Introducción a la Fotografia 3D
UBA/FCEN Marzo 27 – Abril 12 2013
Clase 1 : Miercoles Marzo 27

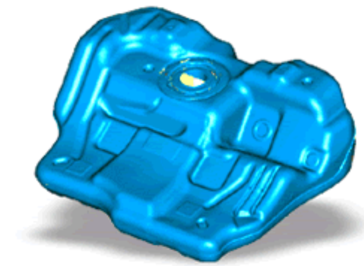
Gabriel Taubin

Brown University

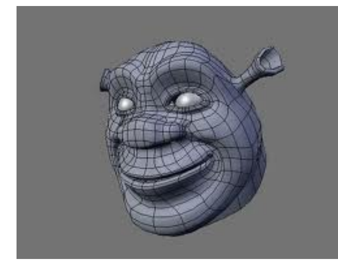
BROWN

3D Shapes

- Industry
  - Reverse engineering
  - Fast metrology
  - Physical simulations

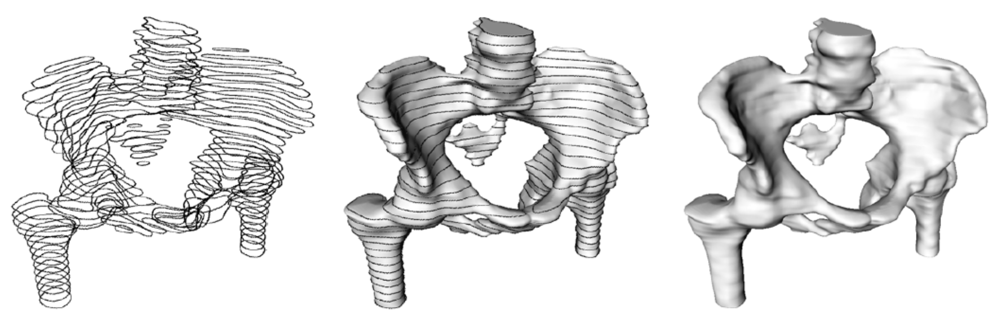


- Entertainment
  - Animating digital clays for movies or games



- Archeology and Art
  - Digitization of cultural heritage and artistic works

- Medical Imaging
  - Visualization
  - Segmentation



Que es la Fotografia 3D ?

Metodos y sistemas para capturar la geometria y la apariencia de objetos tridimensionales, basados en el uso de camaras y fuentes de luz

3D Photography

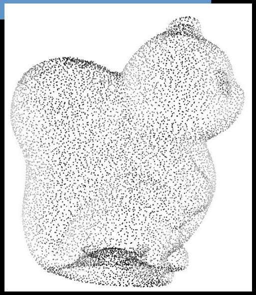
Laser Scanning

Structured Lighting

Multi-View Stereo

Range Images

Oriented Points

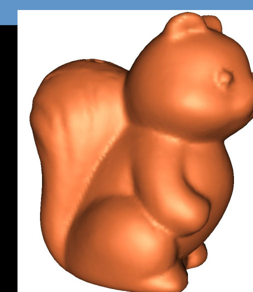


Positions, Normals, Colors

Surface Reconstruction

Oriented Points → Reconstruction Method → Surface Representation

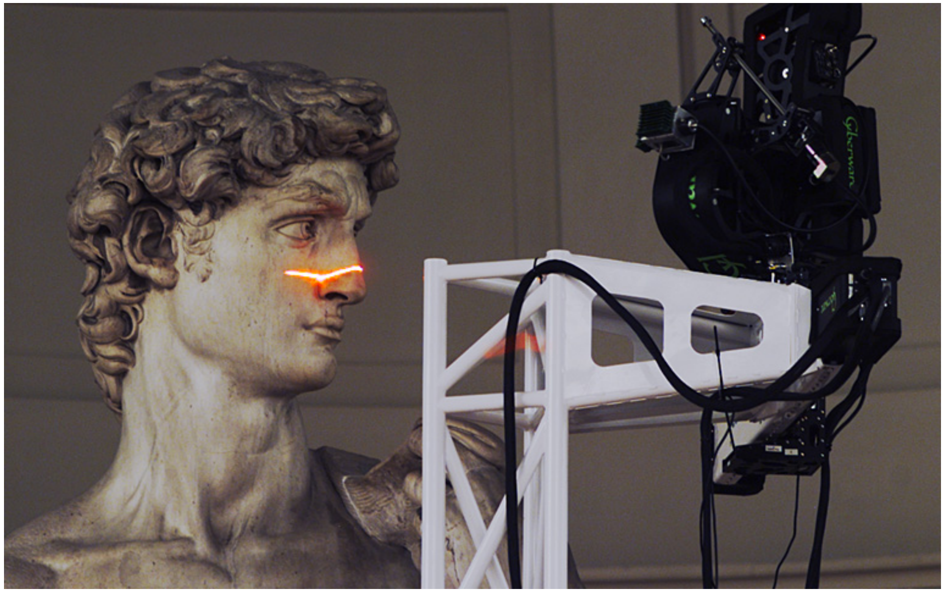
Positions
Normals
Colors



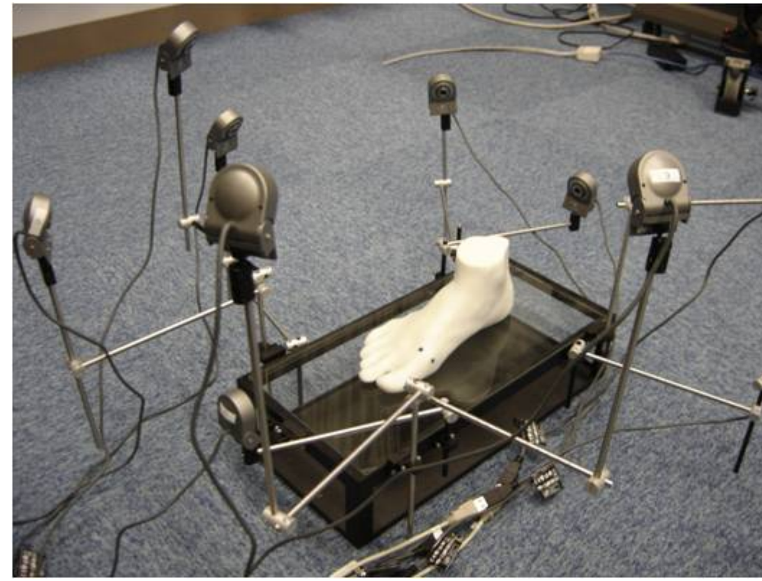
Polygon Mesh

Followed by Geometry Processing (Next Course)

