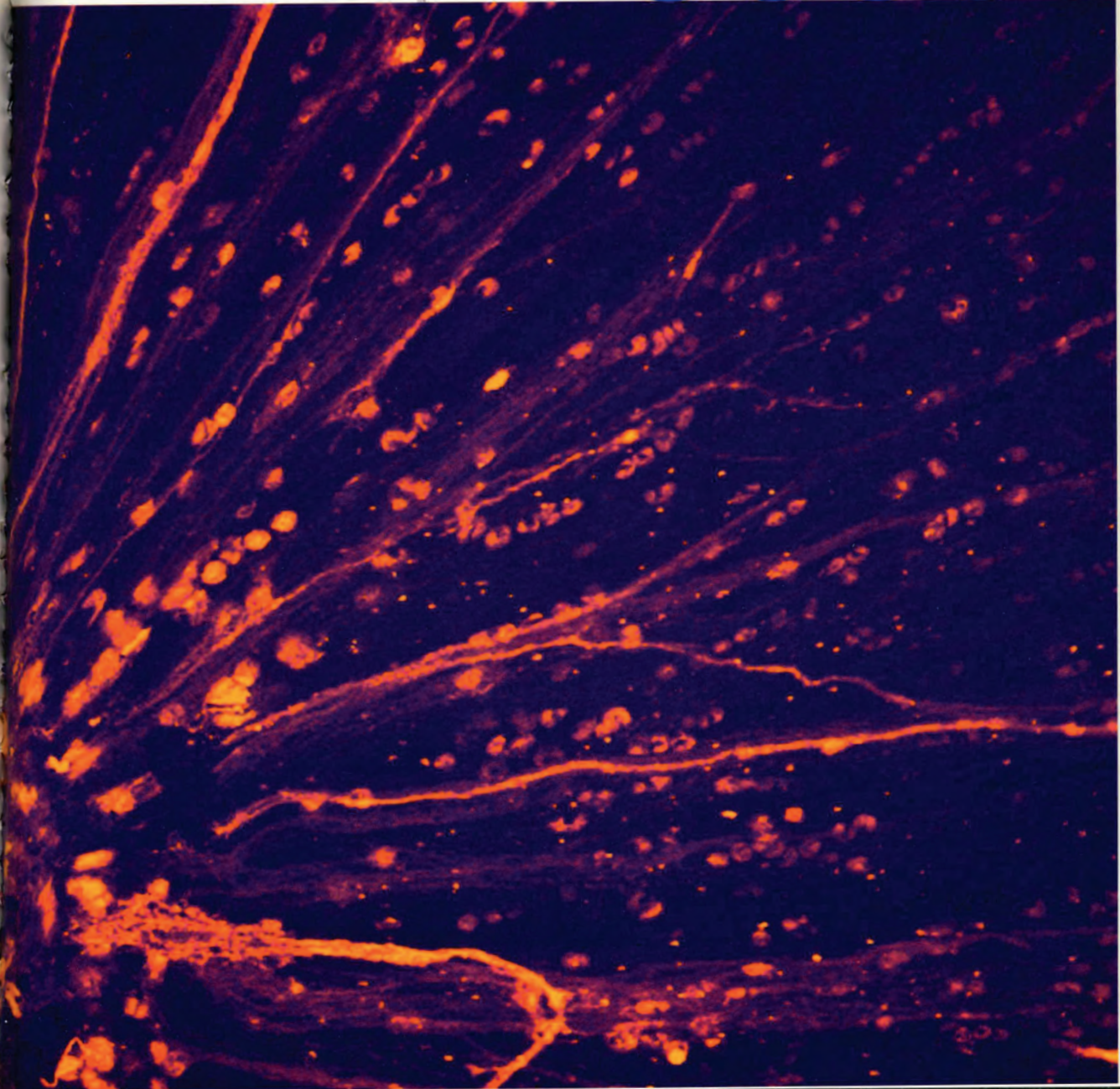
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Journal of

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Volume 191, Part 2, August 1998



Journal of

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FRONT COVER

Two-photon absorption image of the retina of a fish eye using optimally dispersion pre-compensated 170 fs optical pulses. The nucleus of the retina cells is stained with DAPI, whereas the nerve cell fibres are stained with FITC/Rhodamine. See the article by Müller *et al.* beginning on page 141.

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SHORT COMMUNICATION

Real-time three-dimensional imaging of macroscopic structures

T. WILSON, M. A. A. NEIL & R. JUŠKAITIS

Department of Engineering Science, University of Oxford, Parks Road, Oxford OX1 3PJ, U.K.

Key words. 3D imaging, optical sectioning.

Summary

We describe an extremely simple method of obtaining optically sectioned images with conventional low-power imaging systems in real time. A single spatial frequency grid pattern is projected onto an object. Images taken at three spatial positions of the grid projection are processed to provide 3D images of macroscopic structures.

The confocal optical system is very simple and merely involves focusing light from a point source onto an object and refocusing the reflected or fluorescent light onto a point detector. The point detector, or pinhole, acts as a physical obstruction which prevents light from out-of-focus planes contributing efficiently to the image. This is the origin of the optical sectioning or depth discrimination property. The system we have just described merely probes one point of the object – in order to form an image it is necessary to introduce scanning. It is relatively simple to build a scanning system suitable for microscopy and the most common application of the confocal principle has probably been in the form of the confocal microscope (Wilson & Sheppard, 1984; Wilson, 1990; Pawley, 1995). However, the principle applies equally well to the imaging of larger objects and confocal macroscopes may also be built (Dixon *et al.*, 1995a,b). The optics in these systems need careful design and usually a telecentric $f^*\theta$ laser scan lens is used to permit large specimens to be scanned quickly. An alternative method of producing optically sectioned images in real time using simple white light sources has recently been proposed for microscopy (Neil *et al.*, 1997) and we will show in this short communication that this approach also permits a simple, cheap, optically sectioning microscope to be built with the minimum modification of existing low-power imaging systems.

The basis of the approach is to realize that in a conventional microscope it is only the zero spatial

frequency in the transfer function which does not attenuate with defocus – all the other spatial frequencies do attenuate with defocus and hence we can see that a conventional microscope may be thought to exhibit optical sectioning for all spatial frequencies imaged apart from zero. Our method therefore is to modify the illumination system so as to project a one-dimensional single spatial frequency fringe pattern onto the object. The microscope will then image the fringe pattern efficiently only on those portions of the object that are in focus. We can therefore obtain an optically sectioned image by extracting only those parts of the image where the fringe pattern is visible. Let us assume that the single spatial frequency fringe pattern which illuminates the object may be written as

$$s(x, y) = 1 + m \cos(2\pi\nu x + \phi_0) \quad (1)$$

where m denotes the modulation depth, ν the spatial frequency and ϕ_0 an arbitrary spatial phase. A full theory is presented elsewhere (Neil *et al.*, 1997) but it will suffice for our purposes to claim that this illumination leads to an image of the form

$$I = I_0 + I_s \cos(2\pi\nu x + \phi_0) \quad (2)$$

where I_0 denotes a conventional image due to the constant term in Eq.(1) and I_s is the desired sectioned image modulated by the fringe pattern.

A simple way to extract I_s and I_0 is to take three images I_1 , I_2 and I_3 which correspond to three relative spatial phases $\phi_0 = 0^\circ$, 120° and 240° . We then find that

$$I_s = [\sqrt{(2)/3}][I_1 + I_2)^2 + (I_1 - I_3)^2 + (I_2 - I_3)^2]^{1/2} \quad (3)$$

and

$$I_0 = (I_1 + I_2 + I_3)/3 \quad (4)$$

which permits us to extract both the sectioned image and the conventional image from the same three raw images. We emphasize that Eq.(2) is approximate for the purposes

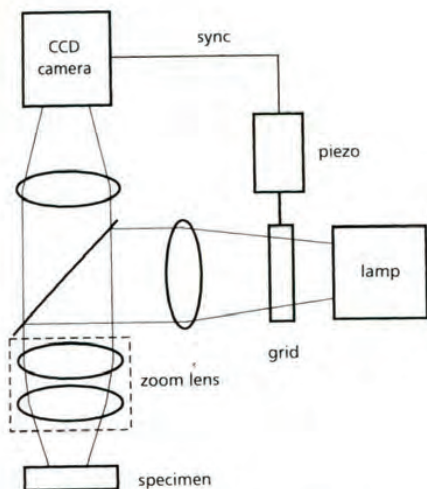


Fig. 1. Schematic diagram of the macroscope system.

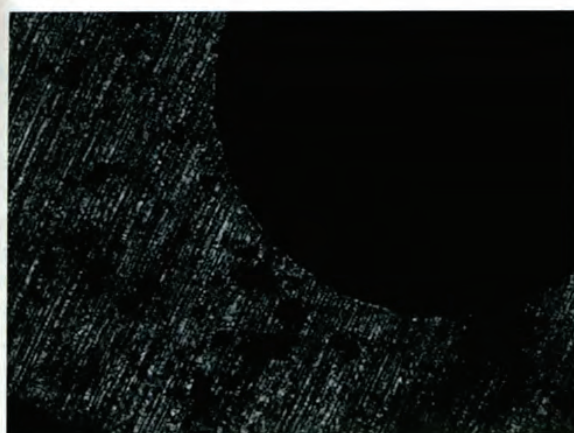
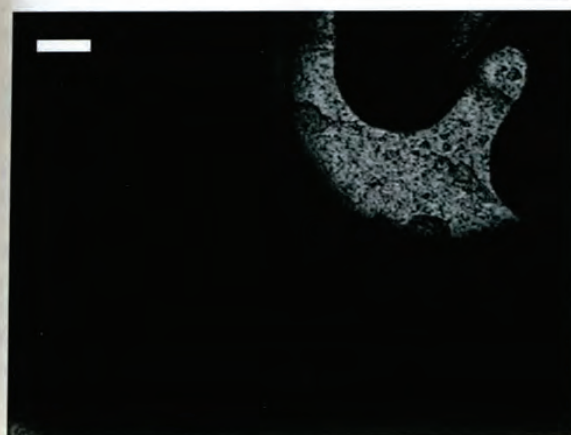
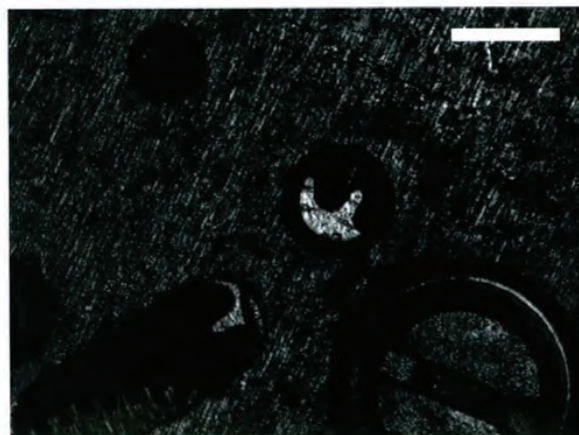


Fig. 2. Optically sectioned images, taken at focal settings 1.25 mm apart, of a section of a wrist watch mechanism: the scale bar depicts a length of 100 μ m.



Fig. 3. Three autofocus images of the wrist watch mechanism at relative zoom settings of 1.25, 3 and 7. The scale bar depicts a length of 1 mm in the 1.25 zoom image.

of explanation but that Eqs. (3) and (4) also follow from a more detailed theory (Neil *et al.*, 1997).

Equations (3) and (4) are the basis of our approach. We introduce a one-dimensional grid pattern into the illumination path of our low-power imaging system so that a grid (fringe) pattern is imaged onto the object. We then obtain three images at three spatial positions of the grid and hence compute the sectioned and conventional images according to Eqs. (3) and (4).

Figure 1 shows a schematic of the system which was built around an Optem Zoom 70 magnifier which could be set to magnifications between 0.75 and 5.25. We merely introduced a 40-line mm⁻¹ one-dimensional grid into the illumination path. A standard 15-W tungsten halogen lamp was used as the light source, together with a green filter (100 nm bandwidth). Images were recorded with a CCD camera and transferred to a Matrox Meteor frame grabber. The grid was moved in a simple sawtooth fashion synchronized to the CCD camera frame rate such that three successive camera images correspond to a spatial shift of one-third of a period of the projected image of the grid. Optically sectioned images were obtained from Eq. (3), together with a look-up table which mapped all possible combinations of I_1 , I_2 and I_3 from our 8-bit camera to I_s .

In order to demonstrate the optical sectioning capacity of our microscope we show in Fig. 2 two images taken at focal settings 1.25 mm apart of a portion of a wrist watch mechanism. The optical sectioning is clearly demonstrated. Finally on Fig. 3 we show three autofocus images, obtained by displaying the maximum image intensity at each pixel throughout the entire image volume, at relative zoom settings of 1.25, 3 and 7.

In conclusion, we have described a very simple modification to a low-power imaging system which results in an optical sectioning capability which permits three-dimensional imaging of macroscopic structures to be performed in real time.

Acknowledgments

This work was funded by the Paul Instrument Fund of the Royal Society. We thank Amarel Precision Instruments for the supply of the Optem Zoom 70.

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ATTACHMENT A-2

SHORT COMMUNICATION

Real-time three-dimensional imaging of macroscopic structures

T. WILSON, M. A. A. NEIL & R. JUŠKAITIS

Department of Engineering Science, University of Oxford, Parks Road, Oxford OX1 3PJ, U.K.

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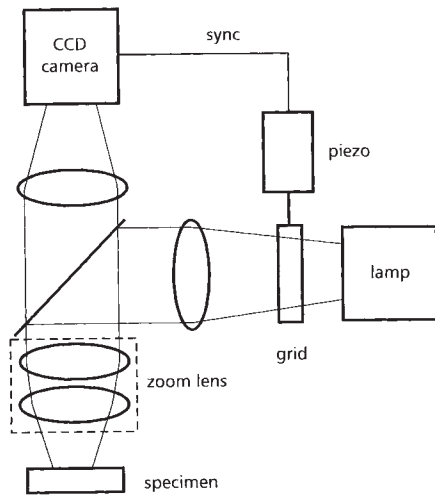


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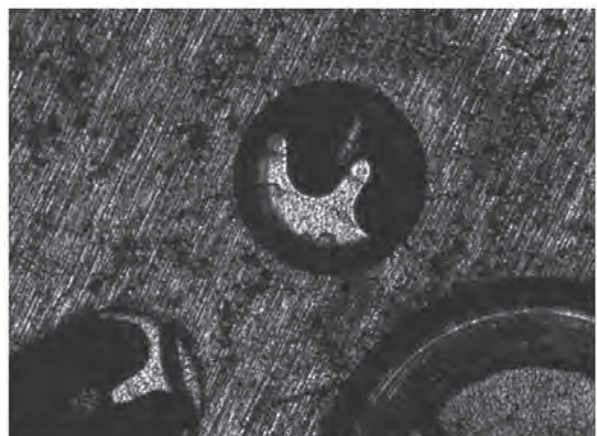
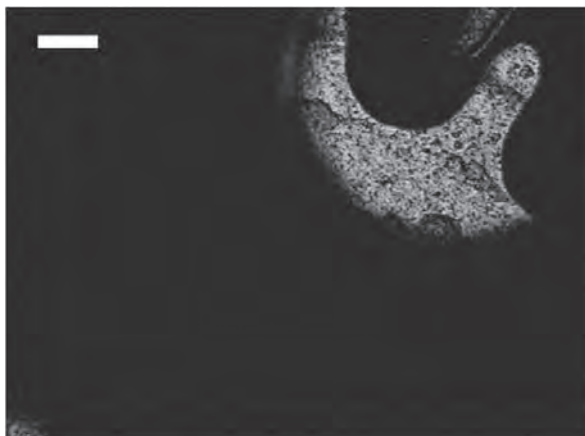
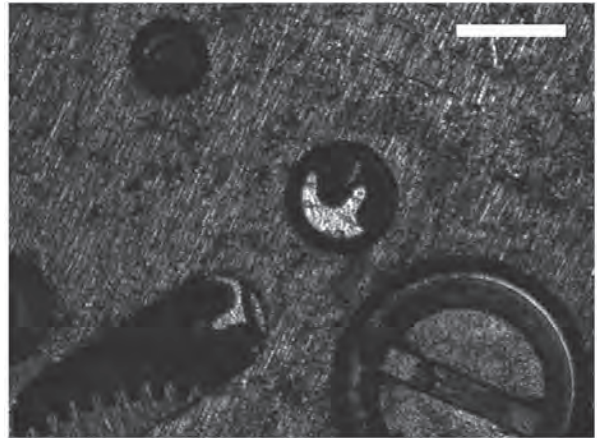


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In conclusion, we have described a very simple modification to a low-power imaging system which results in an optical sectioning capability which permits three-dimensional imaging of macroscopic structures to be performed in real time.

Acknowledgments

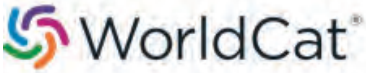
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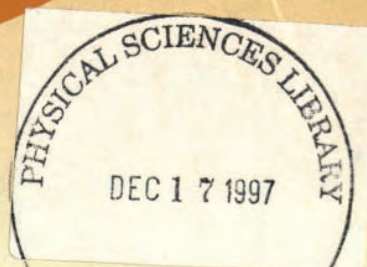
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December 15 1997



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M. A. A. Neil, R. Juškaitis, and T. Wilson

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Received August 26, 1997

We describe a simple method of obtaining optical sectioning in a conventional wide-field microscope by projecting a single-spatial-frequency grid pattern onto the object. Images taken at three spatial positions of the grid are processed in real time to produce optically sectioned images that are substantially similar to those obtained with confocal microscopes. © 1997 Optical Society of America

The confocal scanning optical microscope is a coherent image-formation system in which all spatial frequencies within the transfer function attenuate with defocus.^{1,2} This means that only in-focus detail is imaged efficiently, which permits volume structures to be examined in three dimensions. The image formation in a conventional wide-field microscope, on the other hand, is in general partially coherent, and not all spatial frequencies within the transfer function attenuate with defocus; hence these systems do not possess the optical sectioning properties of the confocal instruments. However, if we examine the weak object transfer function for these instruments,¹ we find that it is only the zero spatial frequency that does not attenuate with defocus. This suggests the basis of our approach to obtain optically sectioned images from a conventional wide-field microscope. We modify the illumination system of the microscope to project a single-spatial-frequency grid pattern onto the object. The microscope will then image efficiently only that portion of the object where the grid pattern is in focus. We will thus obtain an optically sectioned image of the object but with the unwanted grid pattern superimposed. The rate of attenuation with defocus or optical sectioning strength will, of course, depend on the particular spatial frequency that is projected onto the object. The ideal of projecting various patterns onto an object to obtain information about their three-dimensional structure is not new, and various methods for doing this have been suggested.^{3,4} The fundamental problem with all these approaches is that to be useful a simple method must be available to remove the unwanted grid pattern from the optically sectioned image. The approaches to microscopy with which we are familiar^{3,4} all involve the use of some form of matched detector grid that must be aligned to within stringent requirements. It therefore seems unlikely that these approaches will lead to rugged, easily implementable designs. In this Letter we present a simple method to remove the grid pattern that permits us to obtain optically sectioned images from a conventional microscope in real time.

The optical system consists simply of an illumination mask $S(t_0, w_0)$, which is imaged onto an object of amplitude transmittance or reflectance $\tau(t_1, w_1)$. The final image is recorded by a CCD camera in the image

plane (t, w) . The mask is illuminated incoherently, which permits us to write the image intensity as

$$I(t, w) = \iint S(t_0, w_0) \left| \iint h_1(t_0 + t_1, w_0 + w_1) \times \tau(t_1, w_1) h_2(t_1 + t, w_1 + w) dt_1 dw_1 \right|^2 dt_0 dw_0, \quad (1)$$

where $h_{1,2}$ represents the amplitude point-spread functions of the two lenses. We also elect to work in optical coordinates (t, w) that are related to real coordinates (x, y) through $(t, w) = (2\pi/\lambda)(x, y)n \sin \alpha$, where $n \sin \alpha$ is the numerical aperture (NA) and λ denotes the wavelength.^{1,2}

Let us now assume that the illumination mask takes the form of a one-dimensional grid, which we can write for simplicity as

$$S(t_0, w_0) = 1 + m \cos(\tilde{\nu} t_0 + \phi_0), \quad (2)$$

where m denotes a modulation depth and ϕ_0 is an arbitrary spatial phase. The normalized spatial frequency $\tilde{\nu}$ is related to the actual spatial frequency ν through $\tilde{\nu} = \beta \lambda \nu / \text{NA}$, where β denotes the magnification between the grid plane and the specimen plane. If we now substitute Eq. (2) into Eq. (1) we have

$$I(t, w) = I_0 + I_c \cos \phi_0 + I_s \sin \phi_0, \quad (3)$$

where I_0 is given by Eq. (1) with $S = 1$ and, of course, represents a conventional wide-field image. I_c and I_s represent the images that are due to masks of forms $m \cos(\tilde{\nu} t_0)$ and $m \sin(\tilde{\nu} t_0)$, respectively. These definitions suggest that if we are able to form $I_p = (I_c^2 + I_s^2)^{1/2}$ we would remove the grid pattern from the image of the specimen. We can readily achieve this result by taking three images, I_1, I_2 , and I_3 , which correspond to the relative spatial phases $\phi_0 = 0, \phi_0 = 2\pi/3$, and $\phi_0 = 4\pi/3$, respectively. We can thus obtain an optically sectioned image, which does not contain I_0 , by calculating

$$I_p = \left[(I_1 - I_2)^2 + (I_1 - I_3)^2 + (I_2 - I_3)^2 \right]^{1/2}, \quad (4)$$

which is analogous to square-law detection in communications systems.⁵ Alternatively, I_p can be formed as

$$I_p = \left| I_1 + I_2 \exp j \frac{2\pi}{3} + I_3 \exp \frac{4\pi}{3} \right|, \quad (5)$$

which is the equivalent of homodyne detection. We note that the conventional image, I_0 , can be recovered from $I_1 + I_2 + I_3$.

