3D Photography

Course Notes for SIGGRAPH 99
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Organizers

Brian Curless University of Washington
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Speakers

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**Course Abstract**

3D photography is the process of using cameras and light to capture the shape and appearance of real objects. This process provides a simple way of acquiring graphical models of unparalleled detail and realism by scanning them in from the real world. This course provides an introduction to the emerging area of 3D photography, focusing on the current state of the art and the principles underlying several leading approaches.

After introducing fundamental concepts, the course surveys a variety of techniques and provides an in-depth analysis of a few successful approaches at the forefront of 3D photography, presented by leading researchers in the field. The focus is on passive and active optical methods, including stereo vision, photogrammetry, structured light, imaging radar, interferometry, and optical triangulation. The course concludes with a field study: capturing 3D photographs of Michelangelo's statues.

**Scope**

The course will cover a variety of methods for recovering shape from images. Introductory material will describe the fundamentals of cameras from lenses to CCD's and ways of calibrating them. A number of standard and emerging passive vision methods will be presented, including stereo, structure from motion, shape from focus/defocus, shape from shading, interactive photogrammetry, and voxel coloring. Active vision methods will include imaging radar, optical triangulation, moire, active stereo, active depth from defocus, and desktop shadow striping. An overview of reconstructing shape and appearance from range images will be followed by the first presentation of the Digital Michelangelo Project to the SIGGRAPH community.

**Prerequisites**

Participants will benefit from an understanding of basic techniques for representing and rendering surfaces and volumes. In particular, the course will assume familiarity with triangular meshes, voxels, and implicit functions (isosurfaces of volumes). Rendering concepts will include light interaction with surfaces (e.g., diffuse and specular reflection) and the mathematics of perspective projection. Understanding of basic image-processing will also be important. Experience with still photography will be helpful.

**Course Notes Description**

Course notes consist of copies of the speakers’ slides, images and VRML files of some of the demonstrations, references to related work, and copies of related papers. Links to online 3D Photography resources, additional slides, and other materials may be found on the course web page at: [http://www.cs.cmu.edu/~seitz/3DPhoto.html](http://www.cs.cmu.edu/~seitz/3DPhoto.html)
Speaker Biographies

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Brian Curless is an assistant professor of Computer Science and Engineering at the University of Washington. He received a B.S. in Electrical Engineering from the University of Texas at Austin in 1988 and M.S. and Ph.D. degrees in Electrical Engineering from Stanford University in 1991 and 1997, respectively. After the B.S. degree, Curless developed and implemented high speed, parallel, digital signal processing algorithms at SRI International. While earning the Ph.D., he consulted for Silicon Graphics and built the prototype for SGI's Annotator product, a system for hyper-media annotation of 3D databases. Curless's recent research has focused on acquiring and building complex geometric models using structured light scanning systems. In the vision literature, he has published results on fundamentally better methods for optical triangulation, and at SIGGRAPH, he published a new method for combining range images that led to the first "3D fax" of a geometrically complex object. Curless currently sits on the Technical Advisory Board for Paraform, Inc., a company that is commercializing Stanford-developed technology for building CAD-ready models from range data and polygonal meshes. In the winter of 1999, Curless will work with Marc Levoy on the Digital Michelangelo Project in Florence where they will capture the geometry and appearance of Michelangelo's statues. His teaching experience includes both graduate and undergraduate graphics courses, including courses related to 3D photography taught at both Stanford and the University of Washington. Curless received a university-wide Outstanding Teaching Award from Stanford University in 1992.

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Steven Seitz is an Assistant Professor of Robotics and Computer Science at Carnegie Mellon University, where he conducts research in image-based rendering, graphics, and computer vision. Before joining the Robotics Institute in August 1998, he spent a year visiting the Vision Technology Group at Microsoft Research, and a previous summer in the Advanced Technology
Group at Apple Computer. His current research focuses on the problem of acquiring and manipulating visual representations of real environments using semi- and fully-automated techniques. This effort has led to the development of "View Morphing" techniques for interpolating different images of a scene and voxel-based algorithms for computing photorealistic scene reconstructions. His work in these areas has appeared at SIGGRAPH and in international computer vision conferences and journals. He received his B.A. in computer science and mathematics at the University of California, Berkeley in 1991 and his Ph.D. in computer sciences at the University of Wisconsin, Madison in 1997.