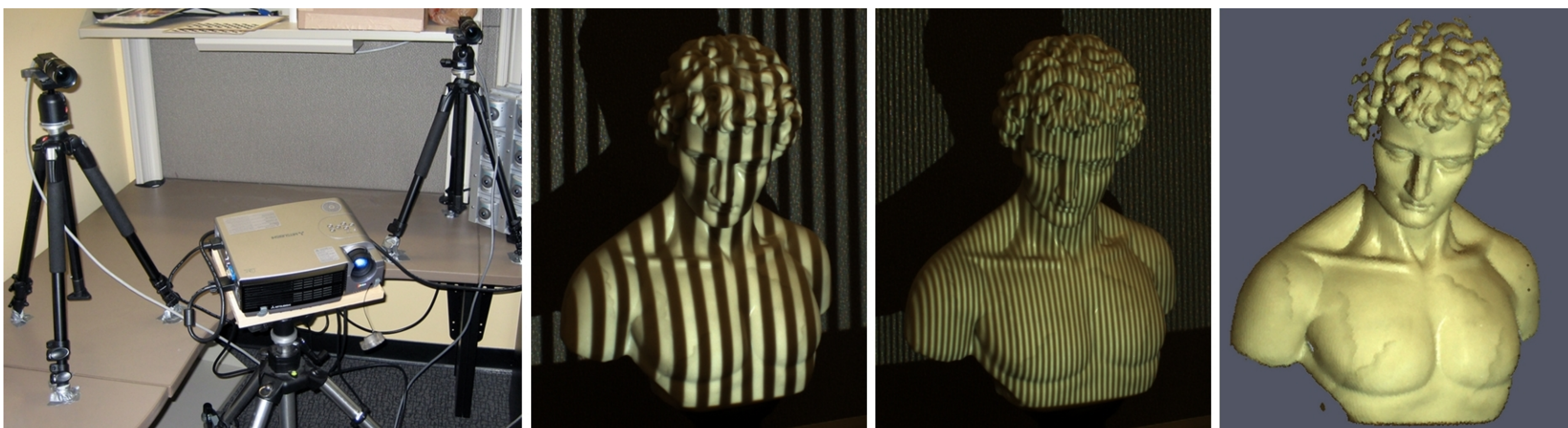
3D Shape and Appearance Capture



Laser range scanning devices



Multi-camera systems



Structured lighting systems

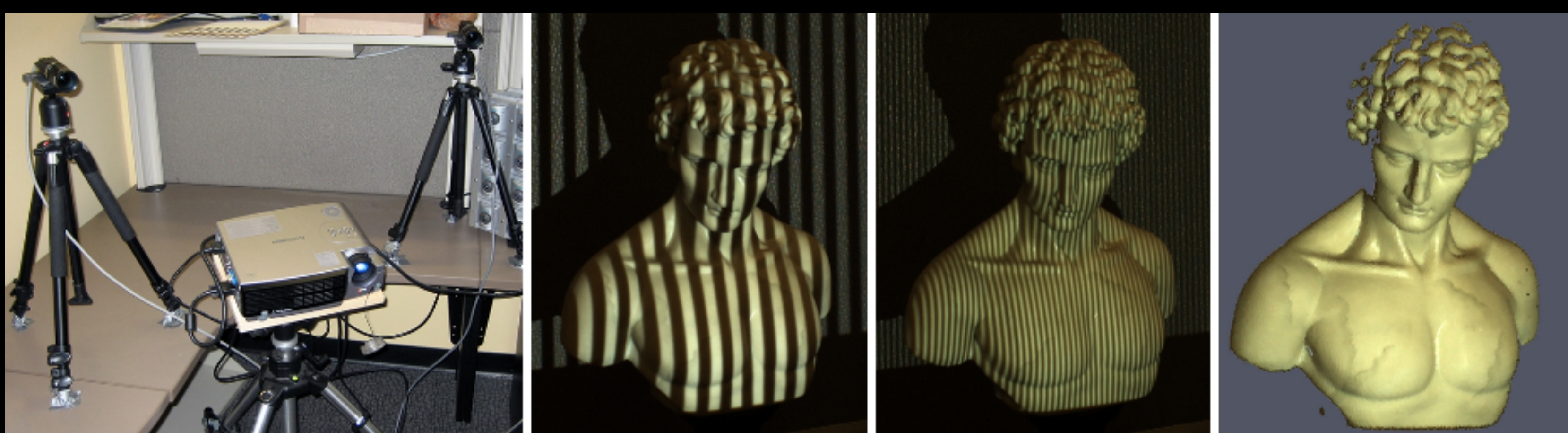
Objetivos

Adquirir conocimientos básicos sobre:

- Métodos y sistemas para la captura, reconstrucción y procesamiento de objetos en 3D
- Fundamentos Matemáticos, en particular de métodos basados en cámaras y proyectores
- Requerimientos para implementar y calibrar sistemas de bajo costo
- Diseñar e implementar, como trabajos practicos, dos metodos para la captura de objetos en 3D
- Identificar ideas para projectos que resulten en publicaciones