To confirm that the image obtained in this way does possess an optical sectioning property in the sense usually understood in confocal microscopy we consider how the image intensity decays with defocus when a plane mirror is used as a specimen. We set $\tau(t_0, w_0) = 1$ in Eq. (1), which together with Eq. (3)–(5) permits us to write

$$I_p(t, w) = \left| \iint \exp \tilde{\nu} t_0 \left| \iint h_1(t_0 + t_1, w_0 + w_1) \right. \right. \\ \left. \left. \times h_2(t_1 + t, w_1 + w) dt_1 dw \right|^2 dt_0 dw_0 \right|. \quad (6)$$

It is then a simple matter to introduce the pupil functions $P_{1,2}(\xi, \eta)$ through the Fourier transform of the amplitude point-spread functions, $h_{1,2}(t, w)$, to give

$$I_p = \left| \iint P_1(\xi, \eta) P_2(\xi, \eta) P_1^*(\xi - \tilde{\nu}, \eta) \right. \\ \left. \times P_2^*(\xi - \tilde{\nu}, \eta) d\xi d\eta \right|, \quad (7)$$

which, for the case of equal pupil functions $P_1 = P_2$, can be written, in the presence of defocus u , as

$$I_p(u) = |g(2u, \tilde{\nu})|, \quad (8)$$

where $g(u, \tilde{\nu}) = P \otimes P^*$, where $\otimes$ denotes the convolution operation and the normalized defocus parameter u is related to the actual defocus z through $u = 8(\pi/\lambda)z \sin^2(\alpha/2)$.

We note that the function $g(u, \tilde{\nu})$ is formally identical to the weak object transfer function in a conventional microscope. That function can readily be evaluated numerically, but it will suffice for our purposes to use an approximation that is due to Stokseth,⁶ which permits us to write

$$g(u, \tilde{\nu}) = f(\tilde{\nu}) \left\{ 2 \frac{J_1[u\tilde{\nu}(1 - \tilde{\nu}/2)]}{[u\tilde{\nu}(1 - \tilde{\nu}/2)]} \right\}, \quad (9)$$

with $f(\tilde{\nu}) = 1 - 0.69\tilde{\nu} + 0.0076\tilde{\nu}^2 + 0.043\tilde{\nu}^3$. We therefore find that

$$I_p(u) \sim \left| 2 \frac{J_1[2u\tilde{\nu}(1 - \tilde{\nu}/2)]}{[2u\tilde{\nu}(1 - \tilde{\nu}/2)]} \right|, \quad (10)$$

which confirms that our instrument does exhibit optical sectioning in the same fashion as a confocal microscope. The strength of the sectioning does, of course, depend on the value of $\tilde{\nu}$ chosen. We note that in the limit of $\tilde{\nu} = 0$, which corresponds to removing the grid pattern, $I_s(u) = \text{constant}$, as would be expected in the conventional microscope limit. The maximum sectioning strength is found to correspond to a normalized spatial frequency $\tilde{\nu} = 1$.

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troduce separate lenses both to project the image of the grid onto the specimen and to image the specimen onto the CCD camera. The result was an effective magnification between the illumination plane and the specimen of $(50/180)M$, where M is the nominal magnification of the objective lens. A 15-W tungsten-halogen lamp was used as the light source, together with a green filter (bandwidth 100 nm). Images were recorded with a CCD camera and transferred to a Matrox Meteor frame grabber. The grid was moved in a simple saw-tooth fashion synchronized to the camera frame rate such that any three successive camera images corresponded to a spatial shift of one third of a period in the position of the projected image of the grid (Fig. 1). The fact that the grid is in motion during the integration time of each frame results in a reduction in the values of I_c and I_s in Eq. (3) by a factor of $\text{sinc}(\pi t/3T)$, where t is the integration time of the camera and T is the time between the recording of successive frames. In our case $T = 2t = 40$ ms, and hence this factor is only 0.955. In the worst case, $T = t$, the factor falls to only 0.827. The optically sectioned images were obtained by use of Eq. (4) together with a look-up table that mapped all possible combinations of I_1 , I_2 , and I_3 from our 8-bit camera to I_p .

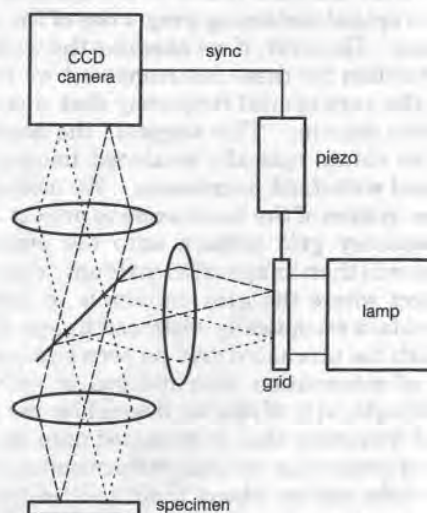


Fig. 1. Schematic of the optical arrangement.

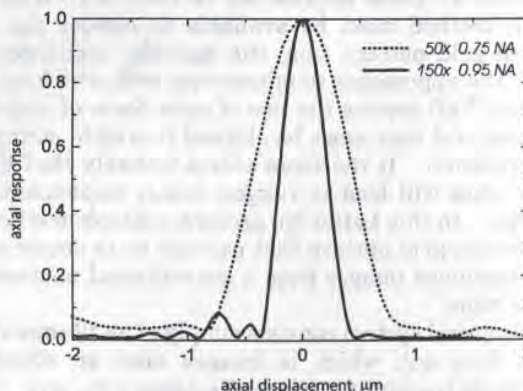


Fig. 2. Measured axial responses of the system.

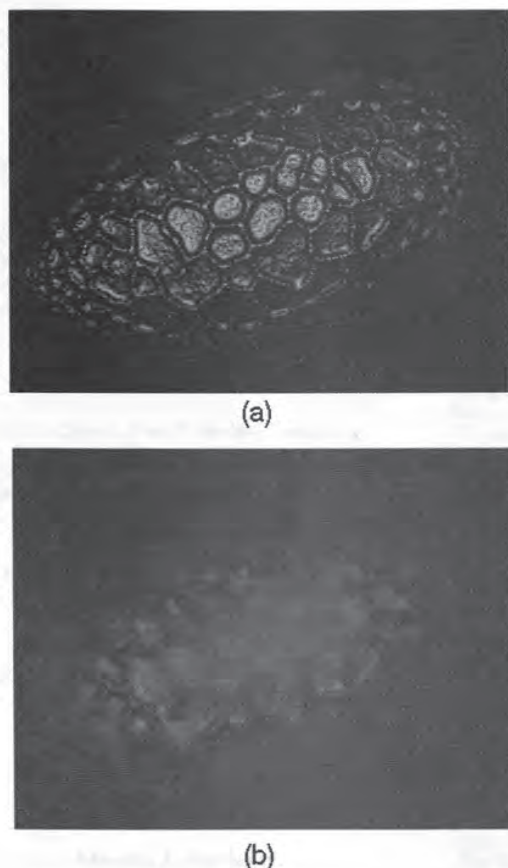


Fig. 3. (a) Autofocus image of lily pollen grain. The field size is $100\ \mu\text{m} \times 70\ \mu\text{m}$. (b) Conventional image of the lily pollen grain when the microscope is focused in a mid-depth plane.

To measure the optical sectioning strength of our microscope we used a plane mirror together with a calibrated axial translation stage; the resulting axial responses are shown in Fig. 2 for two Olympus MD Plan objectives. We note that the use of the $50\times$, $0.75\ \text{NA}$ corresponds to $\tilde{\nu} = 0.4$ in our system, for which relation (10) predicts a FWHM of $0.87\ \mu\text{m}$, which compares well with the measured value of $0.91\ \mu\text{m}$. Theory predicts that the $150\times$, $0.95\ \text{NA}$ dry objective should give $\tilde{\nu} = 0.8$ and hence a FWHM of $0.27\ \mu\text{m}$. In practice, we measured $0.43\ \mu\text{m}$, which

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Finally, in Fig. 3 we show images obtained by imaging the thick volume structure of a lily pollen grain. Figure 3(a) represents an autofocus image obtained by displaying the maximum image intensity at each pixel throughout a $30\text{-}\mu\text{m}$ axial scan with the $50\times$, $0.75\ \text{NA}$ objective lens. The full surface texture of the grain is well resolved over the entire image volume. Figure 3(b), on the other hand, shows a conventional image taken at a plane midway through the grain. It is clear that a good deal of out-of-focus blur is present here, which prevents any meaningful three-dimensional image processing from being carried out.

In conclusion, we have presented an extremely simple modification to a conventional microscope illumination system that permits optically sectioned images to be obtained and hence volume rendering of thick objects to be carried out. The image formation is formally different from that obtained in a confocal microscope, and the transfer function is found to be slightly different for object features that vary in the t and w directions. However, the differences are not great, and in all the specimens that we examined with this simple technique we obtained images that were substantially similar to those obtained with laser-based confocal systems.

This research was funded by the Paul Instrument Fund of the Royal Society.

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ATTACHMENT B-2

Method of obtaining optical sectioning by using structured light in a conventional microscope

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We describe a simple method of obtaining optical sectioning in a conventional wide-field microscope by projecting a single-spatial-frequency grid pattern onto the object. Images taken at three spatial positions of the grid are processed in real time to produce optically sectioned images that are substantially similar to those obtained with confocal microscopes. © 1997 Optical Society of America

The confocal scanning optical microscope is a coherent image-formation system in which all spatial frequencies within the transfer function attenuate with defocus.^{1,2} This means that only in-focus detail is imaged efficiently, which permits volume structures to be examined in three dimensions. The image formation in a conventional wide-field microscope, on the other hand, is in general partially coherent, and not all spatial frequencies within the transfer function attenuate with defocus; hence these systems do not possess the optical sectioning properties of the confocal instruments. However, if we examine the weak object transfer function for these instruments,¹ we find that it is only the zero spatial frequency that does not attenuate with defocus. This suggests the basis of our approach to obtain optically sectioned images from a conventional wide-field microscope. We modify the illumination system of the microscope to project a single-spatial-frequency grid pattern onto the object. The microscope will then image efficiently only that portion of the object where the grid pattern is in focus. We will thus obtain an optically sectioned image of the object but with the unwanted grid pattern superimposed. The rate of attenuation with defocus or optical sectioning strength will, of course, depend on the particular spatial frequency that is projected onto the object. The ideal of projecting various patterns onto an object to obtain information about their three-dimensional structure is not new, and various methods for doing this have been suggested.^{3,4} The fundamental problem with all these approaches in that to be useful a simple method must be available to remove the unwanted grid pattern from the optically sectioned image. The approaches to microscopy with which we are familiar^{3,4} all involve the use of some form of matched detector grid that must be aligned to within stringent requirements. It therefore seems unlikely that these approaches will lead to rugged, easily implementable designs. In this Letter we present a simple method to remove the grid pattern that permits us to obtain optically sectioned images from a conventional microscope in real time.

The optical system consists simply of an illumination mask $S(t_0, w_0)$, which is imaged onto an object of amplitude transmittance or reflectance $\tau(t_1, w_1)$. The final image is recorded by a CCD camera in the image

plane (t, w) . The mask is illuminated incoherently, which permits us to write the image intensity as

$$I(t, w) = \iint S(t_0, w_0) \left| \iint h_1(t_0 + t_1, w_0 + w_1) \times \tau(t_1, w_1) h_2(t_1 + t, w_1 + w) dt_1 dw_1 \right|^2 dt_0 dw_0, \quad (1)$$

where $h_{1,2}$ represents the amplitude point-spread functions of the two lenses. We also elect to work in optical coordinates (t, w) that are related to real coordinates (x, y) through $(t, w) = (2\pi/\lambda)(x, y)n \sin \alpha$, where $n \sin \alpha$ is the numerical aperture (NA) and λ denotes the wavelength.^{1,2}

Let us now assume that the illumination mask takes the form of a one-dimensional grid, which we can write for simplicity as

$$S(t_0, w_0) = 1 + m \cos(\tilde{\nu} t_0 + \phi_0), \quad (2)$$

where m denotes a modulation depth and ϕ_0 is an arbitrary spatial phase. The normalized spatial frequency $\tilde{\nu}$ is related to the actual spatial frequency ν through $\tilde{\nu} = \beta \lambda \nu / \text{NA}$, where β denotes the magnification between the grid plane and the specimen plane. If we now substitute Eq. (2) into Eq. (1) we have

$$I(t, w) = I_0 + I_c \cos \phi_0 + I_s \sin \phi_0, \quad (3)$$

where I_0 is given by Eq. (1) with $S = 1$ and, of course, represents a conventional wide-field image. I_c and I_s represent the images that are due to masks of forms $m \cos(\tilde{\nu} t_0)$ and $m \sin(\tilde{\nu} t_0)$, respectively. These definitions suggest that if we are able to form $I_p = (I_c^2 + I_s^2)^{1/2}$ we would remove the grid pattern from the image of the specimen. We can readily achieve this result by taking three images, I_1, I_2 , and I_3 , which correspond to the relative spatial phases $\phi_0 = 0, \phi_0 = 2\pi/3$, and $\phi_0 = 4\pi/3$, respectively. We can thus obtain an optically sectioned image, which does not contain I_0 , by calculating

$$I_p = \left[(I_1 - I_2)^2 + (I_1 - I_3)^2 + (I_2 - I_3)^2 \right]^{1/2}, \quad (4)$$

which is analogous to square-law detection in communications systems.⁵ Alternatively, I_p can be formed as

$$I_p = \left| I_1 + I_2 \exp j \frac{2\pi}{3} + I_3 \exp \frac{4\pi}{3} \right|, \quad (5)$$

which is the equivalent of homodyne detection. We note that the conventional image, I_0 , can be recovered from $I_1 + I_2 + I_3$.

To confirm that the image obtained in this way does possess an optical sectioning property in the sense usually understood in confocal microscopy we consider how the image intensity decays with defocus when a plane mirror is used as a specimen. We set $\tau(t_0, w_0) = 1$ in Eq. (1), which together with Eq. (3)–(5) permits us to write

$$I_p(t, w) = \left| \iint \exp \tilde{\nu} t_0 \left| \iint h_1(t_0 + t_1, w_0 + w_1) \right. \right. \\ \left. \left. \times h_2(t_1 + t, w_1 + w) dt_1 dw \right|^2 dt_0 dw_0 \right|. \quad (6)$$

It is then a simple matter to introduce the pupil functions $P_{1,2}(\xi, \eta)$ through the Fourier transform of the amplitude point-spread functions, $h_{1,2}(t, w)$, to give

$$I_p = \left| \iint P_1(\xi, \eta) P_2(\xi, \eta) P_1^*(\xi - \tilde{\nu}, \eta) \right. \\ \left. \times P_2^*(\xi - \tilde{\nu}, \eta) d\xi d\eta \right|, \quad (7)$$

which, for the case of equal pupil functions $P_1 = P_2$, can be written, in the presence of defocus u , as

$$I_p(u) = |g(2u, \tilde{\nu})|, \quad (8)$$

where $g(u, \tilde{\nu}) = P \otimes P^*$, where $\otimes$ denotes the convolution operation and the normalized defocus parameter u is related to the actual defocus z through $u = 8(\pi/\lambda)z \sin^2(\alpha/2)$.

We note that the function $g(u, \tilde{\nu})$ is formally identical to the weak object transfer function in a conventional microscope. That function can readily be evaluated numerically, but it will suffice for our purposes to use an approximation that is due to Stokseth,⁶ which permits us to write

$$g(u, \tilde{\nu}) = f(\tilde{\nu}) \left\{ 2 \frac{J_1[u\tilde{\nu}(1 - \tilde{\nu}/2)]}{[u\tilde{\nu}(1 - \tilde{\nu}/2)]} \right\}, \quad (9)$$

with $f(\tilde{\nu}) = 1 - 0.69\tilde{\nu} + 0.0076\tilde{\nu}^2 + 0.043\tilde{\nu}^3$. We therefore find that

$$I_p(u) \sim \left| 2 \frac{J_1[2u\tilde{\nu}(1 - \tilde{\nu}/2)]}{[2u\tilde{\nu}(1 - \tilde{\nu}/2)]} \right|, \quad (10)$$

which confirms that our instrument does exhibit optical sectioning in the same fashion as a confocal microscope. The strength of the sectioning does, of course, depend on the value of $\tilde{\nu}$ chosen. We note that in the limit of $\tilde{\nu} = 0$, which corresponds to removing the grid pattern, $I_s(u) = \text{constant}$, as would be expected in the conventional microscope limit. The maximum sectioning strength is found to correspond to a normalized spatial frequency $\tilde{\nu} = 1$.

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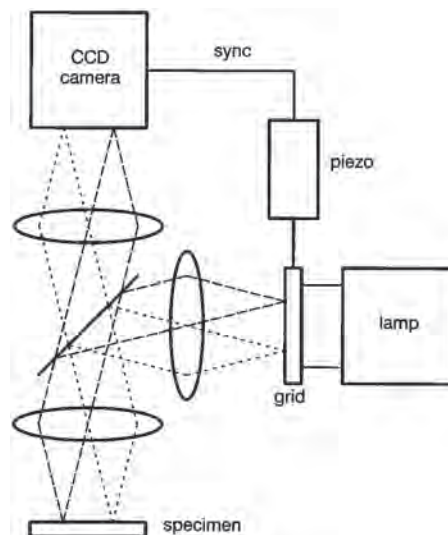


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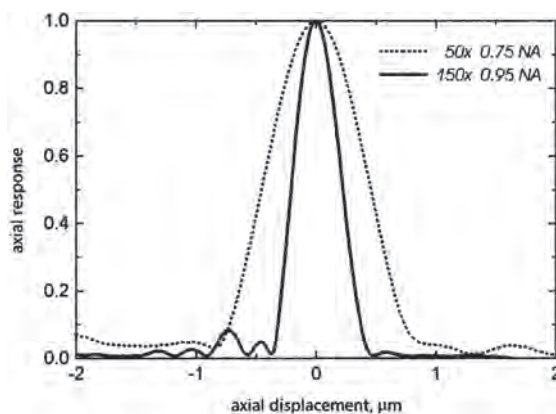


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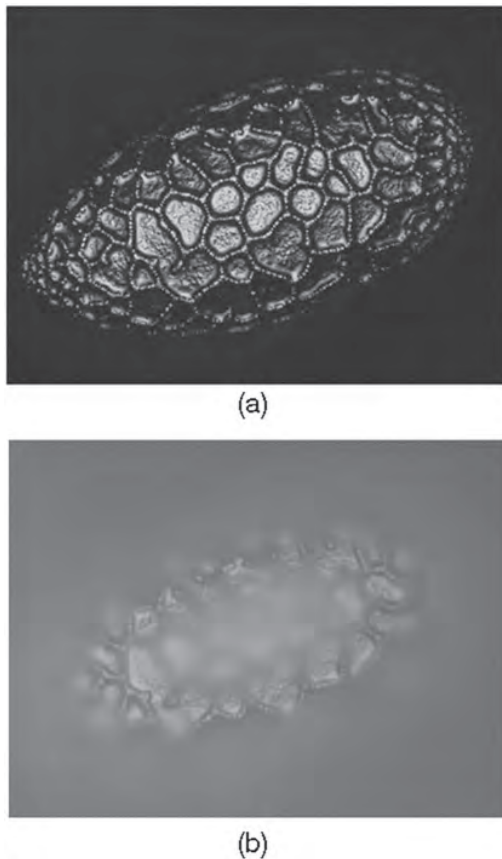