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Jean-Yves Bouguet received his diplome d'ingenieur from the Ecole Superieure d'ingenieurs en Electrotechnique et Electronique (ESIEE) in 1994 and the MS degree in Electrical Engineering from the California Institute of Technology (Caltech) in 1994. He is now completing his Ph.D. in Electrical Engineering at Caltech in the computational vision group under the supervision of Pietro Perona. His research interests cover passive and active techniques for three-dimensional scene modeling. He has developed a simple and inexpensive method for scanning objects using shadows. This work was first presented at ICCV'98 and a patent is pending on that invention. He also collaborated with Jim Arvo, Peter Schrder and Pietro Perona in teaching a class on 3D photography from 1996 to 1998 at Caltech. Jean-Yves is currently working in collaboration with Larry Matthies at JPL on the development of passive visual techniques for three dimensional autonomous navigation targeted towards comet modeling and landing.

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Paul Debevec earned degrees in Math and Computer Engineering at the University of Michigan in 1992 and completed his Ph.D. at the University of California at Berkeley in 1996, where he is now a research scientist. Debevec has worked on a number of image-based modeling and rendering projects, beginning in 1991 in deriving a 3D model of a Chevette from photographs for an animation project. Debevec has collaborated on projects at Interval Research Corporation in Palo Alto that used a variety of image-based techniques for interactive applications; the "Immersion '94" project done with Michael Naimark and John Woodfill developed an image-based walkthrough of the Banff national forest and his art installation "Rouen Revisited" done
Marc Levoy showed at the SIGGRAPH 96 art show. His Ph.D. thesis under Jitendra Malik in collaboration with C.J. Taylor presented an interactive method of modeling architectural scenes from sparse sets of photographs and for rendering these scenes realistically. Debevec led the creation of an image-based model of the Berkeley campus for "The Campanile Movie" shown at the SIGGRAPH 97 Electronic Theater, and directed the animation "Rendering with Natural Light" at the SIGGRAPH 98 ET which demonstrated image-based lighting from high dynamic range photography. With Steve Gortler, Debevec organized the course "Image-Based Modeling and Rendering" at SIGGRAPH 98.

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Marc Levoy is an associate professor of Computer Science and Electrical Engineering at Stanford University. He received a B. Architecture in 1976 from Cornell University, an M.S. in 1978 from Cornell University, and a Ph.D. in Computer Science in 1989 from the University of North Carolina at Chapel Hill. Levoy's early research centered on computer-assisted cartoon animation, leading to development of a computer animation system for Hanna-Barbera Productions. His recent publications are in the areas of volume visualization, rendering algorithms, computer vision, geometric modeling, and user interfaces for imaging and visualization. His current research interests include digitizing the shape and appearance of physical objects using multiple sensing technologies, the creation, representation, and rendering of complex geometric models, image-based modeling and rendering, and applications of computer graphics in art history, preservation, restoration, and archeology. Levoy received the NSF Presidential Young Investigator Award in 1991 and the SIGGRAPH Computer Graphics Achievement Award in 1996 for his work in volume rendering.
Course Syllabus

A. 8:30 - 8:50, 20 min
Introduction (Curless)
1. Overview of area and the course
2. Acquiring 3D models from images
3. Applications to computer graphics

B. 8:50 - 9:35, 45 min
Acquiring Images (Curless and Seitz)
1. Image formation
   - The lens law
   - Aberrations
2. Media and Sensors
   - Film
   - CCD's
3. Cameras as radiometric tools
4. Camera calibration

C. 9:35 - 10:15, 40 min
Overview of passive vision techniques (Seitz)
1. Cues for 3D inference (parallax, shading, focus, texture)
2. Reconstruction techniques
   - Stereo
   - Structure from motion
   - Shape from shading
   - Photometric stereo
   - Other approaches
3. Strengths and Limitations
<> 10:15 - 10:30 Break

D. 11:20 - 12:00, 40 min
Voxel-based techniques for reconstruction (Seitz)
1. Reconstructing discretized scenes from images
   - Complexity and computability
2. Volume intersection
   - Shape from silhouettes
3. Voxel coloring
   - Plane-sweep visibility
   - Reconstructing small objects and panoramic scenes
4. Space carving
   - Toward 3D photorealistic walkthroughs
   - Ambiguities in scene reconstruction
   - Convergence properties
5. Related approaches
E. 10:30 - 11:20, 50 min

**Façade: modeling architectural scenes (Debevec)**

1. Capabilities and Limitations of passive stereo  
   - Immersion '94 project, Interval Research Corporation
2. Constrained structure recovery  
   - Architectural primitives
3. Photogrammetry  
   - Recovering camera parameters  
   - Making use of user-interaction
4. Refining structure with Model-based stereo
5. Connections to image-based rendering  
   - Impact of geometric accuracy on rendering quality  
   - Local vs. global 3D models  
   - Geometry's role in view interpolation, virtual environment construction, and reflectance recovery.