Triangulation and Scanning with Swept-Planes

Structured Lighting using Projector-Camera Systems



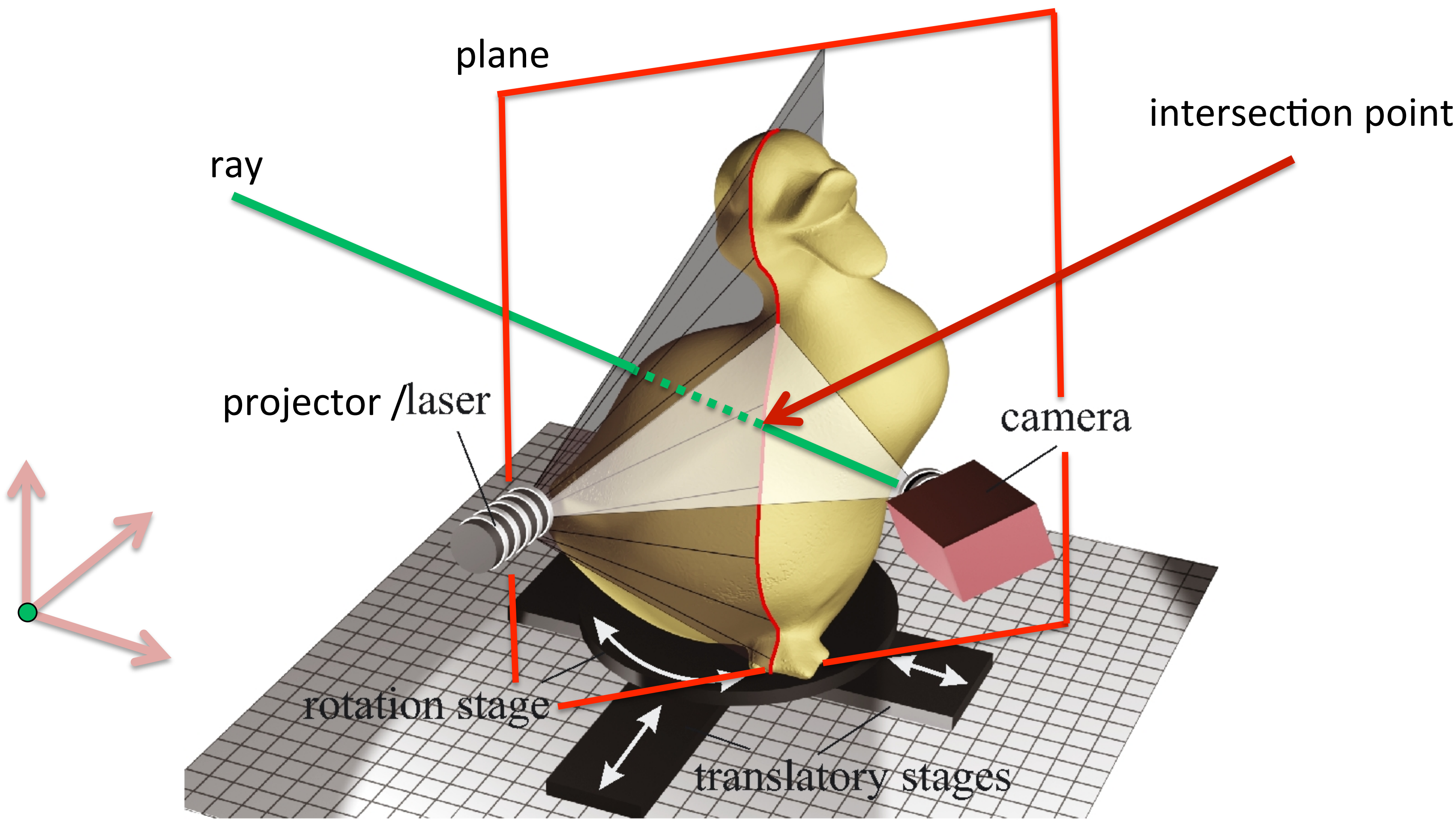
Que hace falta saber?

- Algebra Lineal
- Geometria Analítica en 3D
- Geometria Afin y Projectiva
- Estructuras de Datos / Complejidad
- Metodos Numericos
- Procesamiento de Imagenes
- Programacion en Matlab, C++ y/o Java
- Interes en construir y armar (DIY)