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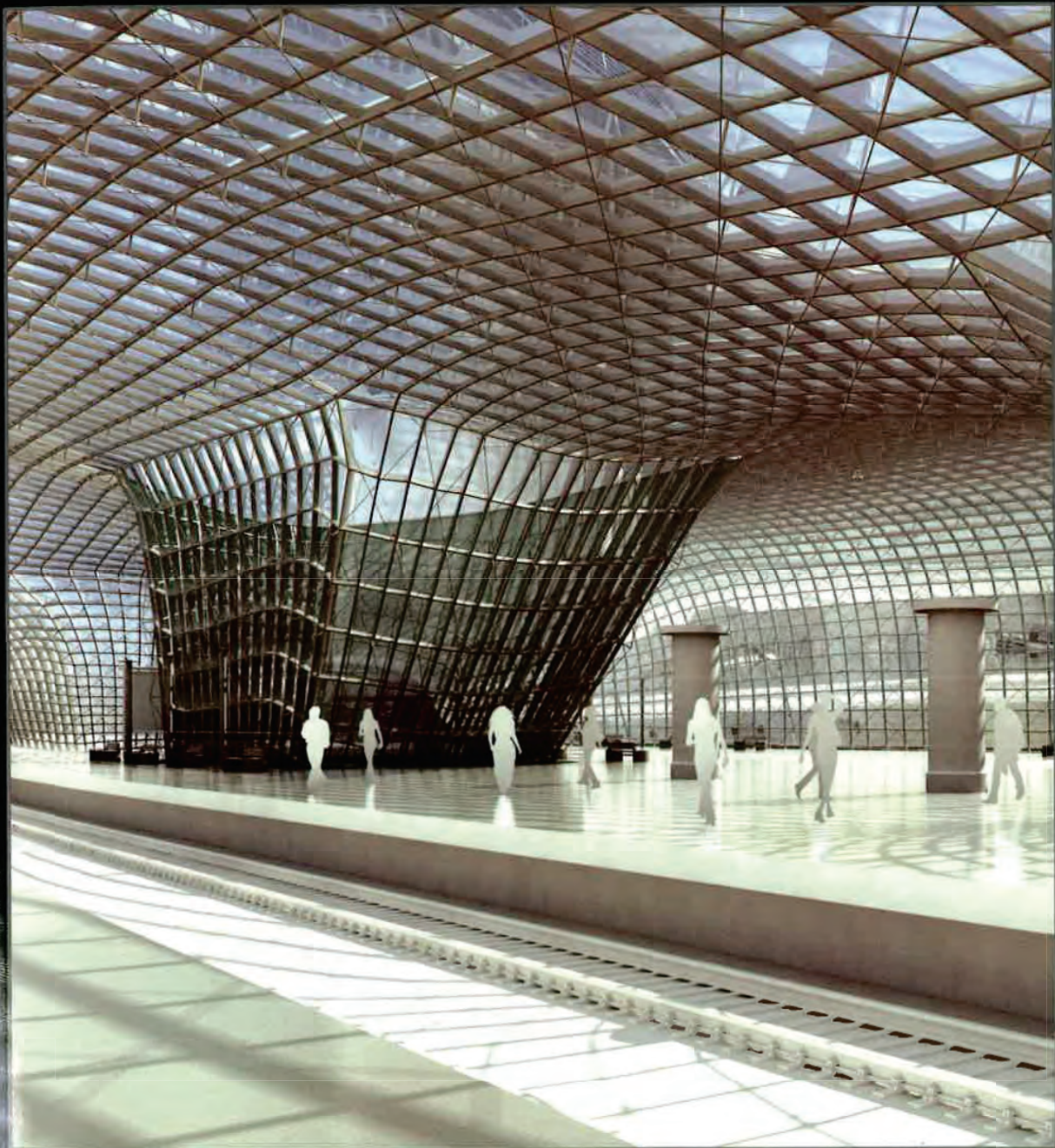
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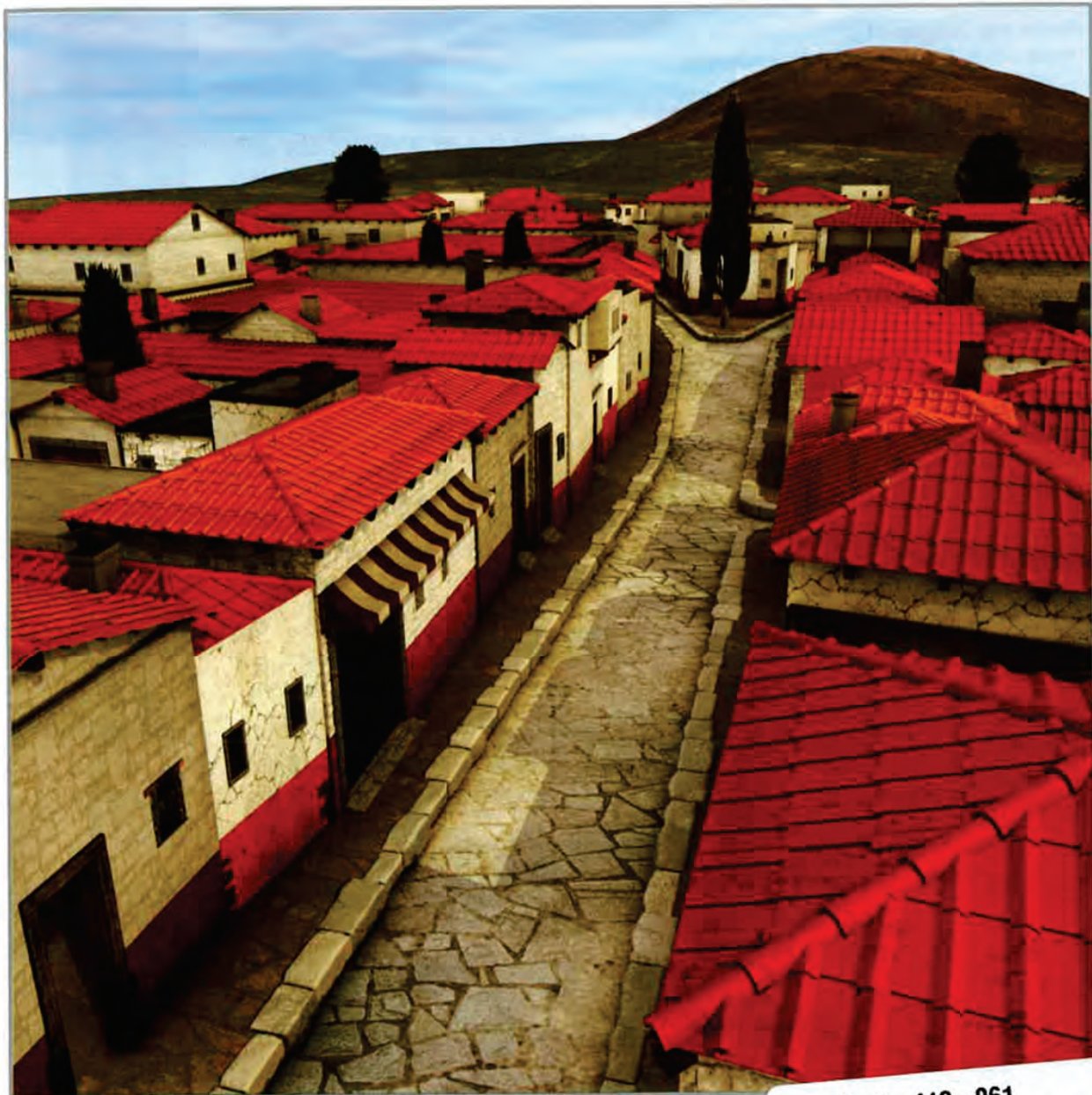
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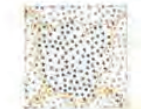
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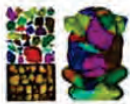
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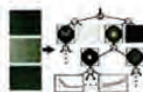


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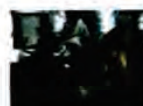
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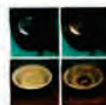
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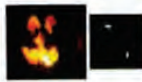
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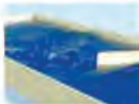
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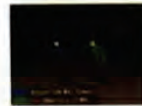
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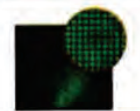
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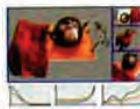


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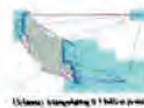
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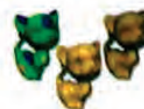
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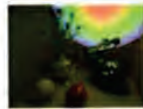
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Projection Defocus Analysis for Scene Capture and Image Display *

Li Zhang

Shree Nayar

Columbia University

Abstract

In order to produce bright images, projectors have large apertures and hence narrow depths of field. In this paper, we present methods for robust scene capture and enhanced image display based on projection defocus analysis. We model a projector's defocus using a linear system. This model is used to develop a novel temporal defocus analysis method to recover depth at each camera pixel by estimating the parameters of its projection defocus kernel in frequency domain. Compared to most depth recovery methods, our approach is more accurate near depth discontinuities. Furthermore, by using a coaxial projector-camera system, we ensure that depth is computed at all camera pixels, without any missing parts. We show that the recovered scene geometry can be used for refocus synthesis and for depth-based image composition. Using the same projector defocus model and estimation technique, we also propose a defocus compensation method that filters a projection image in a spatially-varying, depth-dependent manner to minimize its defocus blur after it is projected onto the scene. This method effectively increases the depth of field of a projector without modifying its optics. Finally, we present an algorithm that exploits projector defocus to reduce the strong pixelation artifacts produced by digital projectors, while preserving the quality of the projected image. We have experimentally verified each of our methods using real scenes.

CR Categories: I.3.3 [Computer Graphics]: Picture/Image Generation—Digitizing and scanning, display algorithm; I.4.8 [Image Processing and Computer Vision]: Scene Analysis—Depth cues, range data, shape.

Keywords: projector defocus, temporal defocus analysis, depth recovery, multi-focal projection, projector depixelation, refocus synthesis, image composition.

1 Introduction

Digital projection technologies, such as Digital Light Processing (DLP) and Liquid Crystal Displays (LCD), are increasingly used in consumer, commercial and scientific applications. In computer graphics and vision, video projectors have recently been used as per-pixel controllable light sources for real-time shape acquisition [Huang et al. 2003; Zhang et al. 2004; Davis et al. 2005; Koninek et al. 2005], for complex appearance capture [Levoy et al. 2004; Sen et al. 2005] and control [Raskar et al. 2001; Grossberg et al. 2004; Bimber et al. 2005]. All these applications require the projectors to be focused for best performance. In practice, projectors are built with large apertures to maximize their brightness. As a result, virtually all projectors have very narrow depths of field; they

are designed to produce focused images on a single fronto-parallel screen. An analysis of the defocus properties of projectors is therefore beneficial as it could lead to new methods that take advantage of, as well as compensate for, projection defocus.

In this paper, we provide the first systematic analysis of projector defocus and demonstrate its applications to robust scene capture and enhanced image display. We first present a simple linear model for projector defocus. Based on this model, we present a frequency-domain method for estimating the spatially-varying defocus kernel of a projector. The kernel estimated at each scene point is used to recover the 3D geometry of the scene. Based on the estimated kernel, we also present a technique that computationally manipulates an input image to minimize its defocus blur when it is projected onto a non-planar scene. Finally, we demonstrate that defocusing can be put to good use. A slight amount of defocusing, in conjunction with a compensation algorithm, can be used to reduce pixelation, a strong artifact produced by all digital projectors. Specifically, this paper makes the following three contributions:

Scene Geometry using Temporal Defocus Analysis: We propose a method called temporal defocus analysis that estimates depth at each camera pixel, independently, without using information from neighboring pixels (Section 3). Our method, compared to existing methods, such as stereo or even traditional depth from focus/defocus algorithms, is more accurate near depth discontinuities. Since the method is not based on triangulation, we can use a coaxial projector-camera system and compute depth at all camera pixels, without any missing parts. These advantages make the method uniquely suited to computer graphics applications like refocus synthesis and image composition, both of which we demonstrate.

Focused Projection at Multiple Depths: We present an iterative, spatially-varying filtering algorithm that compensates for defocus blur based on scene geometry (Section 4). This technique effectively increases the depth of field of a projector without modifying its optics. As a result, we are able to use a single projector to project well-focused images on multiple planes that are at different depths as well as on curved projection surfaces. We believe this capability addresses an important limitation of current projectors and widens their applicability in the real world.

Depixelation by Defocusing: Finally, we generalize our defocus compensation algorithm to reduce the strong pixelation artifacts produced by all digital projectors (Section 5). The key idea is to slightly defocus the projector so as to attenuate the high frequencies produced by pixelation and use the defocus compensation algorithm to make up for the induced projector defocus. This method is especially suited for projecting high resolution images using a low resolution projector, and we show several examples of results to illustrate its effects.

2 Previous Work

Many methods have been proposed in computer vision to recover 3D shape from images, including multi-view triangulation methods, single-view photometric methods, and camera focus/defocus methods. Triangulation-based methods [Faugeras 1993], e.g., structure from motion and stereo, require a point to be visible in at least two views to be reconstructed. Scenes with complex occlusions remain a challenging problem for these methods. Photometric methods [Horn and Brooks 1989], e.g., photometric stereo and shape from shading, estimate surface normals instead of surface depth. Converting normals to depths is an ill-posed problem for scenes with depth discontinuities.

*This work was conducted at the Computer Vision Laboratory at Columbia University. It was supported by an ITR grant from the National Science Foundation (No. IIS-00-85864). The authors thank Gurunandan Krishnan for his help with the experiments and the video and Anne Fleming for her help with the audio recording and the proofreading. The authors also thank www.dpreview.com for permitting us using their images as some of the examples shown in the paper.

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Depth recovery methods based on camera focus and defocus, e.g. [Pentland 1987; Nayar and Nakagawa 1994; Nayar et al. 1996; Schechner et al. 2000; Favaro and Soatto 2005], have the potential to recover depth at every pixel, regardless of the scene complexity and occlusions. To resolve the focus ambiguity of textureless surfaces, patterns can be projected to force scene texture [Girod and Scherrock 1989]. However, camera defocus kernels depend on local surface geometry. To simplify the kernel analysis, most previous works assume that, within a small spatial window, the surface depth is constant, the so-called *equalfocal assumption*. This assumption smears shape details and is invalid across depth discontinuities. To alleviate this problem, Jin et al. [2002] and Rajagopalan and Chaudhuri [1997] estimate depths for all pixels simultaneously via a large scale energy minimization, which is computationally expensive and prone to local minima. Our key observation is that, unlike camera defocus, the kernel for projector defocus is *scene independent*, for most scene surfaces. Specifically, when a 3D scene point sees the entire projector aperture, its defocus kernel depends only on its distance to the projector lens and not on its neighboring surface geometry. This difference arises from the fact that projector defocus convolution happens on the projector's image plane while camera defocus convolution happens on the scene surface. Exploiting this scene-independent property, we project a shifting pattern over the scene and compute depth at each pixel using just its intensity variation over time. Without using the equalfocal assumption, our method works well at depth discontinuities. Furthermore, it is simple and not subject to local minima.

Our temporal per-pixel defocus analysis is inspired by previous structured light range finding methods. In particular, Kanade et al. [1991] and Curless and Levoy [1995] use temporal intensity variation to resolve correspondences between camera pixels and a sweeping laser stripe. Huang et al. [2003] have developed a real-time range finder by sweeping periodic sinusoidal stripes using a DLP projector. Zhang et al. [2004] and Davis et al. [2005] have generalized these ideas to space-time stereo. All these range finding techniques are based on the principle of triangulation, which cannot estimate depth for points that are visible to only the camera or the source but not both. Since our method is not based on triangulation, we are able to use a coaxial configuration where the camera and projector share the same optical center, and compute depth at all camera pixels (no missing parts). To our knowledge, the only other technique that is able to estimate a complete depth map with clean discontinuity boundaries is time-of-flight, e.g., [Gonzales-Banos and Davis 2004], which requires expensive specialized hardware. Raskar et al. [2004] proposed a method to detect depth discontinuities using multiple flash lights. The detected discontinuities can be used to enhance stereo matching algorithms. Compared to this work, our method directly generates reliable depth estimation for all pixels, including the ones near discontinuities.

In addition to scene capture, several methods have been proposed that use cameras to enable projectors to display "better" images. These include compensating distortions due to surface geometry [Raskar et al. 2003] and correcting brightness variations due to surface color and texture [Grossberg et al. 2004; Bimber et al. 2005]. In these works, the projectors are often used to display images onto scenes with considerable depth variation, where defocus blur is inevitable and most often spatially-varying. Complementary to these previous methods, our work seeks to compensate for defocus blur, and hence could be beneficial to the previous methods. In [Bimber and Emmerling 2006], a system is proposed that can project focused images on multiple planes at different depths. This system uses multiple projectors where each projector is focused on a single plane. In our case, we use a single projector to simultaneously project well-focused images at multiple depths. Another interesting related work is by Majumder and Greg [2001], in which multiple projectors at different focal settings are combined to gen-

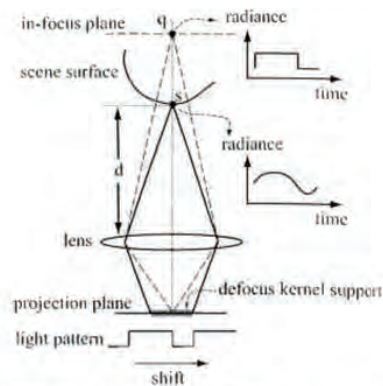


Figure 1: The principle of depth from projection defocus. Points at different distances to the projector lens exhibit different amounts of blur in their temporal radiance profile as a periodic illumination pattern is shifted across the scene.

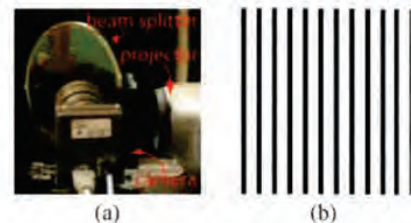


Figure 2: (a) A coaxial projector-camera system for depth from projection defocus. The system is made coaxial only to ensure that depth can be computed at all camera pixels. (b) The illumination pattern that is shifted across the scene to measure depth at each pixel, independently.

erate depth of field effects at an interactive rate.

Deblurring is a well-studied topic in image processing where numerous techniques have been proposed, ranging from classical Wiener filtering and conjugate gradient optimization [Jain 1989] to more recent algorithms based on graph cuts [Raj and Zabih 2005] and belief propagation [Tappen et al. 2004]. Our technique is based on bound-constrained quadratic programming [Nocedal and Wright 1999], which is a variant of existing algorithms that best suits our formulation of the problem. As we show, our deblurring method can also reduce pixelation effects produced by digital projectors.

3 Depth from Projection Defocus

In this section, we formulate the problem of recovering 3D shape from projection defocus and present our solution.

3.1 Temporal Defocus Analysis

Consider a scene that is illuminated by structured light from a projector which is focused behind the scene, as shown in Figure 1. For a point q that is in focus, its irradiance comes from a single point on the projector's image plane. For a point s that is out of focus, its irradiance equals the convolution of its defocus kernel with the structured light pattern on the projector's image plane. Assuming that the surface is opaque, the radiance I of s along any given outgoing direction can be written as

$$I = \alpha f(\mathbf{x}; z) * P(\mathbf{x}) + \beta, \quad (1)$$

where $*$ denotes convolution, α is a factor depending on surface reflectance¹, β is the radiance due to the ambient light. $f(\mathbf{x}; z)$ is the

¹To be precise, α takes into account all surface shading factors: BRDF, orientation with respect to the irradiance direction and the squared distance fall-off of the projector brightness.

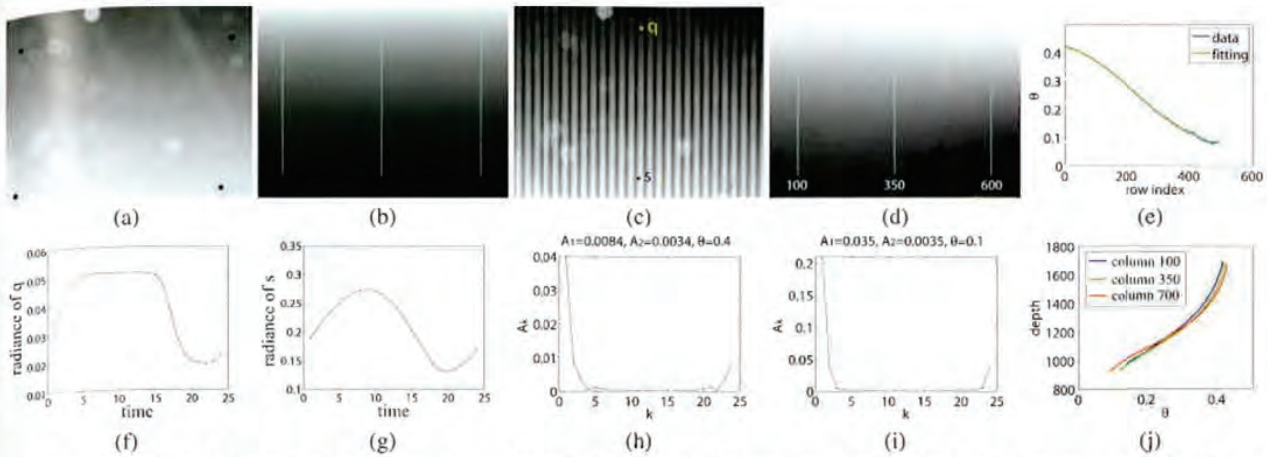


Figure 3: Illustration of the calibration procedure. (a) A white board with four markers tilted in front of the camera. (b) Depth map of the board computed using the markers. (c) The board under one of the stripe projection patterns. (d) θ map for the board. (e) θ values in column 350 of (d). (f,g) Temporal radiance profiles of the points q and s , respectively. (h,i) Discrete-time Fourier series (DFS) of (f) and (g). (j) Mappings from θ to depth z for columns 100, 350 and 600, respectively.

defocus kernel, and $P(\mathbf{x})$ is the illumination pattern. The defocus kernel f depends on the depth z .² We now describe how to recover the depth z by estimating the kernel f from radiance measurements.

3.2 Depth Estimation

To estimate the kernel f , we note that Eq. (1) defines a linear system in which the projection pattern and the scene radiance are the input and the output, respectively. Estimating the kernel of a linear system is a classical problem in system identification [Ljung 1998] and we take a frequency-domain approach to solve it in our setting. Our basic idea is to shift an illumination pattern with a wide range of frequencies within it across the scene. The radiance of a surface point over time is then the response of its defocus kernel to the excitation by the illumination pattern. As the pattern is shifted, points at different distances to the projector exhibit different amounts of blur in their temporal radiance profile, as illustrated in Figure 1. We use this temporal blur for depth recovery.

Given the temporal radiance sequence, I_l , $l = 0, \dots, L-1$, for a point, we quantify its blur by decomposing it into a discrete-time Fourier series (DFS) [Oppenheim and Willsky 1997] as

$$I_l = A_0 + \sum_{k=1}^{L-1} A_k \cos(\omega_k l - \phi_k), \quad (2)$$

where $\omega_k = \frac{2k\pi}{L}$, $A_k = (B_k^2 + C_k^2)^{\frac{1}{2}}$, $\phi_k = \arctan(B_k, C_k)$, $B_k = \frac{1}{L} \sum_{l=0}^{L-1} I_l \sin(\omega_k l)$ and $C_k = \frac{1}{L} \sum_{l=0}^{L-1} I_l \cos(\omega_k l)$. Since the kernel f is a low-pass filter, how quickly the coefficients A_k diminish with k is a measure of the amount of defocus, which in turn yields depth. Note that A_0 cannot be used to estimate depth because it depends on the ambient light β . Although both A_1 and A_2 are scaled by the albedo α , their ratio can be used to determine how severely the defocus kernel attenuates the second-order harmonic with respect to the first-order one. Therefore, we use the following ratio

$$\theta = \frac{A_2}{A_1} \quad (3)$$

as a measure of depth. In Eq. (3), $A_1 > A_2 > 0$ and $\theta \in [0, 1]$ because f is a low-pass filter. Deriving the analytic mapping between θ and z is tedious but possible if we know precisely the optical design of the specific projector. However, analytically deriving a projector-specific mapping is not worth the effort as it would not apply to

other projectors — each projector tends to have a unique optical design. Therefore, in the next section, we present a general data-driven approach that calibrates the $\theta - z$ mapping once and for all, for any given optical setting of any given projector-camera system.

3.3 System Setup and Illumination Pattern

We have built a prototype camera-projector system to implement our depth from projection defocus method. Our system consists of an NEC LT260K DLP projector and a Basler A311f monochrome camera. To avoid shadows and occlusions, we approximately align the optical centers of the projector and the camera with a beam splitter (Edmund Optics stock #NT39-493), as shown in Figure 2(a)³. The projector is always focused on a plane behind the working volume to avoid a two-way defocus ambiguity. As the projector is quite bright⁴, we stop-down the aperture of the camera to F11 so that it works approximately as a pinhole camera — any defocus introduced by the camera is negligible compared to that of the projector.

There are many choices of input sequences (excitation signals) in system identification theory. We have chosen to use a simple one — a binary periodic sequence 011011011011... with period 3, which is one type of M-sequence [Ljung 1998]. We encode this sequence as a stripe pattern in which each bit corresponds to an 8-pixel wide stripe, as shown in Figure 2(b). We shift this pattern, one pixel at a time, and take a total of $L = 24$ images for each experiment⁵.

3.4 Calibration

We calibrate the mapping from the θ in Eq. (3) to the depth z in three steps. **Step 1:** We compute the correspondence between projector and camera pixels. This is achieved by projecting shifted sinusoids in both horizontal and vertical directions. The details of this procedure can be found in [Scharstein and Szeliski 2003]. **Step 2:**

³We align the camera and the projector by projecting an image onto a white board with a fence in front of it and adjusting the camera position until it does not see any shadows cast by the projector.