<> 12:00 - 1:30 Lunch

E. 1:30 - 2:10, 40 min

**Overview of active vision techniques (Curless)**

1. Imaging radar  
   - Time of flight  
   - Amplitude modulation
2. Optical triangulation  
   - Scanning with points and stripes  
   - Spacetime analysis
3. Interferometry  
   - Moire
4. Structured light applied to passive vision  
   - Stereo  
   - Depth from defocus
5. Reflectance capture  
   - From shape-directed lighting  
   - Using additional lighting

F. 2:10 - 2:50, 40 min

**Desktop 3D Photography (Bouguet)**

1. Traditional scanning is expensive, but...  
   - desklamp + pencil = structured light
2. Geometry of shadow scanning  
   - Indoor: on the desktop  
   - Outdoor: the sun as structured light
3. Image processing: Spacetime analysis for better accuracies
4. Calibration issues  
   - Camera calibration  
   - Light source calibration
5. Experimental results (indoor and outdoor)
6. Error analysis and Real-time implementation
G. 2:50 - 3:35, 45 min
Shape and appearance from images and range data (Curless)
1. Registration
2. Reconstruction from point clouds
3. Reconstruction from range images
   - Zippering
   - Volumetric merging
4. Modeling appearance

<> 3:35 - 3:50 Break

H. 3:50 - 4:40, 50 min
Application: The Digital Michelangelo Project (Levoy)
1. Goals
   - Capturing the shape and appearance of:
     - Michelangelo's sculptures
     - Renaissance architecture
2. Motivation
   - Scholarly inquiry
   - Preservation through digital archiving
   - Virtual museums
   - High fidelity reproductions
3. Design requirements
   - Geometry: from chisel marks to building facades
   - Appearance: reflectance of wood, stone, marble
4. Custom scanning hardware
5. Capturing appearance with high resolution photographs

I. 4:40 - 5:00, 20 min
Discussion: 3D cameras and the future of photography (Everyone)
1. What are the killer apps for 3D photography?
2. When are passive vs. active techniques appropriate?
3. How will consumer-grade technology influence 3D photography?
4. Will 3D photography itself become a consumer product?

<> Adjourn
Contents

1. Introduction (Steve Seitz and Brian Curless)
   Abstract

2. Acquiring images (Brian Curless)
   Slides

3. Overview of passive vision techniques (Steve Seitz)
   Extended Abstract
   Papers (printed version only)
   A Versatile Camera Calibration Technique for High Accuracy 3D Machine Vision Metrology Using Off-the-Shelf TV Cameras and Lenses
       R. J. Tsai
   Shape and Motion from Image Streams under Orthography: A Factorization Method
       C. Tomasi and T. Kanade
   A Multiple-Baseline Stereo
       M. Okutomi and T. Kanade
   Photometric Method for Determining Surface Orientation from Multiple Images
       R. J. Woodham

4. Voxel-based techniques for reconstruction (Steve Seitz)
   Slides
   Papers
   Photorealistic Scene Reconstruction by Voxel Coloring
       S. M. Seitz and C. R. Dyer
   A Theory of Shape by Space Carving
       K. N. Kutulakos and S. M. Seitz

5. Façade: modeling architectural scenes (Paul Debevec)
   Introduction
   Paper
   Modeling and Rendering Architecture from Photographs: A Hybrid Geometry- and Image-Based Approach
       P. E. Debevec, C. J. Taylor, and J. Malik
   Paper
   Recovering Arches in Facade using Ray-Plane Intersections in 3D
       G. D. Borshukov and P. Debevec
   Slides

6. Overview of active vision techniques (Brian Curless)
   Slides
   Paper
   Better Optical Triangulation through Spacetime Analysis
       B. Curless and M. Levoy

7. Desktop 3D photography (Jean-Yves Bouguet)
   Slides
Paper
3D Photography on Your Desk
J. Y. Bouguet and P. Perona

VRML models (on CDROM only)

8. Shape and appearance from images and range data (Brian Curless)

Slides
Papers
Zippered Polygon Meshes from Range Images
G. Turk and M. Levoy
Surface Reconstruction from Unorganized Points
H. Hoppe, T. DeRose, and T. Duchamp
Mesh Optimization
H. Hoppe, T. DeRose, T. Duchamp, J. McDonald, and W. Stuetzle
A Volumetric Method for Building Complex Models from Range Images
B. Curless and M. Levoy

9. Application: The Digital Michelangelo Project (Marc Levoy)

Extended Abstract

Bibliography of papers included in this volume