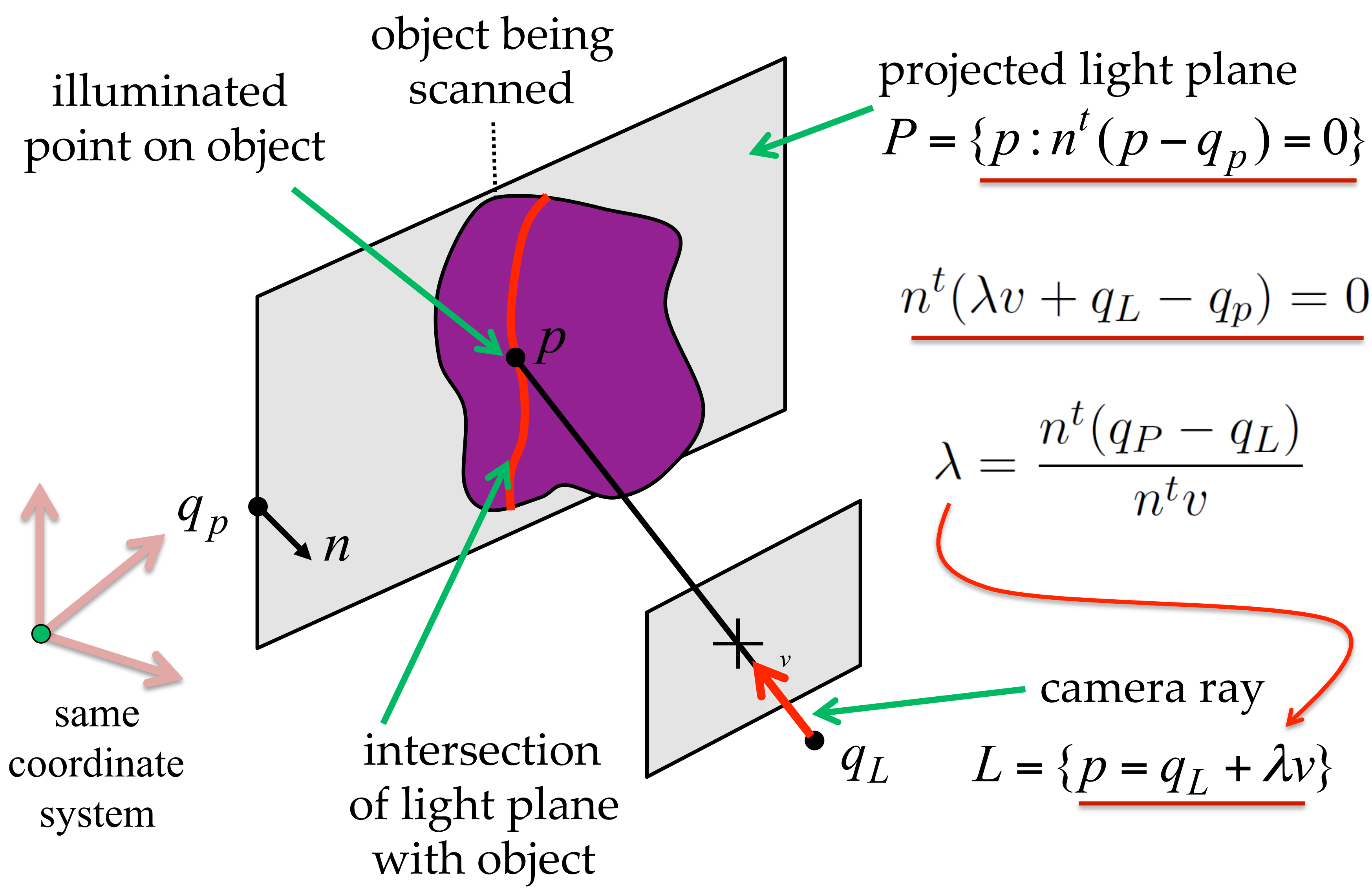
Plan del Curso

1. Introducción
2. Las Matemáticas de la Triangulación en 3D
3. 3D Scanning con Barrido de Planos
4. Calibración de Cameras y Fuentes de Luz
5. Superficies, Nubes de Puntos, Mallas Poligonales
6. Iluminación Estructurada
7. Calibración de Proyectores
8. Combinación de Múltiples Puntos de Vista
9. Reconstrucción de Superficies
10. Procesamiento de Geometria

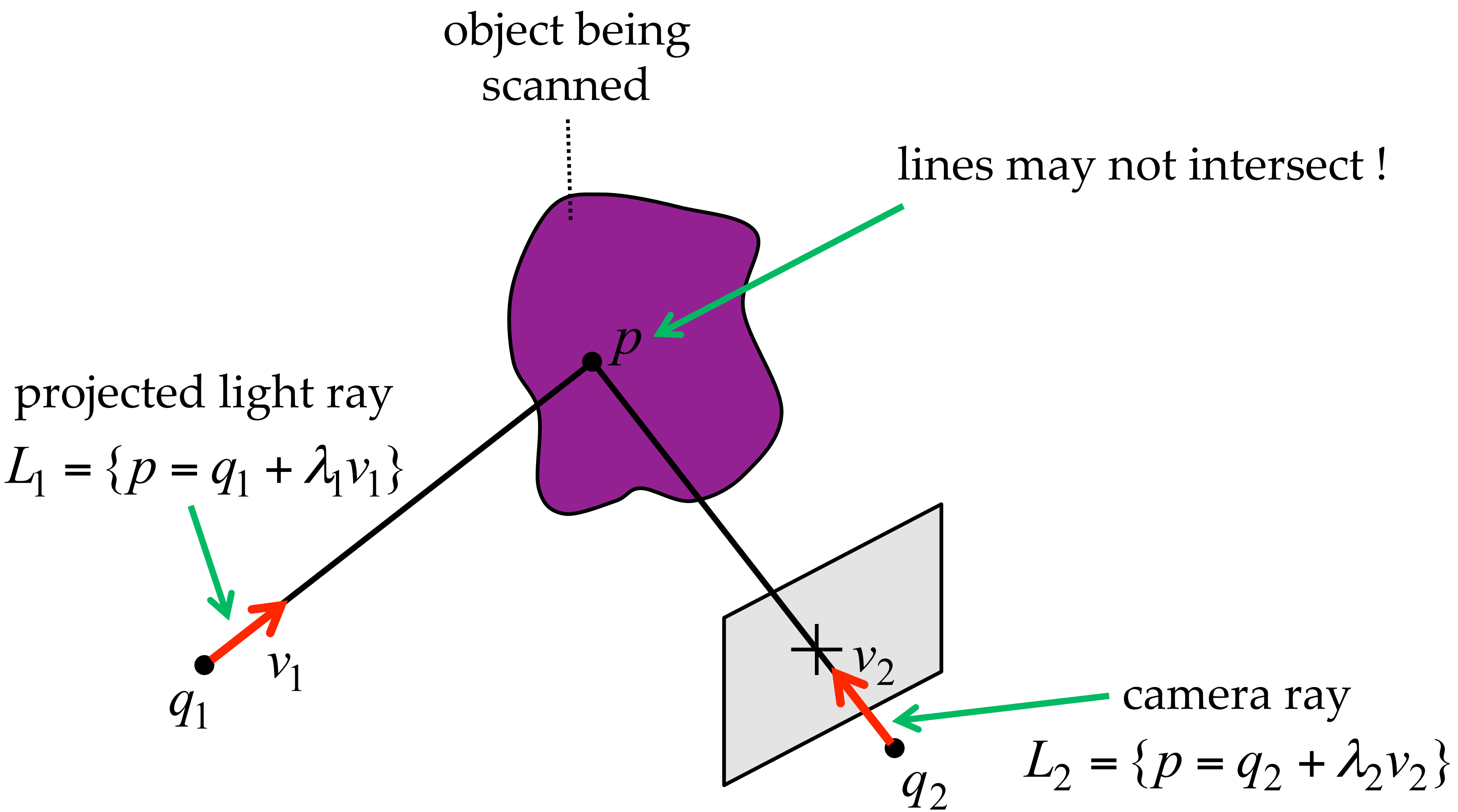
3D Triangulation: Ray-Plane Intersection