⁴During depth estimation, we have used the projector as a grayscale one by removing its color wheel from the light path to boost its brightness.

⁵In our experiments, we have found that the projector produces several undesirable effects: it vibrates at a high frequency, possibly due to the rotation of its fan; its brightness is not stable over time; the imprecise synchronization between the camera and projector causes measured radiances to fluctuate slightly over time. To resolve these issues, we repeat the shifting of the pattern about 85 times and compute a mean image for each shift. The camera runs at 60Hz and the total acquisition time is within a minute.

²Due to lens aberration, f generally also varies across different pixels.

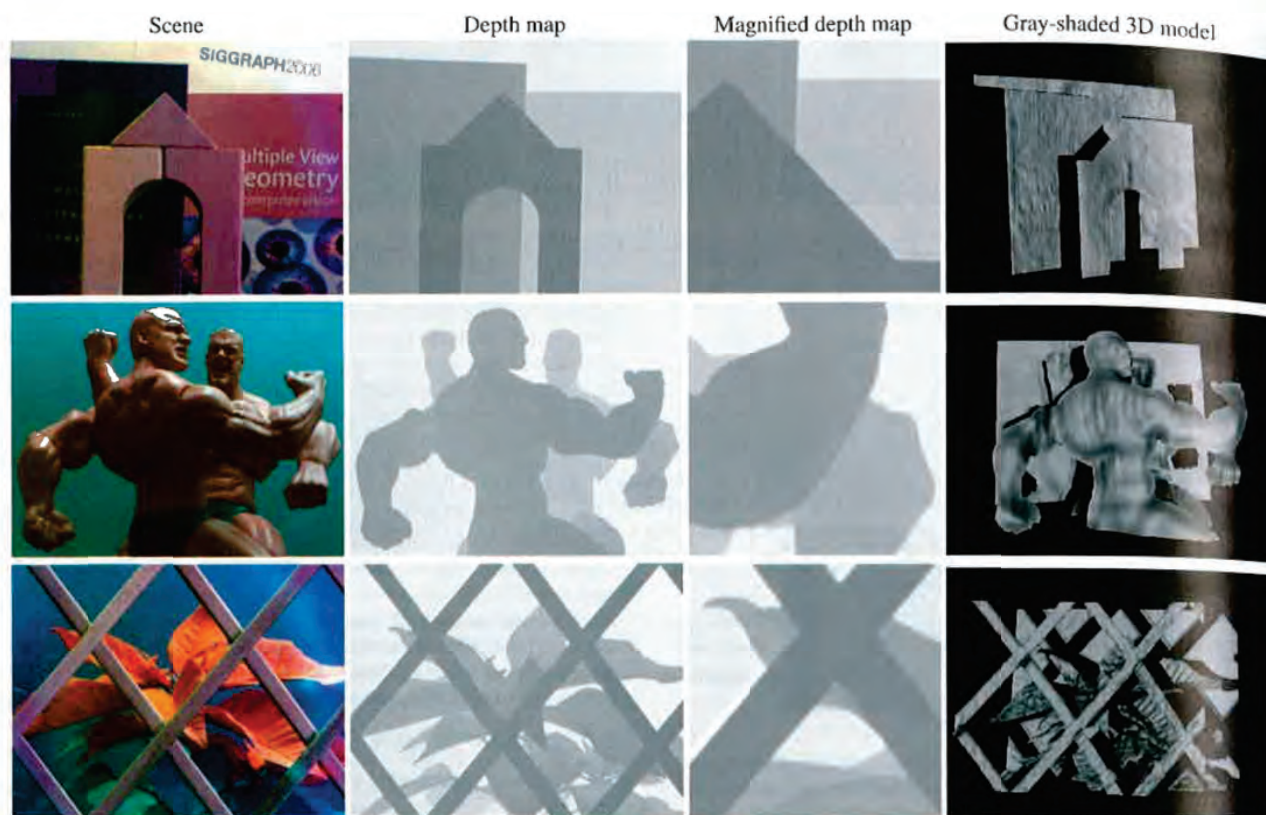


Figure 4: Depth recovery results for three scenes. From left to right: An image of the scene, the computed intensity-coded depth map, a close-up view of the depth map, a gray-shaded 3D model of the scene, as seen from a novel viewpoint. Notice the quality of the computed depth around scene discontinuities. (Please see the companion video.)

We tilt a foam board in front of the system and compute depth for each of its points. This is done by taking an image of the board with a few reference markers, as shown in Figure 3(a),⁶ and computing the homography from the board to the projection plane. As detailed in [Zhang 2000], this homography allows us to estimate the position and orientation of the board⁷, from which the depth of every point of the board can be easily computed. Figure 3(b) shows the intensity-coded depth map of the board. **Step 3:** We compute the θ values for all points on the board by shifting the stripe pattern and computing A_1 and A_2 for each pixel.

Figure 3(c) shows an image of the board under one of the shifted patterns, and (f) and (g) show the temporal radiance profiles of two points, q and s , on the board. As s is closer to the projector and more defocused than q , its temporal radiance profile is more blurred. Figures 3(h) and (i) show plots of the DFS coefficients A_k for the profiles in (f) and (g), respectively. Figure 3(d) shows the intensity-coded θ map and (e) shows a plot of the θ values (blue curve) for the column 350 in (d). The raw θ values include a small amount of noise and hence we fit a smooth curve which is shown as the green curve in (e). Using the depth estimation in Step 2, we can tabulate the mapping from θ to z . In our current implementation, we build a lookup table for each column, assuming that the defo-

cus kernel is vertically invariant but has some horizontal variation. Figure 3(j) shows three θ - z mapping curves for the columns 100, 350 and 600. An even more comprehensive calibration would involve translating the board across the whole working volume and generating a lookup table for each pixel. Such a calibration would account for higher-order projector lens aberrations as well.

3.5 Depth Recovery Results

Once we know the mapping between θ and z , the depth recovery is straightforward. We take 24 images while shifting the illumination pattern across the scene. From these images, we compute θ for each camera pixel using Eqs. (2,3) and then transform the θ image to a depth image using the pre-computed lookup table. Figure 4 shows several depth recovery results. In the first row, we show results for a scene with books and wooden blocks that has simple boundaries. Our method recovers the sharp depth discontinuities at the boundaries. In the second row, we show results for a scene with two toy wrestlers with similar skin color. Again, our method can separate the two figures with clean boundaries, even though the surfaces have a specular component. In the third row, we show results for a scene with leaves behind a fence. This result shows that the performance of our method is independent of occlusion complexity. In fact, it has been shown [Scharstein and Szeliski 2003] that it is very difficult to obtain a depth map that is complete in any camera view for a scene like the one with leaves using triangulation-based methods, even if multiple cameras and projectors are used. All the results are computed within a minute using Matlab.

We have also computed noise statistics for our depth estimation. Specifically, we chose 20 planar patches from the experimented scenes that are located at different depth within the working volume. We then computed the mean and standard deviation of the

⁶The glare is produced by a number of dust particles on the half-mirror. Since the half-mirror is very close to the projector, these particles are lit with roughly 100 times the intensity compared to the scene, thereby producing bright spots in the image that have the shape of the camera aperture.

⁷Zhang [2000] takes several images of a board at different orientations to estimate a camera's intrinsic parameters. In our work, we approximately estimate the projector's intrinsics from the frustum specification in its manual. Therefore, we only take one image of the board to compute its pose.

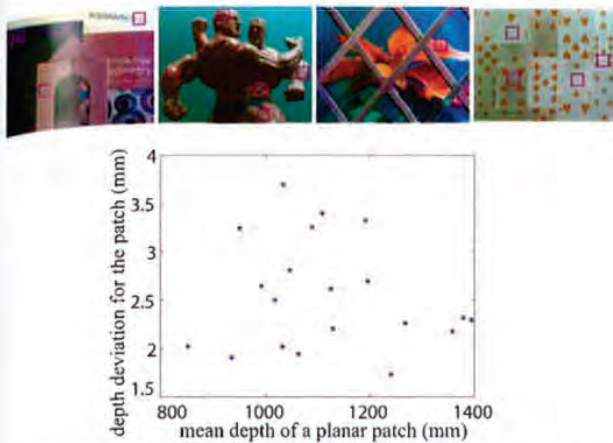


Figure 5: Noise statistics in the depth estimation. Twenty planar patches are chosen from the experimented scenes, shown on the top, and the mean and standard deviation of the depth for those patches are plotted at the bottom. Within a 600mm working volume, our depth estimation noise is around 4mm.

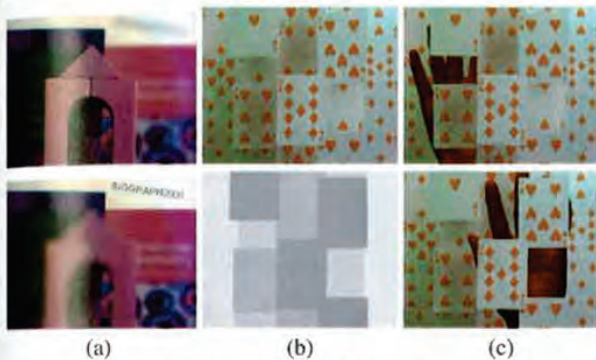


Figure 6: (a) Refocused images of the book scene in Figure 4. The defocus effects are synthesized using the recovered depth map. (b) A collection of playing cards placed at four depth layers and their estimated depth map. (c) A moving hand from another video is inserted into the card scene with all the desired occlusion effects. (Please see the companion video.)

depths inside these patches, as shown in Figure 5. From this figure, we can see that our depth estimation noise is about 4mm for a working volume of 600mm.

3.6 Applications: Refocusing & Video Composition

A distinctive feature of our depth recovery method is that it estimates depth at every pixel in the camera's view and the estimation is reliable near depth discontinuities. This makes our approach particularly well-suited for a variety of image-based applications in computer graphics. Here, we show two examples, namely, refocusing and object insertion to compose a new image or video.

Figure 6(a) shows two refocused images of the book scene in Figure 4: the top one is focused on the foreground wooden blocks and the bottom one is focused on the background letters. These two images were generated with the "lens blur" tool in Adobe PhotoShop.⁸ This tool takes an image and its depth map as inputs to generate new images that are focused at any desired depth.

⁸In theory, without having the full light field available, refocusing can not be simulated exactly. The PhotoShop implementation of lens blur is proprietary. We think a practical way to implement it would be to heuristically inpaint the occluded layers a little bit to obtain the full light field.

Figure 6(b) shows a collection of playing cards placed at four depth layers. The repetitive textures on the cards and the complex occlusions make it very hard to segment the scene into layers automatically, or even manually. Using projection defocus, our method produces a clean depth map that segments the scene into layers. This segmentation makes it easy to insert objects into the scene with correct occlusion effects. Figure 6(c) shows a real hand from another video inserted into the scene with all the desired occlusion effects. **Please see the video for more results.**

We believe that when a complete depth map is available for an image, a variety of image editing applications become possible or easier to implement. Examples other than the ones we have shown are creating layered representations of complex scenes for view morphing, segmentation for matting, object replacement, and shadow removal. In the past, such applications have not been easy to implement as "clean" depth maps have not been easy to obtain. For most image editing tasks, the depth maps need not be highly precise (as with time-of-flight sensors), but they need to be complete and they need to be reliable at discontinuities, as humans are particularly sensitive to edge artifacts. We hope our depth recovery method, although not as accurate as laser scanners or structured light sensors, will inspire new types of image editing applications.

4 Focused Projection at Multiple Depths

Due to their optical design, standard projectors can only be focused on a single fronto-parallel plane. In some applications, it is desirable to project images onto non-planar structures; for example, multiple planes or a dome to create a virtual environment [Raskar et al., 1998]. In such cases, most parts of the image are blurred due to defocus. One way to solve this problem is to design sophisticated optics. Even if this is possible, the optics cannot be modified to accommodate changes in the structure that is being projected onto. Another approach is to use multiple projectors [Bimber and Emmerling 2006], where the number of depths for which the projected image can be in focus equals the number of projectors. In this section, complementary to the multi-projector approach, we propose a computational method that processes an input image in a scene-dependent way to minimize the defocus blur at all points in the projected output image. Our method requires just a camera and can be applied to any off-the-shelf projector.

4.1 Defocus Compensation Algorithm

Consider the scenario where an image I needs to be projected onto a surface with given depth variation. The radiance of a point on the surface due to illumination by the projector is governed by the projection defocus equation Eq. (1). As in previous work, e.g. [Raskar et al. 2003; Fujii et al. 2005], we use a camera as a proxy for the human eye and seek to make the scene radiance captured by the camera be the same as the input image I . To do so, we can project a *compensation image*, P^* , by solving the projection defocus equation as

$$P^* = (\alpha f)^{-1} * (I - \beta), \quad (4)$$

where $(\alpha f)^{-1}$ is the inverse of the kernel αf . Theoretically, if P^* is projected, the scene brightness will be the same as the input image I . However, f is a low-pass filter and its inverse will have strong ringing effects. Therefore, Eq. (4) will not be feasible to implement unless the projector has an infinite dynamic range. Instead, we cast the problem of computing the compensation image as a constrained minimization problem, as follows:

$$P^* = \arg \min_p \{d(\alpha f * P + \beta, I) \mid \forall x, 0 \leq P(x) \leq 255\}, \quad (5)$$

where x is the projector pixel coordinate and $d(\cdot, \cdot)$ is an image distance metric. Eq. (5) finds the compensation image P^* , with all its brightness values within the projector's dynamic range, that after defocus blurring most closely matches the input image I .

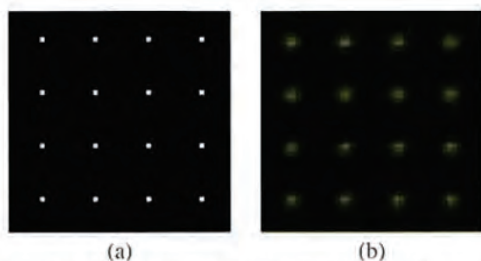


Figure 7: Measuring the spatially-varying defocus kernel. (a) A portion of the dot pattern projected onto the scene. (b) The corresponding camera image with samples of the point spread function.

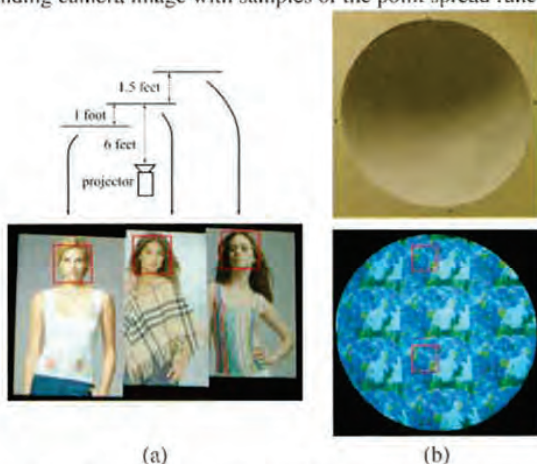


Figure 8: Two test scenes for focused projection at multiple depths. (a) Projection onto three planes at different depths from the projector. (b) Projection onto a hemispherical dome.

In our implementation, we have used the sum-of-squared pixel differences for the image distance metric $d(\cdot, \cdot)$. The compensation image P^* is found by applying an iterative, constrained, steepest-descent algorithm [Nocedal and Wright 1999]. We represent the defocus convolution, $\alpha f * P$, as a matrix multiplication, FP , where each row of F is the defocus kernel of the corresponding pixel modulated by its albedo. The algorithm starts with $P_0 = I$ and iterates the following two steps:

$$\tilde{P}_{i+1} = P_i + \eta_i G_i \quad (6)$$

$$P_{i+1} = \text{CLAMP}(\tilde{P}_{i+1}; 0.255) \quad (7)$$

where $G_i = F^T(I - \beta - FP_i)$, $\eta_i = \frac{\|G_i\|^2}{\|FG_i\|^2}$, and CLAMP is a pixel-wise clamping operation. Notice that G_i is the gradient of the image distance $\|FP + \beta - I\|^2$ with respect to P . Evaluating G_i is straightforward – it involves two image filterings with the kernel matrices F and F^T , respectively. Note that these filterings are spatially-varying and scene-dependent, unlike the standard sharpening operations that are often built into projectors by their manufacturers. Without Eq. (7), iterating Eq. (6) alone is a standard steepest-descent algorithm, which converges to the solution of Eq. (4). Combining Eq. (7) and Eq. (6) minimizes the difference between the defocused compensation image and the original input image within the dynamic range of the projector.

4.2 Kernel Estimation

We now describe how we obtain β and αf for any given scene. We obtain the ambient term β by turning off the projector and taking an image. To obtain αf for each pixel, we could shift a dot pattern across the scene and the temporal radiance profile for each pixel is then its kernel. This method is effective for a scene with intricate geometry, such as the scenes shown in Section 3. However, the

scenes used in our experiments here are at least piece-wise smooth. Therefore, we simply project a sparse binary dot pattern, like the one in Figure 7(a). In our experiments, the distance between neighboring dots is 12 pixels. The point spread patterns captured by the camera, shown in Figure 7(b), are approximately the kernels for the projector pixels that are '1'. From these kernels, we interpolate the kernels for other pixels that are '0' in a bilinear manner. In the end, we have a per-pixel kernel map that accounts for spatially-varying defocus effects. We repeat the same procedure to capture kernels for each of the three color channels of the projector. Calibrating such a kernel map also helps to compensate lens aberrations as well. For the above computations of β and αf , we always warp the image from the camera to the projector's coordinate frame, which makes it convenient to compare the defocused compensation image, $FP + \beta$, and the input image I . The correspondences between the camera's and the projector's pixels are determined by shifting sinusoidal patterns in both horizontal and vertical directions, as in Section 3.

4.3 Focused Projection on Multiple Planes

In our first experiment, our goal was to project an image of three fashion models onto three planes that are at different depths, as shown in Figure 8(a). The projector is focused on the middle plane. We show the focus compensation results for the three face regions in the left three columns of Figure 9. The first row of Figure 9 shows the original image regions for the three faces. The third row shows the defocused original image regions, captured by a camera, without any compensation. This row represents the best the projector (without compensation) can produce. Notice that even though the middle plane is in focus, the face still looks a little blurred for this plane due to projector artifacts.⁹ As expected, the faces on the left and right planes are even more blurred due to defocus. The second row shows the compensation image regions resulting from Eqs. (6,7), which represent the new input to the projector. These image regions look like high-pass filtered versions of the original input ones. This is expected as our method boosts high-frequency components to compensate for the defocus induced by scene geometry. The fourth row shows the defocused compensation image regions captured by the same camera, which represent our results. Notice that these image regions are less blurry and more closely resemble the input image regions. Among these three defocused compensation image regions, the one on the middle plane (second column) is almost identical to the input. The ones on the left and right planes (first and third columns) are slightly blurred with respect to their inputs because defocus is more severe in these two cases, and certain high frequencies in the input image that are cut by the defocus cannot be fully compensated for due to the limited dynamic range of the projector.

4.4 Focused Projection on a Dome

In our second experiment, we project an image of a tiled flower texture onto the inside of a hemispherical dome, as shown in Figure 8(b). The projector is focused on the front plane of the dome. In the right two columns of Figure 9, we show the focus compensation results for two patches on the dome – one is from the top of the dome and the other is from the center. The top patch is less blurred than the center one because the former is closer to the focal plane of the projector. As with the three-plane experiment, the compensation results closely resemble the input images.

5 Depixelation

In this section, we show how the defocus compensation method discussed in Section 4 can be used to reduce projector pixilation.

⁹We found that even if we focus a projector on a fronto-parallel plane, when projecting a binary dot pattern, we see "light leakage" from one pixel into its neighbors. We observed this effect on different projector models.

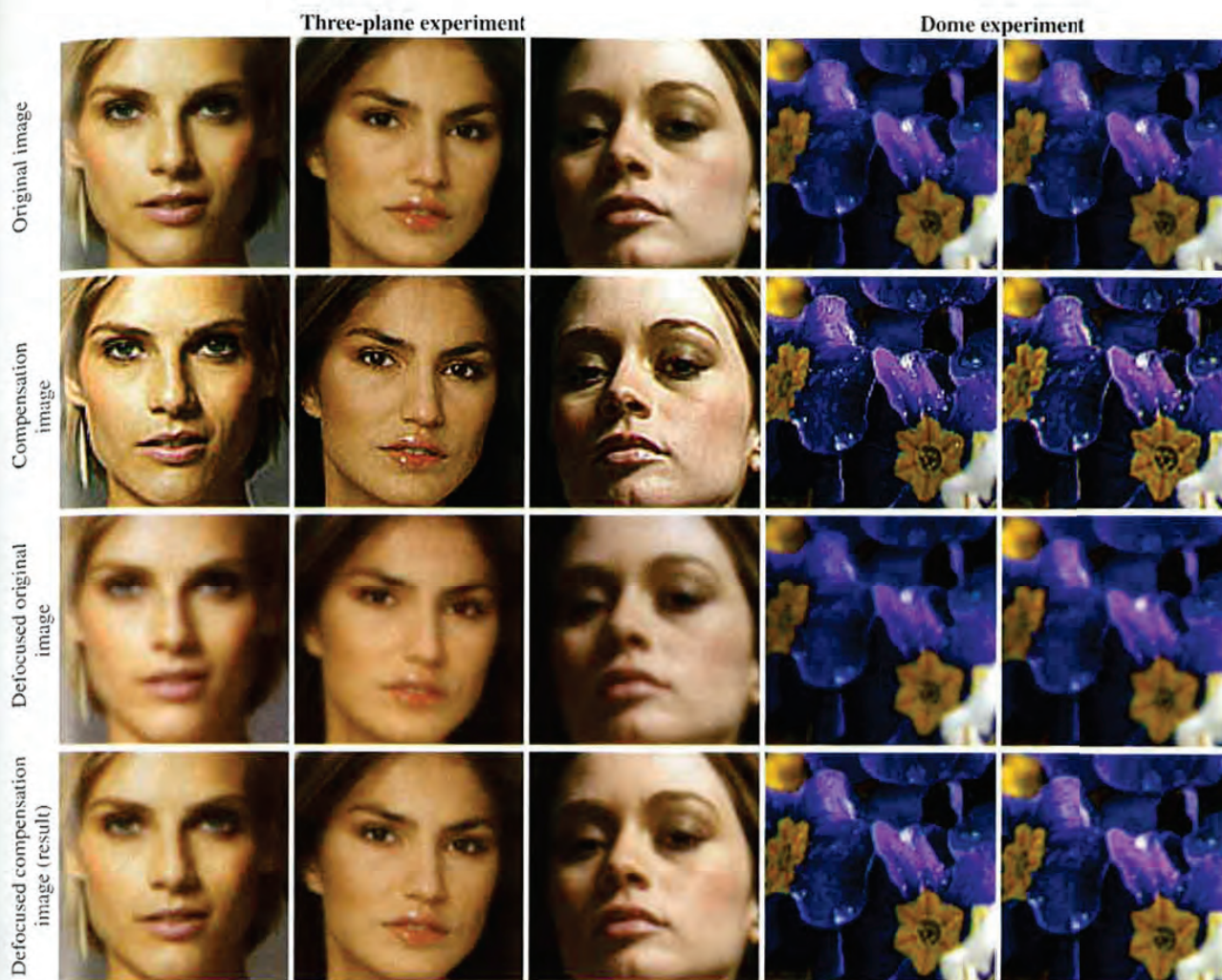


Figure 9: Results for defocus compensation. The three faces on the left were projected onto the three planar surfaces in Figure 8(a). The two flower textures on the right were projected onto the hemispherical dome in Figure 8(b). The defocus compensation method results in less blurry image regions (fourth row) than the uncompensated image regions (third row). The original image regions are shown in the first row and the compensation image regions computed by the method and used as input to the projector are shown in the second row. The compensation method is scene independent as it can handle a spatially-varying defocus kernel. (Please see the companion video.)