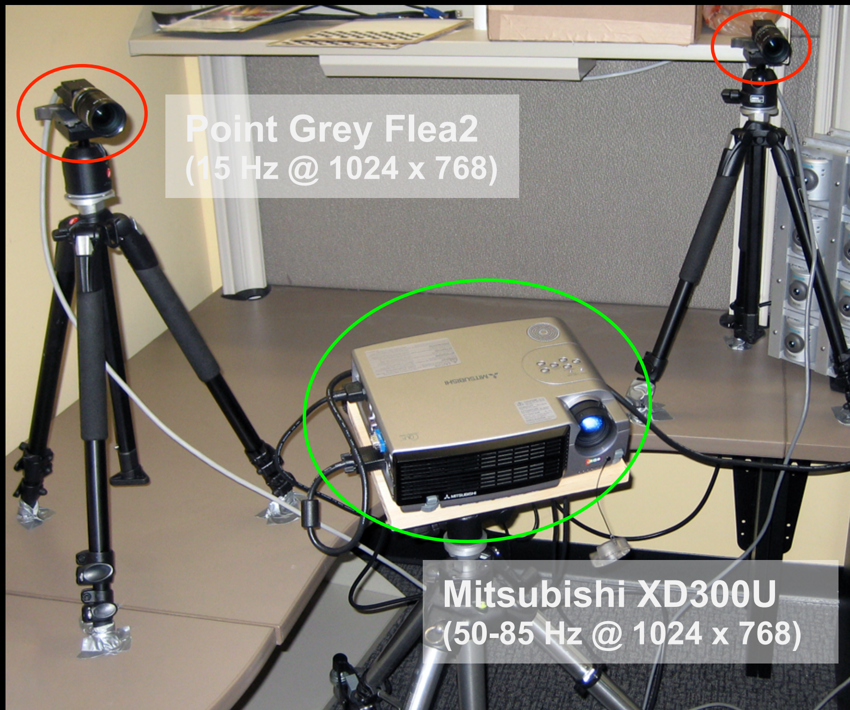
Triangulation by Line-Plane Intersection



Triangulation by Line-Line Intersection



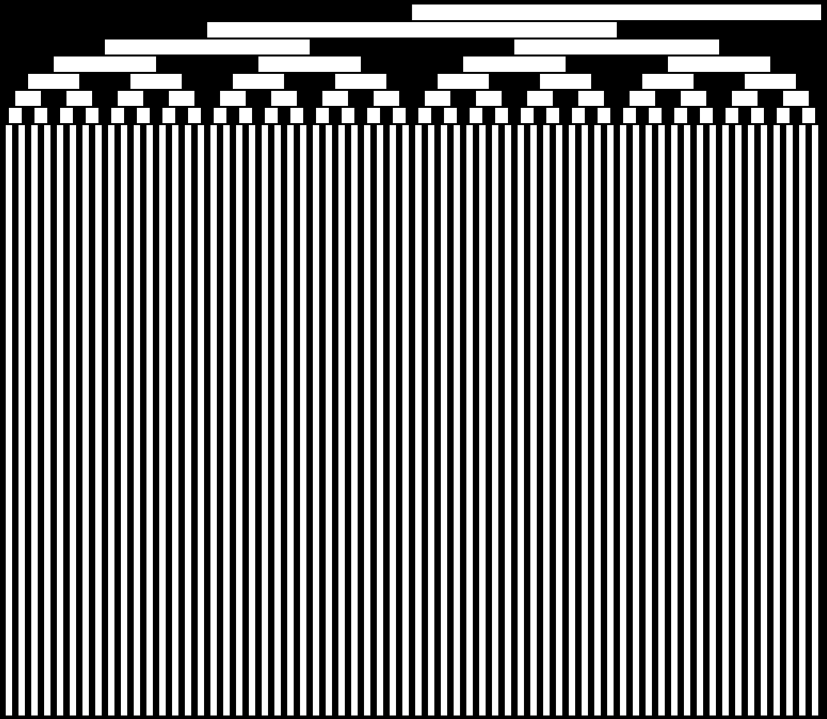
Gray Code Structured Lighting



3D Reconstruction using Structured Light [Inokuchi 1984]

- Recover 3D depth for each pixel using ray-plane intersection
- Determine correspondence between camera pixels and projector planes by projecting a temporally-multiplexed binary image sequence
- Each image is a bit-plane of the Gray code for each projector row/column

Gray Code Structured Lighting



3D Reconstruction using Structured Light [Inokuchi 1984]

- Recover 3D depth for each pixel using ray-plane intersection
- Determine correspondence between camera pixels and projector planes by projecting a temporally-multiplexed binary image sequence
- Each image is a bit-plane of the Gray code for each projector row/column
- Encoding algorithm: integer row/column index → binary code → Gray code

Projector-Camera Calibration

Brown University School of Engineering

Projector-Camera Calibration

http://mesh.brown.edu/calibration

Moreno Home

Taubin Home

Resources

- Paper
- Source code
- Software binary for Microsoft Windows
- MATLAB Projector Calibration [soon]
- Sample data
- Software manual
- Presentation slides

3DIMPVT 2012:

3D Imaging, Modeling, Processing, Visualization and Transmission

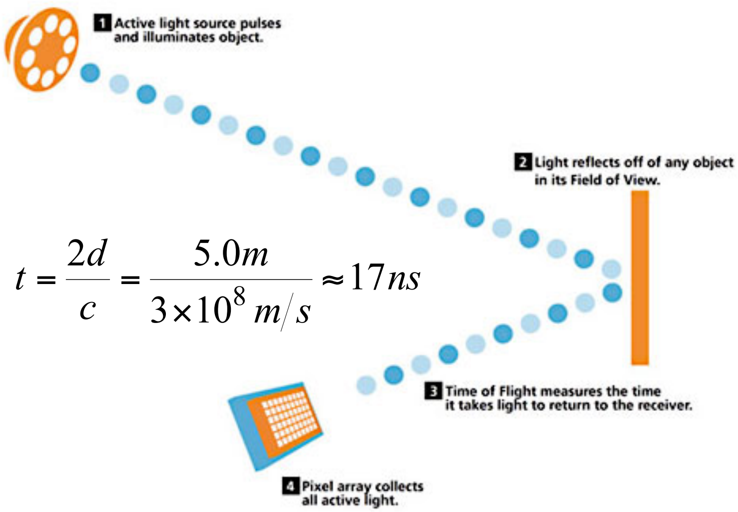
Simple, Accurate, and Robust Projector-Camera Calibration

Daniel Moreno and Gabriel Taubin

Abstract

Structured-light systems are simple and effective tools to acquire 3D models. Built with off-the-shelf components, a data projector and a camera, they are easy to deploy and compare in precision with expensive laser scanners. But such a high precision is only possible if camera and projector are both accurately calibrated. Robust calibration methods are well established for cameras but, while cameras and projectors can both be described with the same mathematical model, it is not clear how to adapt these methods to projectors. In consequence, many of the proposed projector calibration techniques make use of a simplified model, neglecting lens distortion, resulting in loss of precision. In this paper, we present a novel method to estimate the image coordinates of 3D points in the projector image plane. The method relies on an uncalibrated camera and makes use of local homographies to reach sub-pixel precision. As a result, any camera model can be used to describe the projector, including the extended pinhole model with radial and tangential distortion coefficients, or even those with more complex lens distortion models.

Time of Flight 3D Scanning

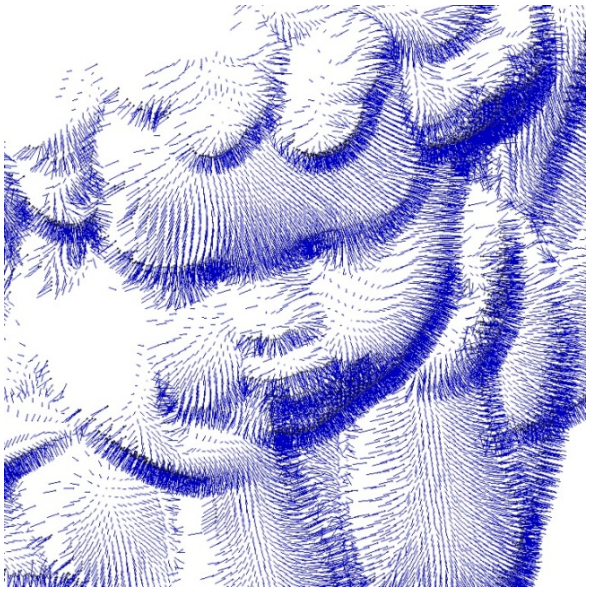


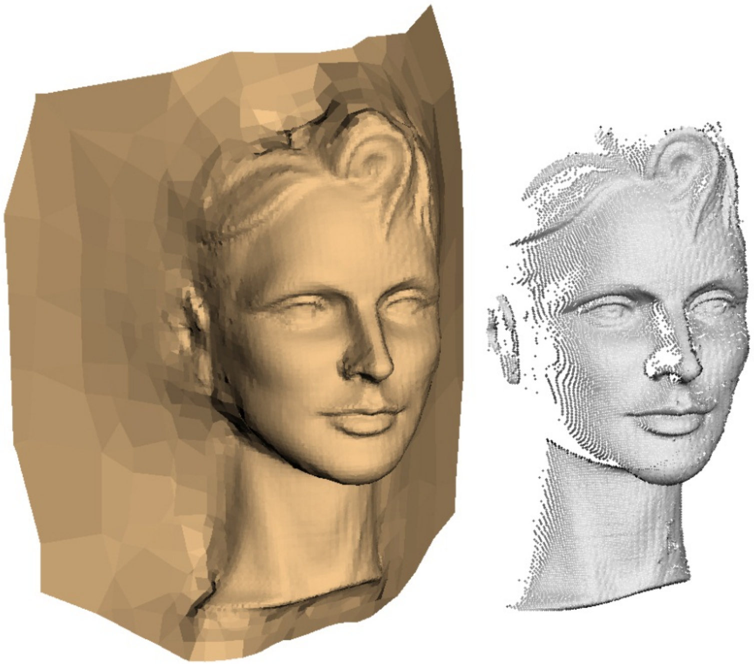
$$t = \frac{2d}{c} = \frac{5.0m}{3\times10^{8}\, m/s} \approx 17ns$$