Pixelation is a clearly noticeable artifact produced by all digital projectors. It is caused by two factors. The first is the spatial digitization due to the finite resolution of the projector. The second is the gap (dead-zone) between adjacent pixels on the projector's physical image plane that arises because the pixel fill-factor is never 100 %. The digitization is known to create jaggy boundaries when the resolution of the projector is not high enough for the given application. This effect is observed particularly when high quality captured images are projected, as the resolution of most LCD and DLP projectors has remained at 1024x768 or less for the last seven years, while digital cameras have tripled in their resolution during the same time period. The dead-zone between pixels does not generate light and produces thin black lines on the projection screen, known as the *screen-door effect*. This effect makes pixelation more pronounced as it clearly marks out pixel boundaries on the screen.

In our implementation of depixelation, we assume that the images are projected onto a single fronto-parallel screen, i.e., the traditional projection scenario. Our basic approach is to focus the projector slightly in front of (or behind) the projection screen so that the image on the screen is slightly blurred. In this case, a slight amount of

light is leaked into the black gaps and neighboring pixels, which reduces the screen-door effect as well as smoothes out the jaggy pixel boundaries. However, doing so also creates blurry images. Since this purposely induced blur is very slight, we can use the compensation method in Section 4 to process the input image so that the defocused projection looks very similar to the original input image. Therefore, the compensation method can be used in conjunction with the minor induced defocus to achieve depixelation.

Specifically, we use the compensation method to compute an optimal image P^* at the projector resolution whose defocused projection most closely resembles the input image, which may have higher resolution. Note that if the input image resolution is higher than the projector's native resolution, the number of rows in F is larger than the number of columns. Each row of F is a defocus kernel modulated by both surface albedo and the screen-door effect.

We have tested the depixelation method on several high resolution input images (each one with 3 times the projector resolution). The capture of β and F is done using the method in Section 4, except that we capture a higher resolution kernel map by zooming-in our camera so that 3×3 camera pixels see about one projector pixel.

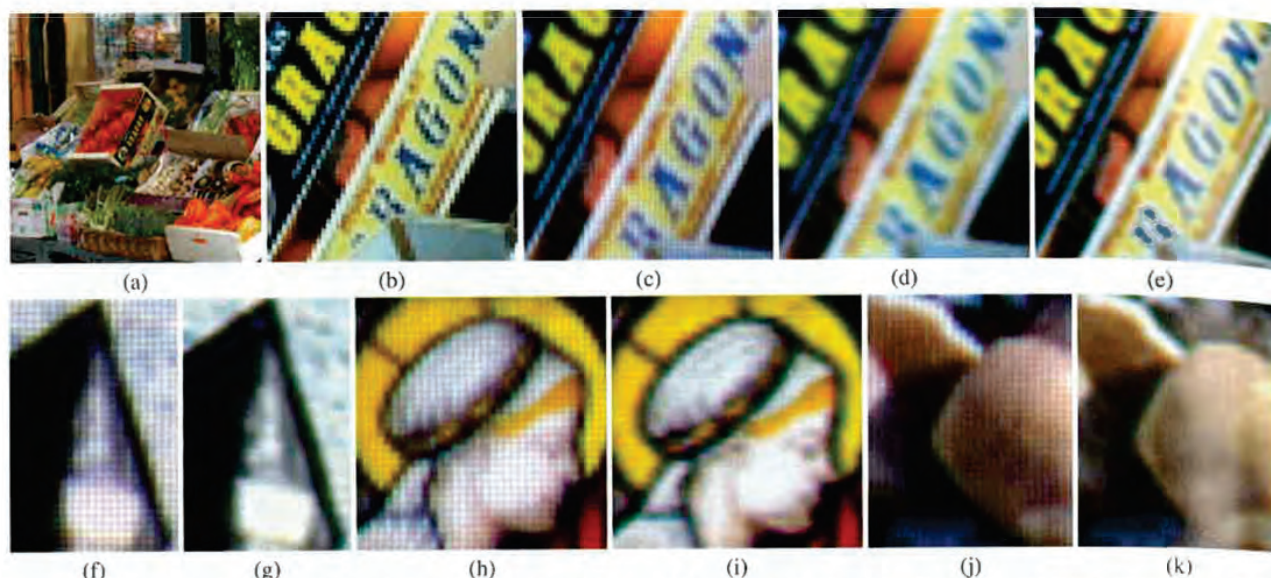


Figure 10: Examples of Projector Depixelation. (a) An original image of $3\times$ projector resolution. (b) A patch in (a) of projector resolution. (c,d) Projection of (b) under focused and defocused settings, respectively. (e) Our depixelation result. (f-k) Three more examples of depixelation with (f,h,j) as focused projection and (g,i,k) as depixelated projection. In all examples, the compensation greatly reduces pixelation effects while preserving image quality. (Please see the companion video.)

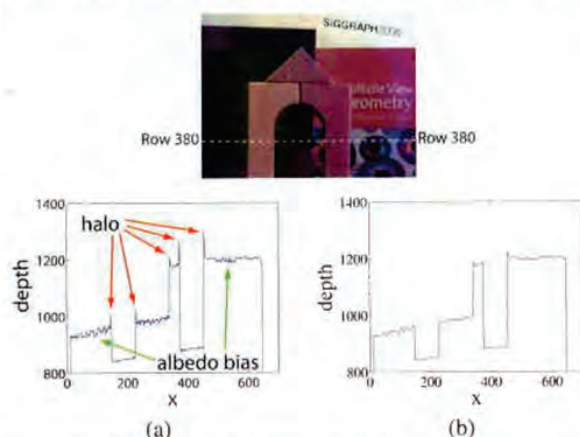


Figure 11: Albedo-correlated bias and halo effects in depth estimation. (a) The depth profile for row 380 of the scene. (b) The depth profile after removing noise and halo by a 7×7 median filter.

Figure 10 shows four examples of depixelation. In all the cases, spatial digitization and screen-door effects are greatly reduced and yet image sharpness is preserved. Our current implementation of the compensation algorithm uses Matlab. The algorithm takes about 10 iterations to converge and takes 3-5 minutes to produce the final compensation image. Since the compensation method only involves filtering with F and F^T , we believe it can be implemented on image processing chips or graphics hardware to achieve real-time (frame-rate) performance.

6 Discussion

In this paper, we have modelled projection defocus as a linear system and developed a temporal defocus method that recovers depth at all pixels in an image, regardless of the scene complexity. We also proposed a scene-dependent filtering algorithm that increases the depth of field of a projector without modifying its optics. Finally, we showed that defocus can be exploited to reduce pixelation artifacts produced by digital projectors. We now discuss the limita-

tions of our work and open problems as topics for future research.

First, our temporal defocus method should, in principle, be invariant to surface albedo. In practice, we found that the surface albedo sometimes does affect the depth estimation, as shown in Figure 11. We believe that this is only an issue with our current implementation. Our beam-splitter not only reflects light from the scene to the camera, but also transmits light from a black backdrop placed behind it. Therefore, the defocus kernel f in Eq. (1) is actually a sum of the defocus kernels of both the scene and the backdrop. If the scene is much brighter than the black backdrop, Eq. (3) is dominated by the scene's defocus kernel. However, when the scene point is dark, due to low albedo or because its surface orientation is near-grazing for the projector, the light from the scene point to the camera is weak and comparable to the light from the backdrop. In this case, Eq. (3) will depend also on the defocus kernel of the backdrop, which causes errors in depth estimation. The backdrop kernel remains constant and can be calibrated to reduce depth estimation errors. Alternatively, the beam-splitter can be placed in a custom-designed chamber that absorbs all forms of stray light.

The projector defocus is for most cases independent of scene geometry, and this independence makes it superior to camera defocus for depth estimation. However, there is a special case that this independence does not hold. Specifically, when a closer object occludes a distant object, there will be a narrow band of points near the occluding contour on the distant object that "see" only part of the projector's aperture; so the projected pattern will be more in-focus than it would be if the entire aperture were visible. This partial aperture effect results in a halo artifact: depth estimation biased toward the focal plane, as shown in Figure 11. However, even in this special case, projector defocus is still better than camera defocus. Camera defocus will cause estimation errors for both the foreground and background pixels near the occluding boundary. In contrast, projector defocus will only cause errors at the background pixels, while leaving the foreground pixels unaffected. Furthermore, in practice, because the solid angle subtended by the projector aperture is only about 1 degree with respect to a scene point, the number of affected background pixels is small. Therefore, as shown in Figure 11, the halo effect can be greatly reduced by a simple median filtering.

In practice, using projector defocus for depth estimation does not require moving detectors or changing optical settings as traditional camera defocus methods do [Pentland 1987; Nayar and Nakagawa 1994]. Therefore, our method can be more conveniently implemented. However, a coaxial implementation of depth from camera defocus, as in [Nayar et al. 1996], allows for capturing dynamic scenes, which our method currently is incapable of, because we use 24 images for depth estimation. We believe this number can be greatly reduced, which would enable us to develop a real-time sensor that can handle dynamic scenes. In Eq. (1), there are three unknowns: α , β , and z . If we can calibrate the defocus kernel f a priori, then, in theory, 3 images are enough to solve for these unknowns. Interestingly, this minimum number is the same for other shape acquisition methods, like the phase-shift method [Huang et al. 2003], the time-of-flight method [Gonzales-Banos and Davis 2004], and photometric stereo [Horn and Brooks 1989].

Our temporal defocus method can deal with specular surfaces, whenever the BRDF's are approximately constant within the solid angle subtended by the projector aperture from the scene point. Nevertheless, the extreme case of near-mirror reflection, as well as saturated highlight pixels, will cause errors. Although our method is developed under the direct illumination assumption, it's not very sensitive to the indirect illumination. This is because indirect illumination usually creates only very low frequency intensity fluctuation, which will mainly affect Fourier coefficient A_0 . Our depth is however estimated via A_1 and A_2 . Of course, for extremely specular reflection, the global illumination can change dramatically with the projected patterns and hence our method will break down.

One challenging open problem for defocus-based methods is handling translucent objects. A translucent material introduces additional blur due to subsurface scattering, which would cause a systematic bias in our methods. The amount of bias depends on the amount of translucency blur compared to defocus blur. If the defocus blur dominates the translucency blur, the error will be small. Otherwise, the error will be large. It would be interesting to extend our analysis to handle blur induced by translucency. In practice, the depth of mixture pixels at boundaries is often a blend of its neighboring depth values. It would be interesting to accurately model the mixture pixels, e.g., combining our approach with the defocus matting method [McGuire et al. 2005], to estimate mattes for scenes with continuous depth variations.

Our method for defocus compensation essentially extends the depth of field of the projector. However, when the blur is very severe, our method cannot fully compensate for the blur due to the limited dynamic range of the projector. In such a case, combining our method with multiple-projector solutions [Bimber and Emmerling 2006] could be beneficial. Finally, we plan to extend our work on depixelation to make it a practical and useful projector feature. How objectionable pixelation artifacts are, is really a subjective issue. For our technique to be incorporated into commercial projectors, a few preset options can be provided so that the user can decide how much focus quality they are willing to tradeoff for depixelation.

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ATTACHMENT C-2

Projection Defocus Analysis for Scene Capture and Image Display *

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Abstract

In order to produce bright images, projectors have large apertures and hence narrow depths of field. In this paper, we present methods for robust scene capture and enhanced image display based on projection defocus analysis. We model a projector's defocus using a linear system. This model is used to develop a novel temporal defocus analysis method to recover depth at each camera pixel by estimating the parameters of its projection defocus kernel in frequency domain. Compared to most depth recovery methods, our approach is more accurate near depth discontinuities. Furthermore, by using a coaxial projector-camera system, we ensure that depth is computed at all camera pixels, without any missing parts. We show that the recovered scene geometry can be used for refocus synthesis and for depth-based image composition. Using the same projector defocus model and estimation technique, we also propose a defocus compensation method that filters a projection image in a spatially-varying, depth-dependent manner to minimize its defocus blur after it is projected onto the scene. This method effectively increases the depth of field of a projector without modifying its optics. Finally, we present an algorithm that exploits projector defocus to reduce the strong pixelation artifacts produced by digital projectors, while preserving the quality of the projected image. We have experimentally verified each of our methods using real scenes.

CR Categories: I.3.3 [Computer Graphics]: Picture/Image Generation—Digitizing and scanning, display algorithm; I.4.8 [Image Processing and Computer Vision]: Scene Analysis—Depth cues, range data, shape.

Keywords: projector defocus, temporal defocus analysis, depth recovery, multi-focal projection, projector depixelation, refocus synthesis, image composition.

1 Introduction

Digital projection technologies, such as Digital Light Processing (DLP) and Liquid Crystal Displays (LCD), are increasingly used in consumer, commercial and scientific applications. In computer graphics and vision, video projectors have recently been used as per-pixel controllable light sources for real-time shape acquisition [Huang et al. 2003; Zhang et al. 2004; Davis et al. 2005; Konickx et al. 2005], for complex appearance capture [Levoy et al. 2004; Sen et al. 2005] and control [Raskar et al. 2001; Grossberg et al. 2004; Bimber et al. 2005]. All these applications require the projectors to be focused for best performance. In practice, projectors are built with large apertures to maximize their brightness. As a result, virtually all projectors have very narrow depths of field; they

are designed to produce focused images on a single fronto-parallel screen. An analysis of the defocus properties of projectors is therefore beneficial as it could lead to new methods that take advantage of, as well as compensate for, projection defocus.

In this paper, we provide the first systematic analysis of projector defocus and demonstrate its applications to robust scene capture and enhanced image display. We first present a simple linear model for projector defocus. Based on this model, we present a frequency-domain method for estimating the spatially-varying defocus kernel of a projector. The kernel estimated at each scene point is used to recover the 3D geometry of the scene. Based on the estimated kernel, we also present a technique that computationally manipulates an input image to minimize its defocus blur when it is projected onto a non-planar scene. Finally, we demonstrate that defocusing can be put to good use. A slight amount of defocusing, in conjunction with a compensation algorithm, can be used to reduce pixelation, a strong artifact produced by all digital projectors. Specifically, this paper makes the following three contributions:

Scene Geometry using Temporal Defocus Analysis: We propose a method called temporal defocus analysis that estimates depth at each camera pixel, independently, without using information from neighboring pixels (Section 3). Our method, compared to existing methods, such as stereo or even traditional depth from focus/defocus algorithms, is more accurate near depth discontinuities. Since the method is not based on triangulation, we can use a coaxial projector-camera system and compute depth at all camera pixels, without any missing parts. These advantages make the method uniquely suited to computer graphics applications like refocus synthesis and image composition, both of which we demonstrate.

Focused Projection at Multiple Depths: We present an iterative, spatially-varying filtering algorithm that compensates for defocus blur based on scene geometry (Section 4). This technique effectively increases the depth of field of a projector without modifying its optics. As a result, we are able to use a single projector to project well-focused images on multiple planes that are at different depths as well as on curved projection surfaces. We believe this capability addresses an important limitation of current projectors and widens their applicability in the real world.

Depixelation by Defocusing: Finally, we generalize our defocus compensation algorithm to reduce the strong pixelation artifacts produced by all digital projectors (Section 5). The key idea is to slightly defocus the projector so as to attenuate the high frequencies produced by pixelation and use the defocus compensation algorithm to make up for the induced projector defocus. This method is especially suited for projecting high resolution images using a low resolution projector, and we show several examples of results to illustrate its effects.

2 Previous Work

Many methods have been proposed in computer vision to recover 3D shape from images, including multi-view triangulation methods, single-view photometric methods, and camera focus/defocus methods. Triangulation-based methods [Faugeras 1993], e.g., structure from motion and stereo, require a point to be visible in at least two views to be reconstructed. Scenes with complex occlusions remain a challenging problem for these methods. Photometric methods [Horn and Brooks 1989], e.g., photometric stereo and shape from shading, estimate surface normals instead of surface depth. Converting normals to depths is an ill-posed problem for scenes with depth discontinuities.

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Depth recovery methods based on camera focus and defocus, e.g. [Pentland 1987; Nayar and Nakagawa 1994; Nayar et al. 1996; Schechner et al. 2000; Favaro and Soatto 2005], have the potential to recover depth at every pixel, regardless of the scene complexity and occlusions. To resolve the focus ambiguity of textureless surfaces, patterns can be projected to force scene texture [Girod and Scherrock 1989]. However, camera defocus kernels depend on local surface geometry. To simplify the kernel analysis, most previous works assume that, within a small spatial window, the surface depth is constant, the so-called *equalfocal assumption*. This assumption smears shape details and is invalid across depth discontinuities. To alleviate this problem, Jin et al. [2002] and Rajagopalan and Chaudhuri [1997] estimate depths for all pixels simultaneously via a large scale energy minimization, which is computationally expensive and prone to local minima. Our key observation is that, unlike camera defocus, the kernel for projector defocus is *scene independent*, for most scene surfaces. Specifically, when a 3D scene point sees the entire projector aperture, its defocus kernel depends only on its distance to the projector lens and not on its neighboring surface geometry. This difference arises from the fact that projector defocus convolution happens on the projector’s image plane while camera defocus convolution happens on the scene surface. Exploiting this scene-independent property, we project a shifting pattern over the scene and compute depth at each pixel using just its intensity variation over time. Without using the equalfocal assumption, our method works well at depth discontinuities. Furthermore, it is simple and not subject to local minima.

Our temporal per-pixel defocus analysis is inspired by previous structured light range finding methods. In particular, Kanade et al. [1991] and Curless and Levoy [1995] use temporal intensity variation to resolve correspondences between camera pixels and a sweeping laser stripe. Huang et al. [2003] have developed a real-time range finder by sweeping periodic sinusoidal stripes using a DLP projector. Zhang et al. [2004] and Davis et al. [2005] have generalized these ideas to space-time stereo. All these range finding techniques are based on the principle of triangulation, which cannot estimate depth for points that are visible to only the camera or the source but not both. Since our method is not based on triangulation, we are able to use a coaxial configuration where the camera and projector share the same optical center, and compute depth at all camera pixels (no missing parts). To our knowledge, the only other technique that is able to estimate a complete depth map with clean discontinuity boundaries is time-of-flight, e.g., [Gonzales-Banos and Davis 2004], which requires expensive specialized hardware. Raskar et al. [2004] proposed a method to detect depth discontinuities using multiple flash lights. The detected discontinuities can be used to enhance stereo matching algorithms. Compared to this work, our method directly generates reliable depth estimation for all pixels, including the ones near discontinuities.

In addition to scene capture, several methods have been proposed that use cameras to enable projectors to display “better” images. These include compensating distortions due to surface geometry [Raskar et al. 2003] and correcting brightness variations due to surface color and texture [Grossberg et al. 2004; Bimber et al. 2005]. In these works, the projectors are often used to display images onto scenes with considerable depth variation, where defocus blur is inevitable and most often spatially-varying. Complementary to these previous methods, our work seeks to compensate for defocus blur, and hence could be beneficial to the previous methods. In [Bimber and Emmerling 2006], a system is proposed that can project focused images on multiple planes at different depths. This system uses multiple projectors where each projector is focused on a single plane. In our case, we use a single projector to simultaneously project well-focused images at multiple depths. Another interesting related work is by Majumder and Greg [2001], in which multiple projectors at different focal settings are combined to gen-

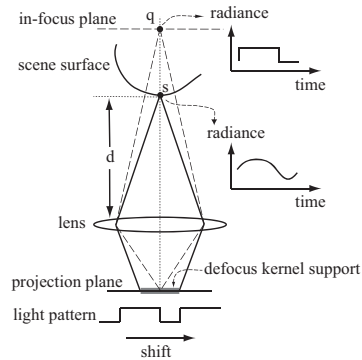


Figure 1: The principle of depth from projection defocus. Points at different distances to the projector lens exhibit different amounts of blur in their temporal radiance profile as a periodic illumination pattern is shifted across the scene.

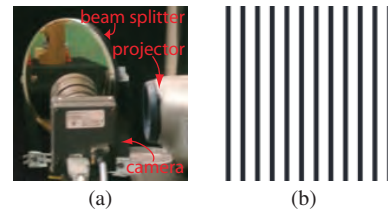


Figure 2: (a) A coaxial projector-camera system for depth from projection defocus. The system is made coaxial only to ensure that depth can be computed at all camera pixels. (b) The illumination pattern that is shifted across the scene to measure depth at each pixel, independently.

erate depth of field effects at an interactive rate.

Deblurring is a well-studied topic in image processing where numerous techniques have been proposed, ranging from classical Wiener filtering and conjugate gradient optimization [Jain 1989] to more recent algorithms based on graph cuts [Raj and Zabih 2005] and belief propagation [Tappen et al. 2004]. Our technique is based on bound-constrained quadratic programming [Nocedal and Wright 1999], which is a variant of existing algorithms that best suits our formulation of the problem. As we show, our deblurring method can also reduce pixelation effects produced by digital projectors.

3 Depth from Projection Defocus

In this section, we formulate the problem of recovering 3D shape from projection defocus and present our solution.