Single Shot Structured Lighting: MS Kinect

SSD: Smooth Signed Distance Surface Reconstruction

F. Calakli, G. Taubin, Computer Graphics Forum, 2011.

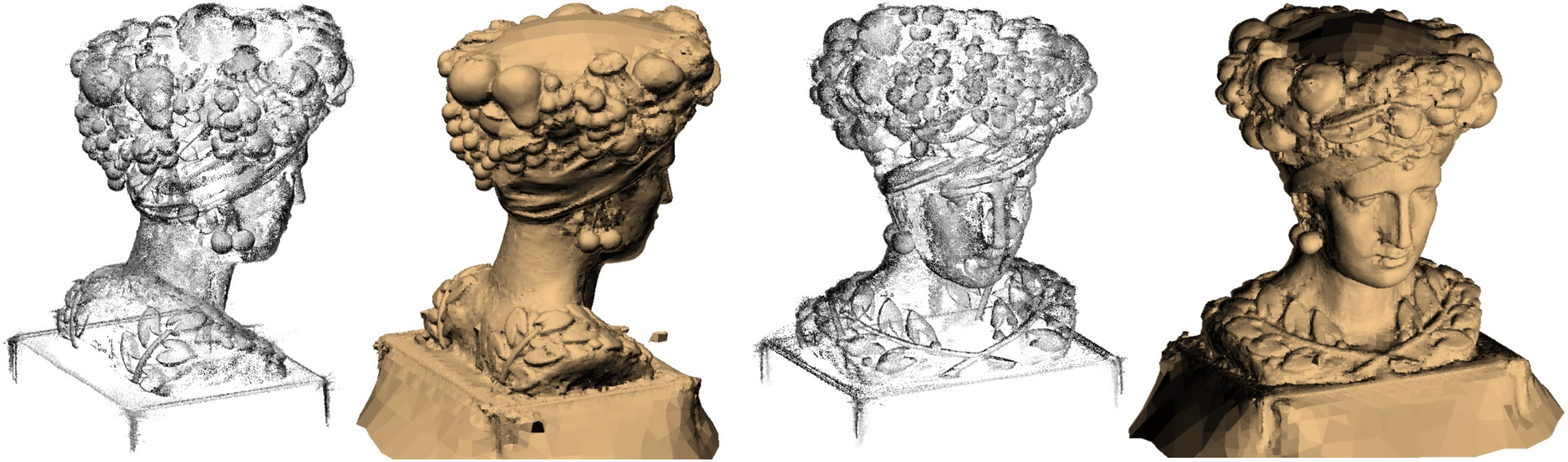


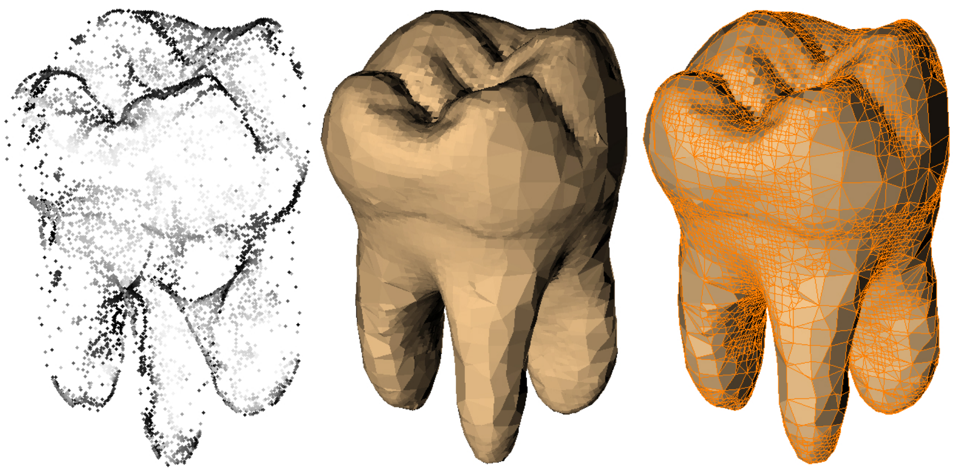


- A new mathematical formulation
- And a particular algorithm
- To reconstruct a watertight surface

From a static oriented point cloud

Particularly Good at Extrapolating Missing Data





Computer Graphics Forum, Vol. 30, No. 7, 2011 [Pacific Graphics 2011]

Smooth Signed Distance Surface Reconstruction

Fatih Calakli and Gabriel Taubin

- Home
- Paper
- Software

Abstract

We introduce a new variational formulation for the problem of reconstructing a watertight surface defined by an implicit equation, from a finite set of oriented points; a problem which has attracted a lot of attention for more than two decades. As in the Poisson Surface Reconstruction approach, discretizations of the continuous formulation reduce to the solution of sparse linear systems of equations. But rather than forcing the implicit function to approximate the indicator function of the volume bounded by the implicit surface, in our formulation the implicit function is forced to be a smooth approximation of the signed distance function to the surface. Since an indicator function is discontinuous, its gradient does not exist exactly where it needs to be compared with the normal vector data. The smooth signed distance has approximate unit slope in the neighborhood of the data points. As a result, the normal vector data can be incorporated directly into the energy function without implicit function smoothing. In addition, rather than first extending the oriented points to a vector field within the bounding volume, and then approximating the vector field by a gradient field in the least squares sense, here the vector field is constrained to be the gradient of the implicit function, and a single variational problem is solved directly in one step. The formulation allows for a number of different efficient discretizations, reduces to a finite least squares problem for all linearly parameterized families of functions, and does not require boundary conditions. The resulting algorithms are significantly simpler and easier to implement, and produce results of quality comparable with state-of-the-art algorithms. An efficient implementation based on a primal-graph octree-based hybrid finite element-finite difference discretization, and the Dual Marching Cubes isosurface extraction algorithm, is shown to produce high quality crack-free adaptive manifold polygon meshes.