3.1 Temporal Defocus Analysis

Consider a scene that is illuminated by structured light from a projector which is focused behind the scene, as shown in Figure 1. For a point q that is in focus, its irradiance comes from a single point on the projector’s image plane. For a point s that is out of focus, its irradiance equals the convolution of its defocus kernel with the structured light pattern on the projector’s image plane. Assuming that the surface is opaque, the radiance I of s along any given outgoing direction can be written as

$$I = \alpha f(\mathbf{x}; z) * P(\mathbf{x}) + \beta, \quad (1)$$

where $*$ denotes convolution, α is a factor depending on surface reflectance¹, β is the radiance due to the ambient light, $f(\mathbf{x}; z)$ is the

¹To be precise, α takes into account all surface shading factors: BRDF, orientation with respect to the irradiance direction and the squared distance fall-off of the projector brightness.

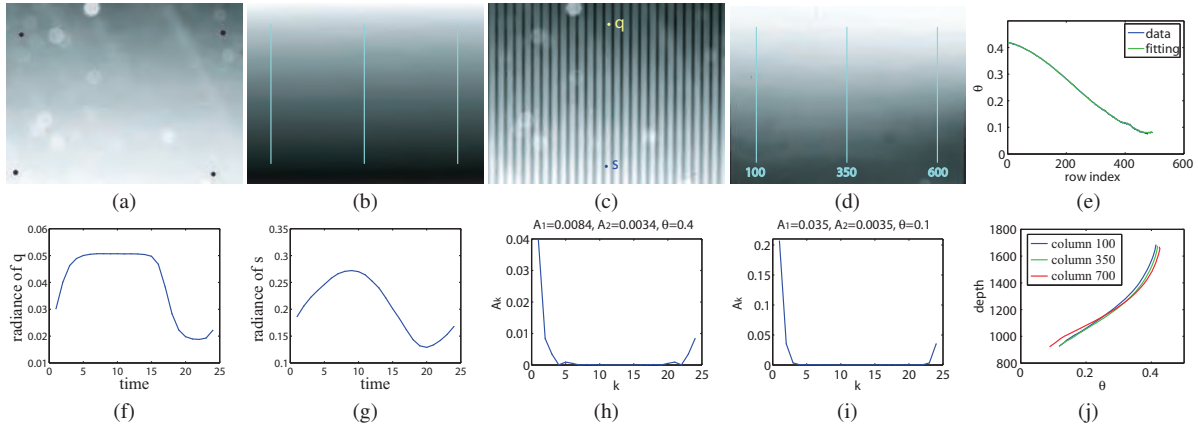


Figure 3: Illustration of the calibration procedure. (a) A white board with four markers tilted in front of the camera. (b) Depth map of the board computed using the markers. (c) The board under one of the stripe projection patterns. (d) θ map for the board. (e) θ values in column 350 of (d). (f,g) Temporal radiance profiles of the points q and s , respectively. (h,i) Discrete-time Fourier series (DFS) of (f) and (g). (j) Mappings from θ to depth z for columns 100, 350 and 600, respectively.

defocus kernel, and $P(\mathbf{x})$ is the illumination pattern. The defocus kernel f depends on the depth z .² We now describe how to recover the depth z by estimating the kernel f from radiance measurements.

3.2 Depth Estimation

To estimate the kernel f , we note that Eq. (1) defines a linear system in which the projection pattern and the scene radiance are the input and the output, respectively. Estimating the kernel of a linear system is a classical problem in system identification [Ljung 1998] and we take a frequency-domain approach to solve it in our setting. Our basic idea is to shift an illumination pattern with a wide range of frequencies within it across the scene. The radiance of a surface point over time is then the response of its defocus kernel to the excitation by the illumination pattern. As the pattern is shifted, points at different distances to the projector exhibit different amounts of blur in their *temporal* radiance profile, as illustrated in Figure 1. We use this temporal blur for depth recovery.

Given the temporal radiance sequence, I_l , $l = 0, \dots, L-1$, for a point, we quantify its blur by decomposing it into a discrete-time Fourier series (DFS) [Oppenheim and Willsky 1997] as

$$I_l = A_0 + \sum_{k=1}^{L-1} A_k \cos(\omega_k l - \phi_k), \quad (2)$$

where $\omega_k = \frac{2k\pi}{L}$, $A_k = (B_k^2 + C_k^2)^{\frac{1}{2}}$, $\phi_k = \arctan(B_k, C_k)$, $B_k = \frac{1}{L} \sum_{l=0}^{L-1} I_l \sin(\omega_k l)$ and $C_k = \frac{1}{L} \sum_{l=0}^{L-1} I_l \cos(\omega_k l)$. Since the kernel f is a low-pass filter, how quickly the coefficients A_k diminish with k is a measure of the amount of defocus, which in turn yields depth. Note that A_0 cannot be used to estimate depth because it depends on the ambient light β . Although both A_1 and A_2 are scaled by the albedo α , their ratio can be used to determine how severely the defocus kernel attenuates the second-order harmonic with respect to the first-order one. Therefore, we use the following ratio

$$\theta = \frac{A_2}{A_1} \quad (3)$$

as a measure of depth. In Eq. (3), $A_1 > A_2 > 0$ and $\theta \in [0, 1]$ because f is a low-pass filter. Deriving the analytic mapping between θ and z is tedious but possible if we know precisely the optical design of the specific projector. However, analytically deriving a projector-specific mapping is not worth the effort as it would not apply to

²Due to lens aberration, f generally also varies across different pixels.

other projectors — each projector tends to have a unique optical design. Therefore, in the next section, we present a general data-driven approach that calibrates the $\theta - z$ mapping once and for all, for any given optical setting of any given projector-camera system.

3.3 System Setup and Illumination Pattern

We have built a prototype camera-projector system to implement our depth from projection defocus method. Our system consists of an NEC LT260K DLP projector and a Basler A311f monochrome camera. To avoid shadows and occlusions, we approximately align the optical centers of the projector and the camera with a beam splitter (Edmund Optics stock #NT39-493), as shown in Figure 2(a)³. The projector is always focused on a plane behind the working volume to avoid a two-way defocus ambiguity. As the projector is quite bright⁴, we stop-down the aperture of the camera to F11 so that it works approximately as a pinhole camera — any defocus introduced by the camera is negligible compared to that of the projector.

There are many choices of input sequences (excitation signals) in system identification theory. We have chosen to use a simple one — a binary periodic sequence 011011011011... with period 3, which is one type of M-sequence [Ljung 1998]. We encode this sequence as a stripe pattern in which each bit corresponds to an 8-pixel wide stripe, as shown in Figure 2(b). We shift this pattern, one pixel at a time, and take a total of $L = 24$ images for each experiment⁵.

3.4 Calibration

We calibrate the mapping from the θ in Eq. (3) to the depth z in three steps. **Step 1:** We compute the correspondence between projector and camera pixels. This is achieved by projecting shifted sinusoids in both horizontal and vertical directions. The details of this procedure can be found in [Scharstein and Szeliski 2003]. **Step 2:**

³We align the camera and the projector by projecting an image onto a white board with a fence in front of it and adjusting the camera position until it does not see any shadows cast by the projector.

⁴During depth estimation, we have used the projector as a grayscale one by removing its color wheel from the light path to boost its brightness.

⁵In our experiments, we have found that the projector produces several undesirable effects: it vibrates at a high frequency, possibly due to the rotation of its fan; its brightness is not stable over time; the imprecise synchronization between the camera and projector causes measured radiances to fluctuate slightly over time. To resolve these issues, we repeat the shifting of the pattern about 85 times and compute a mean image for each shift. The camera runs at 60Hz and the total acquisition time is within a minute.

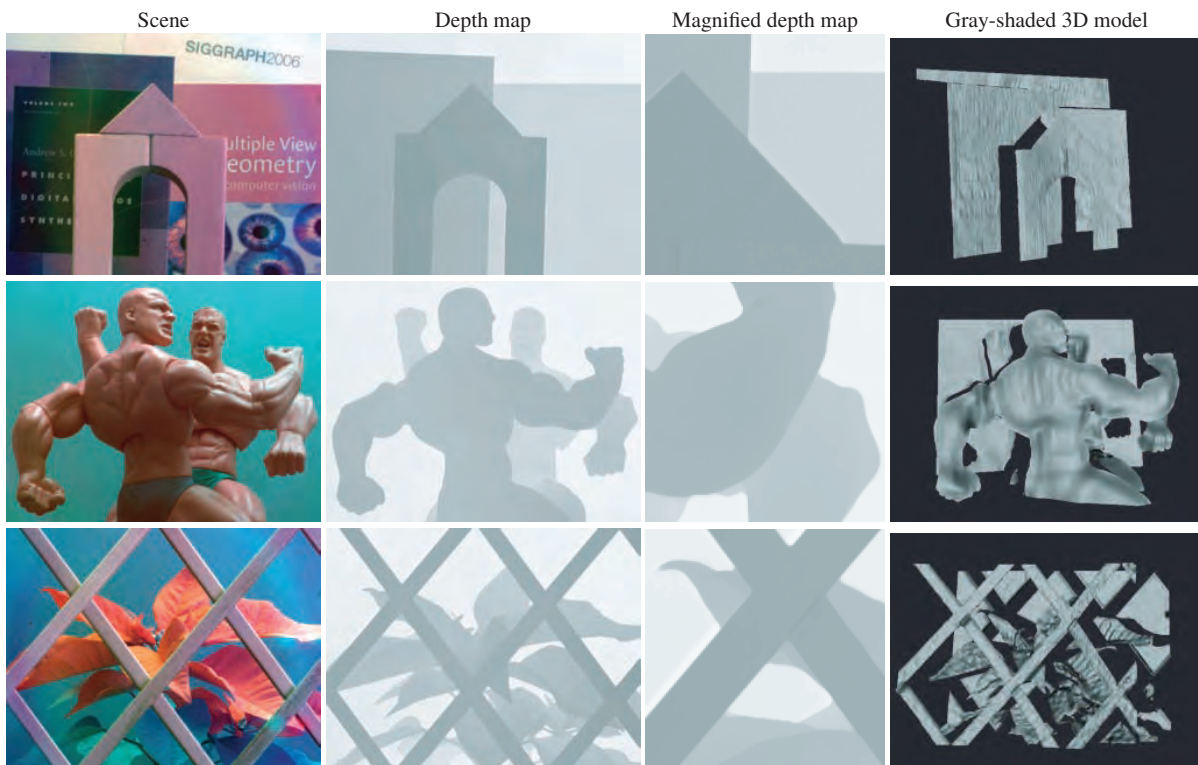


Figure 4: Depth recovery results for three scenes. From left to right: An image of the scene, the computed intensity-coded depth map, a close-up view of the depth map, a gray-shaded 3D model of the scene, as seen from a novel viewpoint. Notice the quality of the computed depth around scene discontinuities. (Please see the companion video.)

We tilt a foam board in front of the system and compute depth for each of its points. This is done by taking an image of the board with a few reference markers, as shown in Figure 3(a),⁶ and computing the homography from the board to the projection plane. As detailed in [Zhang 2000], this homography allows us to estimate the position and orientation of the board⁷, from which the depth of every point of the board can be easily computed. Figure 3(b) shows the intensity-coded depth map of the board. **Step 3:** We compute the θ values for all points on the board by shifting the stripe pattern and computing A_1 and A_2 for each pixel.

Figure 3(c) shows an image of the board under one of the shifted patterns, and (f) and (g) show the temporal radiance profiles of two points, $\mathbf{q}$ and $\mathbf{s}$, on the board. As $\mathbf{s}$ is closer to the projector and more defocused than $\mathbf{q}$, its temporal radiance profile is more blurred. Figures 3(h) and (i) show plots of the DFS coefficients A_k for the profiles in (f) and (g), respectively. Figure 3(d) shows the intensity-coded θ map and (e) shows a plot of the θ values (blue curve) for the column 350 in (d). The raw θ values include a small amount of noise and hence we fit a smooth curve which is shown as the green curve in (e). Using the depth estimation in Step 2, we can tabulate the mapping from θ to z . In our current implementation, we build a lookup table for each column, assuming that the defo-

cus kernel is vertically invariant but has some horizontal variation. Figure 3(j) shows three θ - z mapping curves for the columns 100, 350 and 600. An even more comprehensive calibration would involve translating the board across the whole working volume and generating a lookup table for each pixel. Such a calibration would account for higher-order projector lens aberrations as well.

3.5 Depth Recovery Results

Once we know the mapping between θ and z , the depth recovery is straightforward. We take 24 images while shifting the illumination pattern across the scene. From these images, we compute θ for each camera pixel using Eqs. (2,3) and then transform the θ image to a depth image using the pre-computed lookup table. Figure 4 shows several depth recovery results. In the first row, we show results for a scene with books and wooden blocks that has simple boundaries. Our method recovers the sharp depth discontinuities at the boundaries. In the second row, we show results for a scene with two toy wrestlers with similar skin color. Again, our method can separate the two figures with clean boundaries, even though the surfaces have a specular component. In the third row, we show results for a scene with leaves behind a fence. This result shows that the performance of our method is independent of occlusion complexity. In fact, it has been shown [Scharstein and Szeliski 2003] that it is very difficult to obtain a depth map that is complete in any camera view for a scene like the one with leaves using triangulation-based methods, even if multiple cameras and projectors are used. All the results are computed within a minute using Matlab.

We have also computed noise statistics for our depth estimation. Specifically, we chose 20 planar patches from the experimented scenes that are located at different depth within the working volume. We then computed the mean and standard deviation of the

⁶The glare is produced by a number of dust particles on the half-mirror. Since the half-mirror is very close to the projector, these particles are lit with roughly 100 times the intensity compared to the scene, thereby producing bright spots in the image that have the shape of the camera aperture.

⁷Zhang [2000] takes several images of a board at different orientations to estimate a camera's intrinsic parameters. In our work, we approximately estimate the projector's intrinsics from the frustum specification in its manual. Therefore, we only take one image of the board to compute its pose.

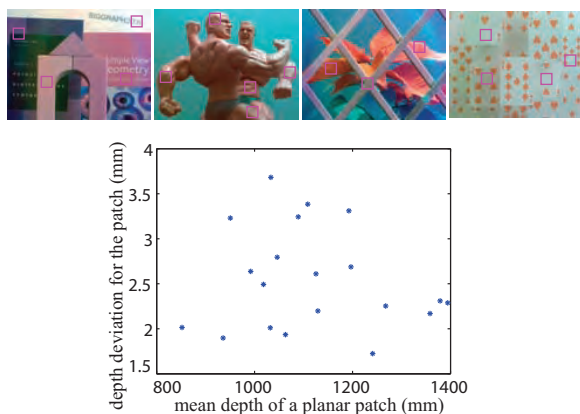


Figure 5: Noise statistics in the depth estimation. Twenty planar patches are chosen from the experimented scenes, shown on the top, and the mean and standard deviation of the depth for those patches are plotted at the bottom. Within a 600mm working volume, our depth estimation noise is around 4mm.

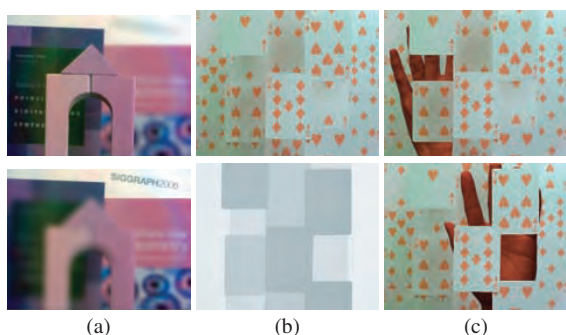


Figure 6: (a) Refocused images of the book scene in Figure 4. The defocus effects are synthesized using the recovered depth map. (b) A collection of playing cards placed at four depth layers and their estimated depth map. (c) A moving hand from another video is inserted into the card scene with all the desired occlusion effects. (Please see the companion video.)

depths inside these patches, as shown in Figure 5. From this figure, we can see that our depth estimation noise is about 4mm for a working volume of 600mm.

3.6 Applications: Refocusing & Video Composition

A distinctive feature of our depth recovery method is that it estimates depth at every pixel in the camera's view and the estimation is reliable near depth discontinuities. This makes our approach particularly well-suited for a variety of image-based applications in computer graphics. Here, we show two examples, namely, refocusing and object insertion to compose a new image or video.

Figure 6(a) shows two refocused images of the book scene in Figure 4: the top one is focused on the foreground wooden blocks and the bottom one is focused on the background letters. These two images were generated with the “lens blur” tool in Adobe PhotoShop.⁸ This tool takes an image and its depth map as inputs to generate new images that are focused at any desired depth.

⁸In theory, without having the full light field available, refocusing can not be simulated exactly. The PhotoShop implementation of lens blur is proprietary. We think a practical way to implement it would be to heuristically inpaint the occluded layers a little bit to obtain the full light field.

Figure 6(b) shows a collection of playing cards placed at four depth layers. The repetitive textures on the cards and the complex occlusions make it very hard to segment the scene into layers automatically, or even manually. Using projection defocus, our method produces a clean depth map that segments the scene into layers. This segmentation makes it easy to insert objects into the scene with correct occlusion effects. Figure 6(c) shows a real hand from another video inserted into the scene with all the desired occlusion effects. **Please see the video for more results.**

We believe that when a complete depth map is available for an image, a variety of image editing applications become possible or easier to implement. Examples other than the ones we have shown are creating layered representations of complex scenes for view morphing, segmentation for matting, object replacement, and shadow removal. In the past, such applications have not been easy to implement as “clean” depth maps have not been easy to obtain. For most image editing tasks, the depth maps need not be highly precise (as with time-of-flight sensors), but they need to be complete and they need to be reliable at discontinuities, as humans are particularly sensitive to edge artifacts. We hope our depth recovery method, although not as accurate as laser scanners or structured light sensors, will inspire new types of image editing applications.

4 Focused Projection at Multiple Depths

Due to their optical design, standard projectors can only be focused on a single fronto-parallel plane. In some applications, it is desirable to project images onto non-planar structures; for example, multiple planes or a dome to create a virtual environment [Raskar et al. 1998]. In such cases, most parts of the image are blurred due to defocus. One way to solve this problem is to design sophisticated optics. Even if this is possible, the optics cannot be modified to accommodate changes in the structure that is being projected onto. Another approach is to use multiple projectors [Bimber and Emmerling 2006], where the number of depths for which the projected image can be in focus equals the number of projectors. In this section, complementary to the multi-projector approach, we propose a computational method that processes an input image in a scene-dependent way to minimize the defocus blur at all points in the projected output image. Our method requires just a camera and can be applied to any off-the-shelf projector.

4.1 Defocus Compensation Algorithm

Consider the scenario where an image I needs to be projected onto a surface with given depth variation. The radiance of a point on the surface due to illumination by the projector is governed by the projection defocus equation Eq. (1). As in previous work, e.g. [Raskar et al. 2003; Fujii et al. 2005], we use a camera as a proxy for the human eye and seek to make the scene radiance captured by the camera be the same as the input image I . To do so, we can project a *compensation image*, P^* , by solving the projection defocus equation as

$$P^* = (\alpha f)^{-1} * (I - \beta), \quad (4)$$

where $(\alpha f)^{-1}$ is the inverse of the kernel αf . Theoretically, if P^* is projected, the scene brightness will be the same as the input image I . However, f is a low-pass filter and its inverse will have strong ringing effects. Therefore, Eq. (4) will not be feasible to implement unless the projector has an infinite dynamic range. Instead, we cast the problem of computing the compensation image as a constrained minimization problem, as follows:

$$P^* = \arg \min_P \{d(\alpha f * P + \beta, I) \mid \forall \mathbf{x}, 0 \leq P(\mathbf{x}) \leq 255\}, \quad (5)$$

where $\mathbf{x}$ is the projector pixel coordinate and $d(\cdot, \cdot)$ is an image distance metric. Eq. (5) finds the compensation image P^* , with all its brightness values within the projector's dynamic range, that after defocus blurring most closely matches the input image I .

⁹We found that even if we focus a projector on a fronto-parallel plane, when projecting a binary dot pattern, we see "light leakage" from one pixel into its neighbors. We observed this effect on different projector models.

In this section, we show how the defocus compensation method discussed in Section 4 can be used to reduce projector pixelation.

5 Depixelation

compensation results closely resemble the input images. In our second experiment, we project an image of a tiled flower texture onto the inside of a hemispherical dome, as shown in Figure 8(b). The projector is focused on the front plane of the dome. In the right two columns of Figure 9, we show the focus compensation results for two patches on the dome — one is from the top of the dome and the other is from the center. The top patch is less blurred than the center one because the former is closer to the focal plane of the projector. As with the three-plane experiment, the

4.4 Focused Projection on a Dome

ited dynamic range of the projector. cut by the defocus cannot be fully compensated for due to the limited dynamic range of the projector. In these two cases, and certain high frequencies in the input image that are with respect to their inputs because defocus is more severe in these left and right planes (first and third columns) are slightly blurred (second column) is almost identical to the input. The ones on the focused compensation image regions, the one on the middle plane closely resemble the input image regions. Among these three defocused compensation image regions are less blurry and more our results. Notice that these image regions are less blurry and more scene geometry. The fourth row shows the defocused compensation components to compensate for the defocus induced by original input ones. This is expected as our method boosts high-frequency components to compensate for the defocus induced by these image regions look like high-pass filtered versions of the original input ones. The second row shows the compensation resulting from Eqs. (6,7), which represent the new input to the projector. on the left and right planes are even more blurred due to defocus. for this plane due to projector artifacts.⁹ As expected, the faces the middle plane is in focus, the face still looks a little blurred (without compensation) can produce. Notice that even though without any compensation. This row represents the best the projector shows the defocused original image regions, captured by a camera. shows the original image regions for the three faces. The third row in the left three columns of Figure 9. The first row of Figure 9 We show the focus compensation results for the three face regions shown in Figure 8(a). The projector is focused on the middle plane. fashion models onto three planes that are at different depths, as In our first experiment, our goal was to project an image of three

4.3 Focused Projection on Multiple Planes

terms in both horizontal and vertical directions, as in Section 3. and the projector's pixels are determined by shifting sinusoidal pattern and the input image I . The correspondences between the camera's convenient to compare the defocused compensation image, $F^P + \beta$, from the camera to the projector's coordinate frame, which makes it such a kernel map also helps to compensate lens aberrations as well. for each of the three color channels of the projector. Calibrating defocus effects. We repeat the same procedure to capture kernels we have a per-pixel kernel map that accounts for spatially-varying kernels for other pixels that are '0' in a bilinear manner. In the end, projector pixels that are '1'. From these kernels, we interpolate the camera, shown in Figure 7(b), are approximately the kernels for the boring dots is 12 pixels. The point spread patterns captured by the one in Figure 7(a). In our experiments, the distance between neighboring dots is 12 pixels. Therefore, we simply project a sparse binary dot pattern, like the scenes used in our experiments here are at least piece-wise smooth.

We now describe how we obtain β and αf for any given scene. We obtain the ambient term β by turning off the projector and taking an image. To obtain αf for each pixel, we could shift a dot pattern across the scene and the temporal radiance profile for each pixel is then its kernel. This method is effective for a scene with intricate geometry, such as the scenes shown in Section 3. However, the

4.2 Kernel Estimation

dynamic range of the projector. compensation image and the original input image within the dynamic range of the projector. Eq. (7) and Eq. (6) minimizes the difference between the defocused algorithm, which converges to the solution of Eq. (4). Combining out Eq. (7), iterating Eq. (6) alone is a standard steepest-descent algorithm, which converges to the solution of Eq. (4). Combining that are often built into projectors by their manufacturers. With scene-dependent, unlike the standard sharpening operations and F^T , respectively. Note that these filterings are spatially-varying forward — it involves two image filterings with the kernel matrices F^T and F^T , respectively. Note that these filterings are spatially-varying distance $\|F^T P + \beta - I\|_2^2$ with respect to P . Evaluating G_i is straightforward clamping operation. Notice that G_i is the gradient of the image where $G_i = F^T(I - \beta - F^T P)$, and CLAMP is a pixel-wise

$$P_{t+1} = P_t + \eta_i G_i \quad (6)$$

$$P_{t+1} = \text{CLAMP}(P_{t+1}; 0, 255) \quad (7)$$

the following two steps: The algorithm starts with $P_0 = I$ and iterates each row of F is the defocus kernel of the corresponding pixel model defocus convolution, $\alpha f * P$, as a matrix multiplication, $F^T P$, where descent algorithm [Nocedal and Wright 1999]. We represent the image P^* is found by applying an iterative, constrained, steepest-descent algorithm [Nocedal and Wright 1999]. The compensation differences for the image distance metric $d(\cdot, \cdot)$. In our implementation, we have used the sum-of-squared pixel differences for the image distance metric $d(\cdot, \cdot)$. The compensation

for. (b) Projection onto a hemispherical dome. (a) Projection onto three planes at different depths from the projector.

Figure 8: Two test scenes for focused projection at multiple depths.

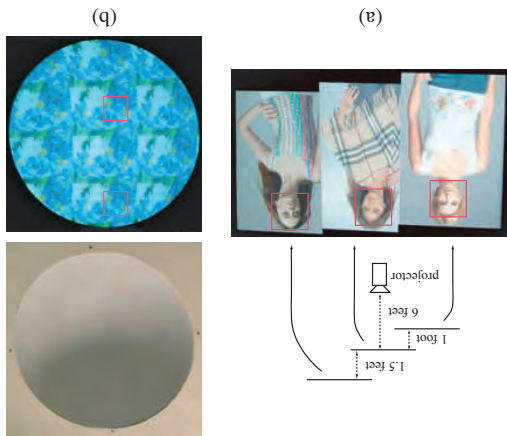
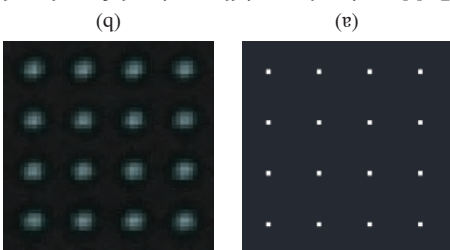


Figure 7: Measuring the spatially-varying defocus kernel. (a) A portion of the dot pattern projected onto the scene. (b) The corresponding camera image with samples of the point spread function.



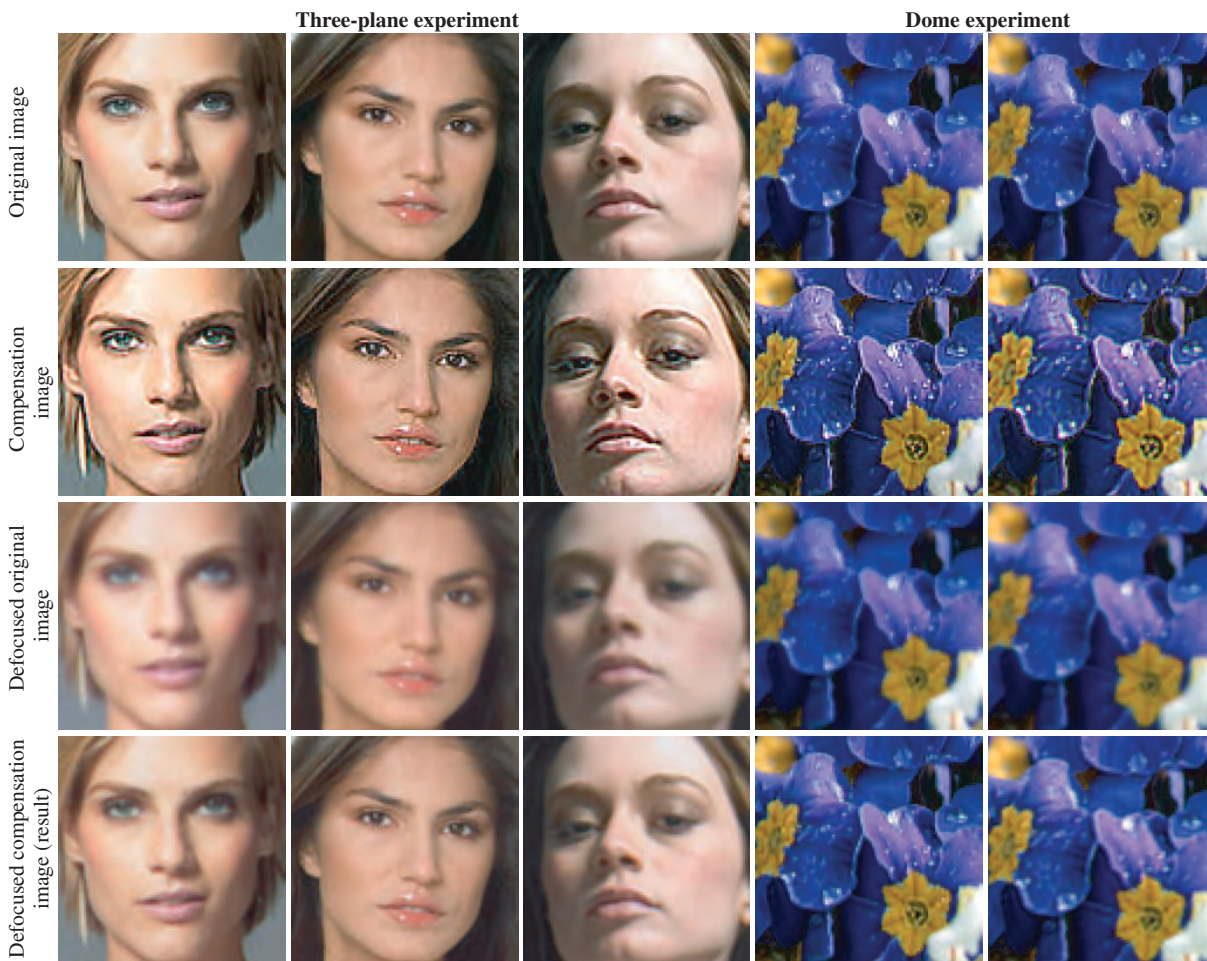


Figure 9: Results for defocus compensation. The three faces on the left were projected onto the three planar surfaces in Figure 8(a). The two flower textures on the right were projected onto the hemispherical dome in Figure 8(b). The defocus compensation method results in less blurry image regions (fourth row) than the uncompensated image regions (third row). The original image regions are shown in the first row and the compensation image regions computed by the method and used as input to the projector are shown in the second row. The compensation method is scene independent as it can handle a spatially-varying defocus kernel. **(Please see the companion video.)**

Pixelation is a clearly noticeable artifact produced by all digital projectors. It is caused by two factors. The first is the spatial digitization due to the finite resolution of the projector. The second is the gap (dead-zone) between adjacent pixels on the projector's physical image plane that arises because the pixel fill-factor is never 100 %. The digitization is known to create jaggy boundaries when the resolution of the projector is not high enough for the given application. This effect is observed particularly when high quality captured images are projected, as the resolution of most LCD and DLP projectors has remained at 1024x768 or less for the last seven years, while digital cameras have tripled in their resolution during the same time period. The dead-zone between pixels does not generate light and produces thin black lines on the projection screen, known as the *screen-door effect*. This effect makes pixelation more pronounced as it clearly marks out pixel boundaries on the screen.

In our implementation of depixelation, we assume that the images are projected onto a single fronto-parallel screen, i.e., the traditional projection scenario. Our basic approach is to focus the projector slightly in front of (or behind) the projection screen so that the image on the screen is slightly blurred. In this case, a slight amount of

light is leaked into the black gaps and neighboring pixels, which reduces the screen-door effect as well as smoothes out the jaggy pixel boundaries. However, doing so also creates blurry images. Since this purposely induced blur is very slight, we can use the compensation method in Section 4 to process the input image so that the defocused projection looks very similar to the original input image. Therefore, the compensation method can be used in conjunction with the minor induced defocus to achieve depixelation.

Specifically, we use the compensation method to compute an optimal image P^* at the projector resolution whose defocused projection most closely resembles the input image, which may have higher resolution. Note that if the input image resolution is higher than the projector's native resolution, the number of rows in F is larger than the number of columns. Each row of F is a defocus kernel modulated by both surface albedo and the screen-door effect.

We have tested the depixelation method on several high resolution input images (each one with 3 times the projector resolution). The capture of β and F is done using the method in Section 4, except that we capture a higher resolution kernel map by zooming-in our camera so that 3×3 camera pixels see about one projector pixel.

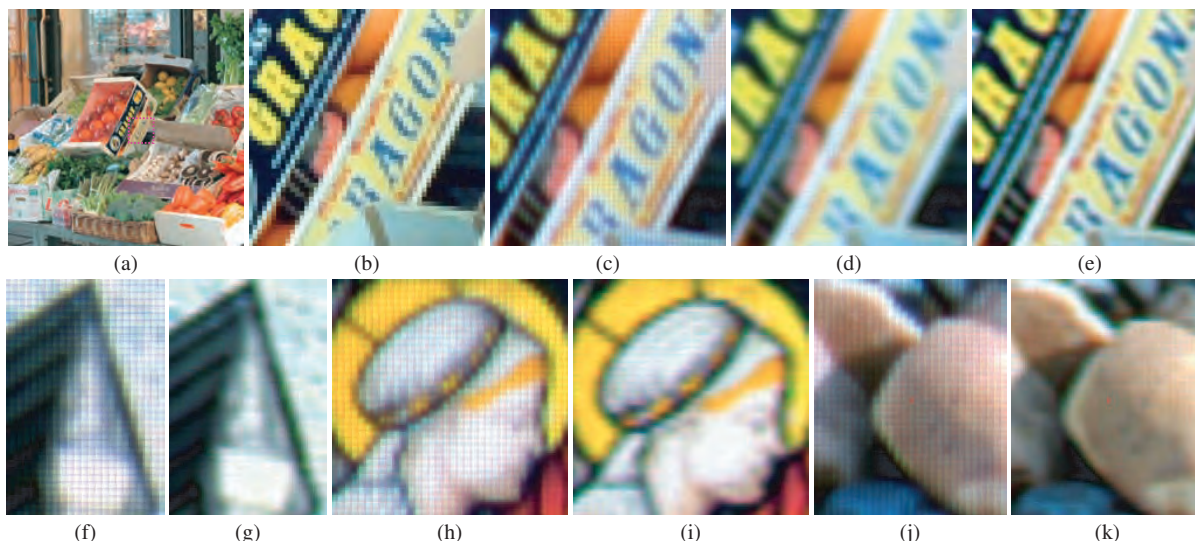


Figure 10: Examples of Projector Depixelation. (a) An original image of $3\times$ projector resolution. (b) A patch in (a) of projector resolution. (c,d) Projection of (b) under focused and defocused settings, respectively. (e) Our depixelation result. (f-k) Three more examples of depixelation with (f,h,j) as focused projection and (g,i,k) as depixelated projection. In all examples, the compensation greatly reduces pixelation effects while preserving image quality. (Please see the companion video.)

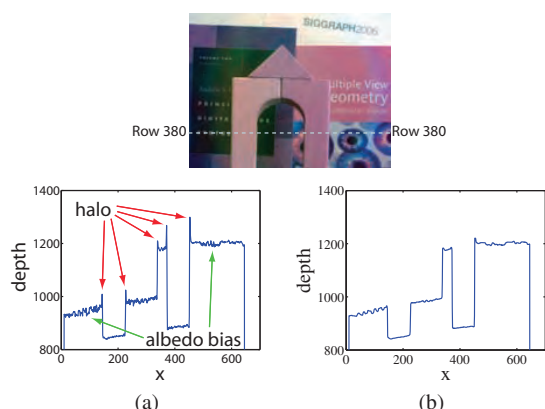


Figure 11: Albedo-correlated bias and halo effects in depth estimation. (a) The depth profile for row 380 of the scene. (b) The depth profile after removing noise and halo by a 7×7 median filter.

Figure 10 shows four examples of depixelation. In all the cases, spatial digitization and screen-door effects are greatly reduced and yet image sharpness is preserved. Our current implementation of the compensation algorithm uses Matlab. The algorithm takes about 10 iterations to converge and takes 3-5 minutes to produce the final compensation image. Since the compensation method only involves filtering with F and F^T , we believe it can be implemented on image processing chips or graphics hardware to achieve real-time (frame-rate) performance.

6 Discussion

In this paper, we have modelled projection defocus as a linear system and developed a temporal defocus method that recovers depth at all pixels in an image, regardless of the scene complexity. We also proposed a scene-dependent filtering algorithm that increases the depth of field of a projector without modifying its optics. Finally, we showed that defocus can be exploited to reduce pixelation artifacts produced by digital projectors. We now discuss the limita-

tions of our work and open problems as topics for future research.

First, our temporal defocus method should, in principle, be invariant to surface albedo. In practice, we found that the surface albedo sometimes does affect the depth estimation, as shown in Figure 11. We believe that this is only an issue with our current implementation. Our beam-splitter not only reflects light from the scene to the camera, but also transmits light from a black backdrop placed behind it. Therefore, the defocus kernel f in Eq. (1) is actually a sum of the defocus kernels of both the scene and the backdrop. If the scene is much brighter than the black backdrop, Eq. (3) is dominated by the scene's defocus kernel. However, when the scene point is dark, due to low albedo or because its surface orientation is near-grazing for the projector, the light from the scene point to the camera is weak and comparable to the light from the backdrop. In this case, Eq. (3) will depend also on the defocus kernel of the backdrop, which causes errors in depth estimation. The backdrop kernel remains constant and can be calibrated to reduce depth estimation errors. Alternatively, the beam-splitter can be placed in a custom-designed chamber that absorbs all forms of stray light.

The projector defocus is for most cases independent of scene geometry, and this independence makes it superior to camera defocus for depth estimation. However, there is a special case that this independence does not hold. Specifically, when a closer object occludes a distant object, there will be a narrow band of points near the occluding contour on the distant object that "see" only part of the projector's aperture; so the projected pattern will be more infocus than it would be if the entire aperture were visible. This partial aperture effect results in a halo artifact: depth estimation biased toward the focal plane, as shown in Figure 11. However, even in this special case, projector defocus is still better than camera defocus. Camera defocus will cause estimation errors for both the foreground and background pixels near the occluding boundary. In contrast, projector defocus will only cause errors at the background pixels, while leaving the foreground pixels unaffected. Furthermore, in practice, because the solid angle subtended by the projector aperture is only about 1 degree with respect to a scene point, the number of affected background pixels is small. Therefore, as shown in Figure 11, the halo effect can be greatly reduced by a simple median filtering.

In practice, using projector defocus for depth estimation does not require moving detectors or changing optical settings as traditional camera defocus methods do [Pentland 1987; Nayar and Nakagawa 1994]. Therefore, our method can be more conveniently implemented. However, a coaxial implementation of depth from camera defocus, as in [Nayar et al. 1996], allows for capturing dynamic scenes, which our method currently is incapable of, because we use 24 images for depth estimation. We believe this number can be greatly reduced, which would enable us to develop a real-time sensor that can handle dynamic scenes. In Eq. (1), there are three unknowns: α , β , and z . If we can calibrate the defocus kernel f a priori, then, in theory, 3 images are enough to solve for these unknowns. Interestingly, this minimum number is the same for other shape acquisition methods, like the phase-shift method [Huang et al. 2003], the time-of-flight method [Gonzales-Banos and Davis 2004], and photometric stereo [Horn and Brooks 1989].

Our temporal defocus method can deal with specular surfaces, whenever the BRDF's are approximately constant within the solid angle subtended by the projector aperture from the scene point. Nevertheless, the extreme case of near-mirror reflection, as well as saturated highlight pixels, will cause errors. Although our method is developed under the direct illumination assumption, it's not very sensitive to the indirect illumination. This is because indirect illumination usually creates only very low frequency intensity fluctuation, which will mainly affect Fourier coefficient A_0 . Our depth is however estimated via A_1 and A_2 . Of course, for extremely specular reflection, the global illumination can change dramatically with the projected patterns and hence our method will break down.

One challenging open problem for defocus-based methods is handling translucent objects. A translucent material introduces additional blur due to subsurface scattering, which would cause a systematic bias in our methods. The amount of bias depends on the amount of translucency blur compared to defocus blur. If the defocus blur dominates the translucency blur, the error will be small. Otherwise, the error will be large. It would be interesting to extend our analysis to handle blur induced by translucency. In practice, the depth of mixture pixels at boundaries is often a blend of its neighboring depth values. It would be interesting to accurately model the mixture pixels, e.g., combining our approach with the defocus matting method [McGuire et al. 2005], to estimate mattes for scenes with continuous depth variations.

Our method for defocus compensation essentially extends the depth of field of the projector. However, when the blur is very severe, our method cannot fully compensate for the blur due to the limited dynamic range of the projector. In such a case, combining our method with multiple-projector solutions [Bimber and Emmerling 2006] could be beneficial. Finally, we plan to extend our work on depixelation to make it a practical and useful projector feature. How objectionable pixelation artifacts are, is really a subjective issue. For our technique to be incorporated into commercial projectors, a few preset options can be provided so that the user can decide how much focus quality they are willing to tradeoff for depixelation.

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ATTACHMENT C-3



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APPENDIX D

JAMES L. MULLINS, PhD

Prior Art Documentation Librarian Services, LLC

205 Saint Cuthbert, Williamsburg, VA 23188

jlmullins@priorartdoclib.com

ph. 765 479 4956

Prior Art Documentation Librarian Services, LLC. (PADLS). Founded January 2018. As of August, 2022, 103 declarations have been completed for 35 law firms; four depositions scheduled, three cancelled a few days prior, and only one was held in February, 2019.

Library Experience:

2018-present Dean Emeritus, Libraries & Norton Professor Emeritus, Purdue University
2011 - 2017 Dean of Libraries & Esther Ellis Norton Professor, Purdue University
2004 - 2011 Dean of Libraries & Professor, Purdue University, West Lafayette, IN
**2000-2004 Assistant/Associate Director for Administration, MIT Libraries,
Massachusetts Institute of Technology, Cambridge, MA.**
**1996-2000 University Librarian & Director, Falvey Memorial Library. Villanova University,
Villanova, PA.**
1978-1996 Director of Library Services, Indiana University South Bend.
**1974-1978 Associate Librarian, Indiana University Bloomington, School of Law. 1973-
1974 Instructor/Catalog Librarian. Georgia Southern College (now University).**

Teaching Experience:

**1977-1996 Associate Professor (part-time), School of Library and Information Science, Indiana
University. Subjects taught: Cataloging, Management, and Academic Librarianship.**

Education:

1972 - University of Iowa. Honors Bachelor of Arts, History, Religion & Political Science.
1973 - University of Iowa. Master of Arts in Library Science.
**1984 - Indiana University. Doctor of Philosophy. Concentration: Academic Library Administration.
Emphasis: Law Librarianship.**

Awards and Recognition:

2017 Wilmeth Active Learning Center/Library of Engineering and Science, Grand Reading Room, was announced by President Mitch Daniels, Purdue University, that it would be re-named the James L. Mullins Reading Room to honor his leadership and reputation in the academic library profession.

September 2017. Portrait unveiled December 2017.

2017 Distinguished Alumnus Award by the School of Informatics and Computing, Indiana University, Bloomington. Given June 25, 2017.

2016 Hugh C. Atkinson Memorial Award, jointly sponsored by the four divisions of the American Library Association (ALA), June 27, 2016.

2015 ACRL Excellence in University Libraries Award, April 23, 2015.

Named Esther Ellis Norton Professor of Library Science by Purdue Trustees, December 11, 2011.

International Review Panel to evaluate the University of Pretoria Library, February 20 – 24, 2011. Pretoria, South Africa.

Publications: (selected)

Designing the Academic Library, Chapter Contributor. Association of College and Research Libraries, American Library Association, 2022.

A Purdue Icon: Creation, Life, and Legacy, edited by James L. Mullins, Founder's Series, Purdue University Press, 138pp., August 2017.

"The policy and institutional framework." In *Research Data Management, Practical Strategies for Information Professionals*, edited by Ray, J M. Purdue University Press, pp.25-44, 2014.

"DataCite: linking research to data sets and content." In Benson, P and Silver, S. *What Editors Want: An Author's Guide to Scientific Journal Publishing*. University of Chicago Press, pp. 21-23, December 2012.

"Library Publishing Services: Strategies for Success," with R. Crow, O. Ivins, A. Mower, C. Murray-Rust, J. Ogburn, D Nesdill, M. Newton, J. Speer, C. Watkinson. *Scholarly Publishing and Academic Resources Coalition (SPARC)*, version 2.0, March 2012.

"The Changing Definition and Role of Collections and Services in the University Research Library." *Indiana Libraries*, Vol 31, Number 1 (2012), pp.18-24.

"Are MLS Graduates Being Prepared for the Changing and Emerging Roles that Librarians must now assume within Research Libraries?" *Journal of Library Administration*. Volume 52, Issue 1, 2012, p. 124-132

Baykoucheva, Svetla. What Do Libraries Have to Do with e-Science?: An Interview with James L. Mullins, Dean of Purdue University Libraries. *Chem. Inf. Bull.* [Online] 2011, 63 (1), 45-49.

<http://www.acscinf.org/publications/bulletin/63-1/mullins.php> (accessed Mar 16, 2011).

“The Challenges of e-Science Data-set Management and Scholarly Communication for Domain Sciences and Technology: a Role for Academic Libraries and Librarians,” chapter in, *The Digital Deluge: Can Libraries Cope with e-Science?*” Deanna B. Marcum and Gerald George, editors, Libraries Unlimited/Teacher Ideas Press, 2009. (a monograph publication of the combined proceedings of the KIT/CLIR proceedings).

“Bringing Librarianship to e-Science,” *College and Research Libraries*. vol. 70, no. 3, May 2009, editorial.

“The Librarian’s Role in e-Science” *Joho Kanri (Journal on Information Processing and Management)*, Japan Science and Technology Agency (formerly Japan Information Center of Science and Technology), Tokyo, Japan. Translated into Japanese by Taeko Kato. March 2008.

The Challenge of e-Science Data-set Management to Domain Sciences and Engineering: a Role for Academic Libraries and Librarians,” KIT (Kanazawa Institute of Technology)/CLIR (Council of Library and Information Resources) International Roundtable for Library and Information Science, July 5-6, 2007. Developments in e-science status quo and the challenge, The Japan Foundation, 2007.

“An Administrative Perspective,” Chapter 14, *Proven Strategies for Building an Information Literacy Program*, Susan Curzon and Lynn Lampert, editors, Neal-Schuman Publishers, Inc., New York, 2007. pp. 229-237.

Library Management and Marketing in a Multicultural World, proceedings of the IFLA Management and Marketing (M&M) Section, Shanghai, China, August 16-17, 2006, edited. K.G. Saur, Munchen, Germany, June 2007. 390 pp.

Top Ten Assumptions for the Future of Academic Libraries and Librarians: a report from the ACRL Research Committee, with Frank R. Allen and Jon R. Hufford. *College & Research Libraries*, April 2007, vol.68, no.4. pp.240-241, 246.

To Stand the Test of Time: Long-term Stewardship of Digital Data Sets in Science and Engineering. A report to the National Science Foundation from the ARL Workshop on New Collaborative Relationships: the Role of Academic Libraries in the Digital Data Universe. September 26-27, 2006, Arlington, VA. p.141. <http://www.arl.org/bm~doc/digdatarpt.pdf>

“Enabling Interaction and Quality in a Distributed Data DRIS,” *Enabling Interaction and Quality: Beyond the Hanseatic League*. 8th International Conference on Current Research Information Systems, with D. Scott Brandt and Michael Witt. Promoted by euro CRIS. Leuven University Press, 2006. pp.55-62. Editors: Anne Garns Steine Asserson and Eduard J. Simons.

"Standards for College Libraries, the final version approved January 2000," prepared by the ACRL College Libraries Standards Committee (member), *C&RL News*, March 2000, p.175-182.

"Standards for College Libraries: a draft," prepared by the ACRL College Libraries Section, Standards Committee (member), *C&RL News*, May 1999, p. 375-381.

"Statistical Measures of Usage of Web-based Resources," *The Serials Librarian*, vol. 36, no. 1-2 (1999) p. 207-10.

"An Opportunity: Cooperation between the Library and Computer Services," in *Building Partnerships: Computing and Library Professionals*. Edited by Anne G. Lipow and Sheila D. Creth. Berkeley and San Carlos, CA, Library Solutions Press, 1995. p. 69-70.

"Faculty Status of Librarians: A Comparative Study of Two Universities in the United Kingdom and How They Compare to the Association of College and Research Libraries Standards, " in *Academic Librarianship, Past, Present, and Future: a Festschrift in Honor of David Kaser*. Englewood, Colorado; Libraries Unlimited, 1989. p. 67-78. Review in: *College & Research Libraries*, vol. 51, no. 6. November 1990, p. 573-574.

Presentations: (Representative)

“How Long the Odyssey? Transitioning the Library and Librarians to Meet the Needs and Expectations of the 21st Century University,” David Kaser Lecture, School of Informatics & Computing, Indiana University, Bloomington, IN, November 16, 2015.

Presentation at University of Cape Town, Cape Town, South Africa, August 20, 2015.

“The Challenge of Discovering Science and Technology Information,” Moderator, International Federation of Library Associations (IFLA) Science and Technological Libraries Section Program, Cape Town, South Africa, August 18, 2015.

“An Odyssey in Data Management: Purdue University,” International Federation of Library Associations (IFLA) Research Data Management: Finding Our Role – A program of the Research Data Alliance, Cape Town, South Africa, August 17, 2015.

Presentation at University of Pretoria, Pretoria, South Africa, August 11, 2015.

Co-Convener with Sarah Thomas, Harvard University, at the Harvard Purdue Symposium on Data Management, Harvard University, Cambridge, MA, June 15-18, 2015.

“Strategic Communication,” panel discussion on the Director's role and perspective on library communications at Committee on Institutional Cooperation (CIC) Center for Library Initiatives (CLI) Annual Conference, University of Illinois Urbana-Champaign, May 20, 2015.

“Issues in Data Management,” panel discussion moderated by Catherine Woteki, United States Undersecretary for Research, Education & Economics at 20th Agriculture Network Information Collaborative (AgNIC) Annual Meeting in the National Agricultural Library, Beltsville, MD, May 6, 2015.

“Active learning/IMPACT & the Active Learning Center at Purdue University,” Florida Institute of Technology, Melbourne, FL, February 11, 2015.

“Science+art=creativity: libraries and the new collaborative thinking,” panel moderator, International Federation of Library Associations (IFLA) 80th General Conference and Assembly, Lyon, France, August 19, 2014.

“Purdue University The Active Learning Center—A new concept for a library,” Association of University Architects 59th Annual National Conference, University of Notre Dame, South Bend, IN, June 23, 2014.

“Big Data & Implications for Academic Libraries,” keynote speaker, Greater Western Library Alliance (GWLA) Cyber-infrastructure Conference, Kansas City, MO, May 28, 2014.

“Research Infrastructure,” panel moderator, Association of Research Libraries (ARL) 164th Membership Meeting, Ohio State University, Columbus, OH, May 7, 2014.

“An Eight Year Odyssey in Data Management: Purdue University,” International Association of Scientific and Technological University Libraries (IATUL) 2013 Workshop Research Data Management: Finding Our Role, University of Oxford, UK, December 2013.

“Purdue University Libraries & Press: from collaboration to integration,” Ithaka Sustainable Scholarship, The Evolving Digital Landscape: New Roles and Responsibilities in Higher Education, libraries as publishers, New York, New York, October 2013.

“Tsinghua and Purdue: Research Libraries for the 21st Century,” Tsinghua University, Tsinghua, China, August 2013.

“Purdue Publishing Experience in the Libraries Publishing Coalition,” Association of American University Presses Annual Meeting, Press-Library Coalition Panel, Boston, Massachusetts, June 21, 2013.

“Indiana University Librarians Day: Purdue University Libraries Ready for the 21st Century,” Indiana University Purdue University Indianapolis (IUPUI), June 7, 2013.

“Purdue University Libraries and Open Access; CNI Project Update,” Coalition for Networked Information, San Antonio, TX, April 5, 2013.

Memorial Resolution, honoring Joseph Brannon, to the Board of the Association of College & Research Libraries, Seattle, WA, January 2013.

“An overview of sustaining e-Science collaboration in an Academic Research Library—the Purdue experience,” Duraspace e-Science Institute webcast, October 17, 2012.

“The Role of Libraries in Data Curation, Access, and Preservation: an International Perspective,” Panel Moderator, 78th General Conference and Assembly, International Federation of Library Associations, Helsinki, Finland, August 15, 2012.

“21st Century Libraries,” moderator of First Plenary Session, International Association of Technological University Libraries 33rd Annual Conference, Singapore, June 4, 2012.

“Planning for New Buildings on Campus,” panel presenter, University of Calgary Building Symposium on Designing Libraries for the 21st Century, Calgary, Alberta, Canada, May 17, 2012.

“Data Management and e-Science, the Purdue Response.” Wiley-Blackwell Executive Seminar-2012, Washington, DC, March 23, 2012.

“An overview of Sustaining e-Science Collaboration in Academic Research Libraries and the Purdue Experience.” Leadership & Career Development Program Institute, Association of Research Libraries (ARL). Houston, TX, March 21, 2012.

“An overview of Data Activities at Purdue University in response to Data Management Requirements.” Coalition for Academic Scientific Computation (CASC). Arlington, VA, September 8, 2011.

“Getting on Track with Tenure,” Association of College and Research Libraries (ACRL) Research Program Committee. Washington, DC, June 26, 2011.

“Integration of the Press and Libraries Collaboration to Promote Scholarly Communication,” Association of Library Collections & Technical Services (ALCTS) Scholarly Communication Interest Group – American Library Association, New Orleans, Louisiana, June 25, 2011.

“Cooperation for improving access to scholarly communication,” with N. Lossau (Germany), C. Mazurek (Poland), J. Stokker (Australia), panel moderator and presenter, Second Plenary Session, International Association of Scientific and Technological University Libraries (IATUL) 32nd Conference 2011, Warsaw, Poland. May 29-June 2, 2011.

“Riding the Wave of Data,” STM Annual Spring Conference 2011. Trailblazing & transforming scholarly publishing 2011. Washington, D.C., April 28, 2011.

“Confronting old assumptions to assume new roles: physical and operational integration of the Press and Libraries at Purdue University,” keynote speaker, 2011 BioOne Publishers & Partners Meeting. Washington, D. C., April 22, 2011.

“Are MLS Graduates Being Prepared for the Changing and Emerging Roles that Librarians must now assume within Research Libraries?” University of Oklahoma Libraries Seminar, March 4, 2011, Oklahoma City, Oklahoma.

“The Future Role of University Librarians,” the University of Cape Town, South Africa, February 25, 2011.

“New Roles for Librarians: the Application of Library Science to Scientific/Technical Research – Purdue University – a case study. International Council for Science and Technology (ICSTI); Ottawa, Canada. June 9, 2009.

“Reinventing Science Librarianship: Models for the Future,” Association of Research Libraries / Coalition for Networked Information. October 16-17th, 2008, Arlington, VA. Moderator and convener of Data Curation: Issues and Challenges.

“Practical Implementation and Opportunities Created at Purdue University,” African Digital Curation Conference, Pretoria, South Africa, (live video transmission), February 12, 2008.

Keynote speaker. “*Scholarly Communication & Academe: The Winter of Our Discontent*,” XXVII Charleston Conference on Issues in Book and Serial Acquisition, Charleston, South Carolina. November 8, 2007.

Keynote speaker. “*Enabling Access to Scientific & Technical Data-sets in e-Science: a role for Library and Archival Sciences*,” Greater Western Library Alliance (GWLA), Tucson, Arizona. September 17, 2007. A meeting of library directors and vice presidents for research of member institutions.

“*The Challenge of e-Science Data-set Management to Domain Sciences and Engineering: a Role for Academic Libraries and Librarians*,” KIT (Kanazawa Institute of Technology)/CLIR (Council of

Library and Information Resources) International Roundtable for Library and Information Science, July 5-6, 2007. Invited to participate by the Deputy Librarian of Congress.

International Association of Technological University Libraries (IATUL), Stockholm, Sweden. June 8, 2007. Invited paper, *Enabling International Access to Scientific Data-sets: creation of the Distributed Data Curation Center (D2C2)*.

“A New Collaboration for Librarians: The Principles of Library and Archival Sciences Applied to the Curation of Datasets,” Symposium of the Libraries and the College of Engineering, University of Louisville, April 6, 2007.

“Purdue University Libraries: Through Pre-eminent Innovation and Creativity, Meeting the Challenges of the Information Age,” Board of Trustees, Purdue University, February 15, 2007.

ARL Workshop on New Collaborative Relationships: The Role of Academic Libraries in the Digital Data Universe, September 26-27, 2006, Arlington, VA. Invited participant.

NARA and SDSC: A partnership. A panel before the National Science Foundation, June 27, 2006. Arlington, VA. Invited participant.

“Kaleidoscope of Scientific Literacy: fusing new connections,” with Diane Rein, American Library Association, Association of College and Research Libraries, Science & Technology Section, Annual Conference, New Orleans, June 26th, 2006.

“Leadership for Learning: Building a Culture of Teaching in Academic Libraries – an administrative perspective,” American Library Association, Association of College and Research Libraries, Instruction Section, Annual Conference, New Orleans, June 25th, 2006.

“Building an interdisciplinary research program in an academic library:

how the Libraries’ associate dean for research makes a difference at Purdue University,” International Association of Technological University Libraries (IATUL), Porto, Portugal, May 23rd, 2006.

“Enabling Interaction and Quality in a Distributed Data DRIS,” *Enabling Interaction and Quality: Beyond the Hanseatic League*. 8th International Conference on Current Research Information Systems, with D. Scott Brandt and Michael Witt. Promoted by euro CRIS, Bergen, Norway, May 12th, 2006, Brandt, and Witt presented in person

“Interdisciplinary Research,” with D. Scott Brandt, Coalition for Networked Information (CNI) Spring Meeting: Project Briefing, Washington, D.C., April 3rd, 2006.

“An Interview with Purdue’s James Mullins,” a podcast submitted by Matt Pasiewicz, on *Educause Connect*, http://connect.educause.edu/James_L_Mullins_Interview_CNI_2005

"Managing Long-Lived Digital Data-sets and their Curation: Interdisciplinary Policy Issues," Managing Digital Assets Forum, Association of Research Libraries (ARL), Washington, D.C., October 28th, 2005.

"The Odyssey of a Librarian." Indiana Library Federation (ILF), District 2 Meeting, South Bend, Indiana. October 4th, 2005.

"New College Library Standards," Standards Committee Presentation, ALA, Chicago, July 7, 2000.

SUNY Library Directors, Lake George, New York. "*The College Library Standards: a Tool for Assessment.*" April 5, 2000.

Tri-State College Library Association, *Finding You Have Talents You Never Knew You Had*, Penn State Great Valley, March 25, 2000.

Using Web Statistics, American Library Association, New Orleans, June 24, 1999.

Keynote speaker at the JSTOR Workshop, January 29, 30, 1999. University of Pennsylvania, Philadelphia, PA.

"The New Standards for Electronic Resources Statistics," Society of Scholarly Publishers, Washington, D.C., September 17, 1998.

"Evaluating Online Resources: Now that you've got them what do you do?," joint presenter with Chuck Hamaker, LSU, at the NASIG Conference, Boulder, Colorado. June 1998.

"What Employers Are Looking for in New Librarians?" Pennsylvania Library Association, Philadelphia. September 26, 1997.

"The Theory of Matrix Management" panel presentation of the Comparative Library Organization Committee of the Library Organization and Management Section of the Library Administration and Management Association, a division of the American Library Association, Annual Meeting, Chicago, June 24, 1990.

Professional Involvement: (summary of recent emphasis)

The focus for my professional involvement and research has moved recently toward managing massive data-sets. This has resulted in working with faculty in the sciences and technology to determine how librarians can collaborate in managing, curating, and preserving data-sets for future access and documentation. This has included various speaking opportunities as well as participation in planning with the National Science Foundation (NSF) on ways in which librarians can be integrated more completely into the funded research process. Participation in the Kanazawa Institute of Technology/Council of Library Resources Roundtable was particularly rewarding and provided new opportunities to share with international colleagues the issues surrounding data-set management. I was

the champion for the creation of the Distributed Data Curation Center (D2C2) at Purdue University (<http://d2c2.lib.purdue.edu/>)

Throughout my career, beginning with my dissertation, I have been actively involved with assessing and evaluating libraries. In the fall of 1999, I contacted twenty-two academic library directors to determine whether the need was also felt by others. The response was overwhelmingly affirmative. This resulted in a meeting at ALA Midwinter, January 2000. A formal meeting followed at Villanova University in April 2000. As convener, I helped to form the University Libraries Group (ULG), modeled after the Oberlin Group for college libraries. The ULG is made up of university libraries that support diverse wide-ranging programs through doctoral level and have a level of support that places them in the top tier of academic institutions. A few of the member libraries, along with Villanova, are William and Mary, Wake Forest, Lehigh, Carnegie-Mellon, Tufts, Marquette, Miami of Ohio, and Southern Methodist. In 1994 appointed to the Standards Committee, College Section, Association of College and Research Libraries. During the next six years, the Committee concentrated on changing the focus of the standards from quantitative analysis of input and output factors to emphasis on assessment of the outcome. Culmination of the work was a re-issue of the *Standards for College Libraries* in 2000. The knowledge gained through my work experience enabled me to formulate the changes needed in the standards. This work allowed for close collaboration with accrediting agencies, both professional and regional. During this same time another focus emerged, the impact of digital resources. Through my work on the JSTOR Statistics Task Force, standards were developed on the collection of use of electronic databases. This Standard was later adopted in 1998 by the International Consortium of Library Consortia (ICOLC). In 2002, the American Library Association appointed me to serve as the liaison to the Marketing and Management Section of the International Federation of Library Associations (IFLA).

Professional Service: (representative list)

Nominations Committee, Association of Research Libraries (ARL), 2016.

Steering Committee, Scholarly Publishing and Academic Resources Coalition (SPARC), 2016 – 2017.

“Excellence in Library Services,” Chair, Review Team, University of Hong Kong, Hong Kong, August 24-27, 2015.

Chair, Management Advisory Board, 2015-2017; Member, Scientific Advisory Board, arXiv, Cornell University, 1/1/2013 – present.

Advisory Board for the Wayne State University School of Library and Information Science, July 2012 – present.

Advisory Board for Microsoft Academic Search, 2012 – 2015. Redmond, WA.

Transforming Research Libraries, a Strategic Direction Steering Committee of the Association of Research Libraries (ARL), 2012-2015.

Science and Technology section, representing ARL, International Federation of Library Associations (IFLA), Chair, 2013 – 2017; Member, 2011 to present.

Member of University of Pretoria, South Africa, Library Review Committee. August 2013.

Co-chair, Local Arrangements Planning Committee for 2013 Conference, Association of College and Research Libraries (ACRL), a division of the American Library Association (ALA).

Association of Research Libraries Leadership & Career Development Program Mentor, 2011-2017.

e-Science Task Force, Association of Research Libraries. July 2006 – present. Chair, October 2011 – October 2012.

Board of Directors, International Association of Technological University Libraries (IATUL). January 2008 – December 2014.

Midwest Collaborative for Library Services (MCLS); Board Member, October 2010 – December 2012.

Chair, Library Directors, Committee on Institutional Cooperation (CIC), July 2010 – June 2012.

Board of Directors, Association of Research Libraries (ARL); October 2008 – October 2011.

Scholarly Communication Steering Committee, Association of Research Libraries (ARL) 2008-2011.

Editorial Board, *College and Research Libraries*, Association of College and Research Libraries, American Library Association. January 2008 – December 2014.

Chair, Organizing Committee for IATUL Conference 2010, June 21-24, 2010, Purdue University, West Lafayette, Indiana/Chicago, Illinois.

Conference Planning Committee for National Conference of the Association of College and Research Libraries, 2009, Seattle, Washington.

Research Committee, Association of College and Research Libraries, ACRL, division of ALA. 2002-2007, chair, 2005-2007.

Association of Research Libraries, Search and Screen Committee, Executive Director. March – January 2008.

Center for Research Libraries, Board of Directors. April 2006 – April 2012.

Academic Libraries of Indiana, Board of Directors, 2004 – present. Vice-president, 2005-2007.

President, 2007- 2009.

ALA Representative to the International Federation of Library Associations (IFLA), Marketing and Management (M&M) Section, initial term 2003-2007, re-appointed for second term, 2007-2011.

Invited to represent Research Libraries at the ACRL/3M Wonewok Retreat to assess Marketing of Academic Libraries, October 2002.

Hugh A. Atkinson Award Committee, LAMA Representative, ALA, 2001-2005.

Program Committee, Library Administrators and Management Association (LAMA), a division of ALA. 1996-2001.

ACRL, Standards and Accreditation Committee, a division of ALA. Liaison to RBMS Section of ACRL. 1997-2002.

Elected to the Executive Committee of LAMA, LOMS, a division of the American Library Association, 1998-2000. Nominated as Chair/Elect for 2003 – 2005.

Columbia University Press Advisory Committee. 1996 - 2000.

LITA/LAMA Conference Evaluation Committee, Pittsburgh, Pennsylvania, October 1996.

"New Learning Communities," Coalition for Networked Information, Indianapolis. November 19-21, 1995. Facilitator for invitational, national conference committed to developing collaborative learning and teaching techniques, involving librarians.

Planning Committee-Evaluation. LITA/LAMA 1996 Conference, Pittsburgh. This first conference, to be held jointly between two divisions of ALA, will focus on new technologies within libraries.

Indiana Cooperative Library Services Authority (InCoLSA), elected to Executive Committee, April 1991, served as President in 1993-94. InCoLSA is a statewide network of academic, public, school, and special libraries that supports library cooperation for cataloging, interlibrary loan, collection development and application of new technologies.

Governor's Conference on Libraries and Information Services. Served on Planning Committee, Academic Libraries Representative, appointed by the Governor to represent academic libraries in Indiana, Chair, Finance Committee, April 1989-July 1991.

Indiana Library Endowment Foundation Board, 1984-92. Charter Member, 1984, President, 1988-1992. 2004-2005.

University Service: (Summary)

Served on search and screen committees for senior positions including chancellor, dean, and directors; most recently I have been asked to serve on the search committee for the provost of Purdue University. At MIT service included the Library Council & appointment to the Administrative Council by President

Vest, 2001-2003 & Member of the Faculty Committee on the Library System. At Purdue appointed by the President to the Search Committee for the Provost, October 2007 to May 2008; member of the Capital Projects Committee, and IT Operational Oversight Committee as senior academic dean, 2008-2014.

Global Council, Global Policy Institute, 2012 – 2016.

Academic Program Excellence and Rankings (APER) project team, 2014.

Representative of the Academic Deans on the Re-engineering Business Operations, Purdue University, 2016 –

Academic Deans Council chaired by Provost – 2004 – 2017.

University Promotion and Tenure Committee – 2006 – 2017.

"Outstanding Team Award, Electronic Reserve Project," served as Chair, recognition awarded by the President of Villanova University to one team who made an outstanding contribution to the operations of the University, selected by a committee of administrators, faculty, and staff. Awarded September 9, 1999.

Nominated for the IUSB Lundquist Award, 1995 & 1996. The Lundquist award is given to faculty who have "exhibited excellence in teaching, scholarly or artistic achievement, and diversified relevant service..."