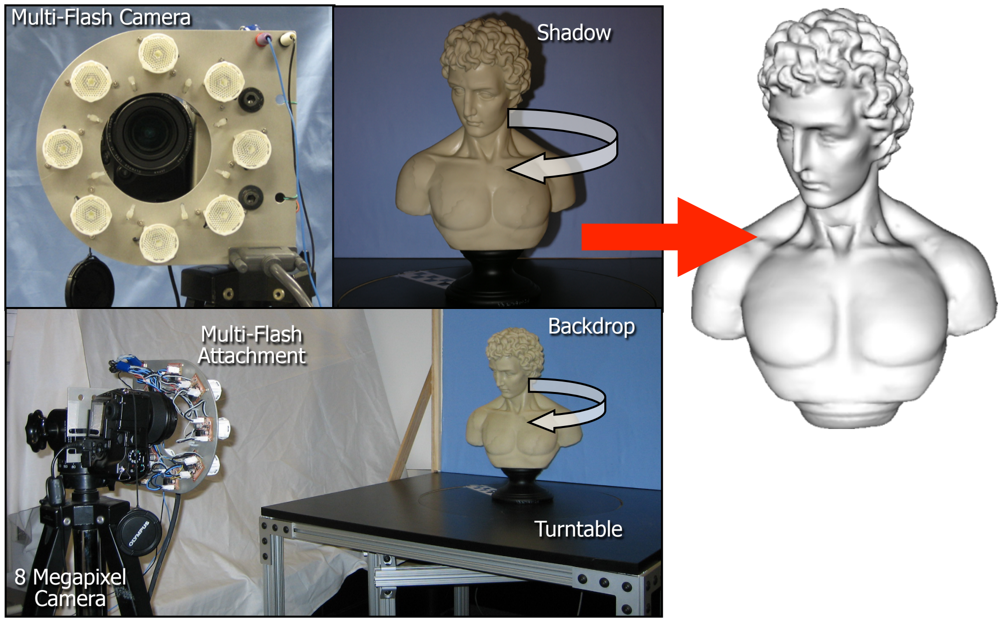
Acknowledgment of Support

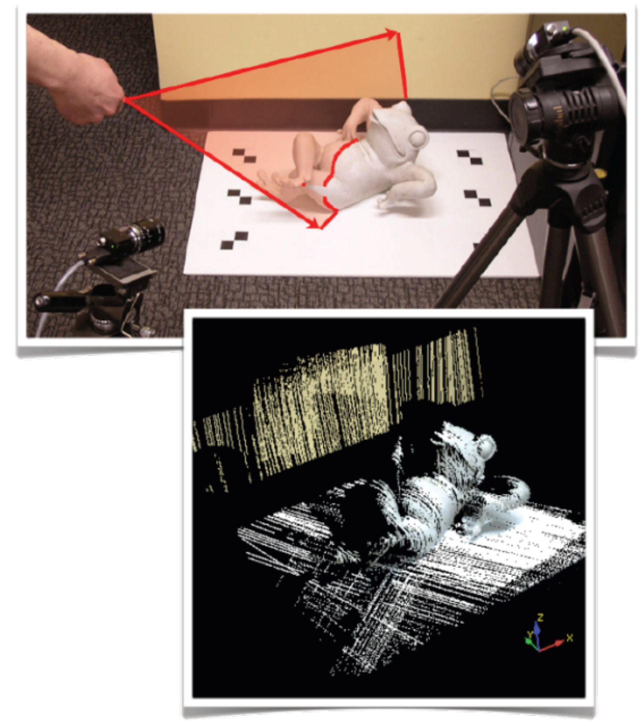
The material presented in this web site describe work supported by the National Science Foundation under Grants No. CCF-0729126, IIS-0808718, and CCF-0915661.

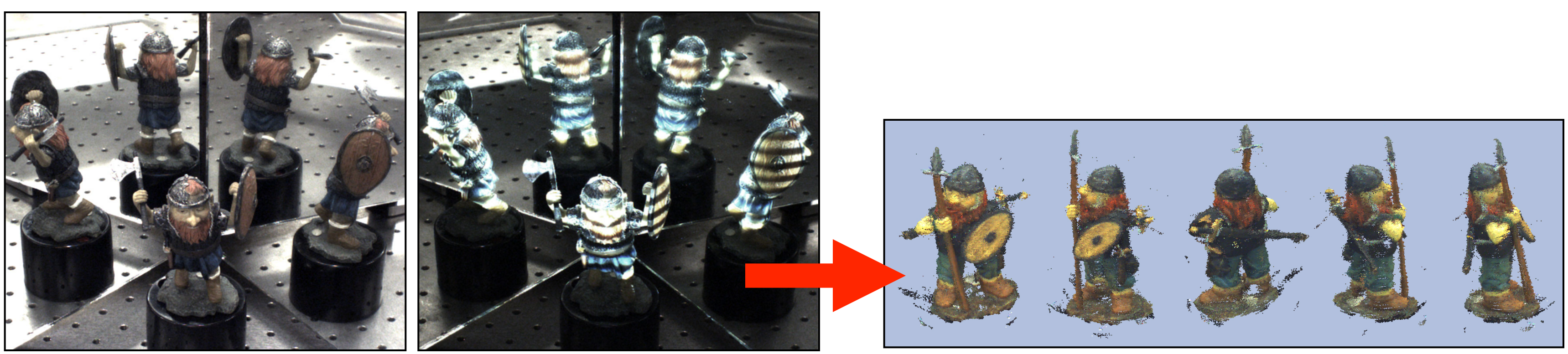
http://mesh.brown.edu/ssd

Final Projects which Resulted in Publications

Some Methods to Capture 3D Point Clouds

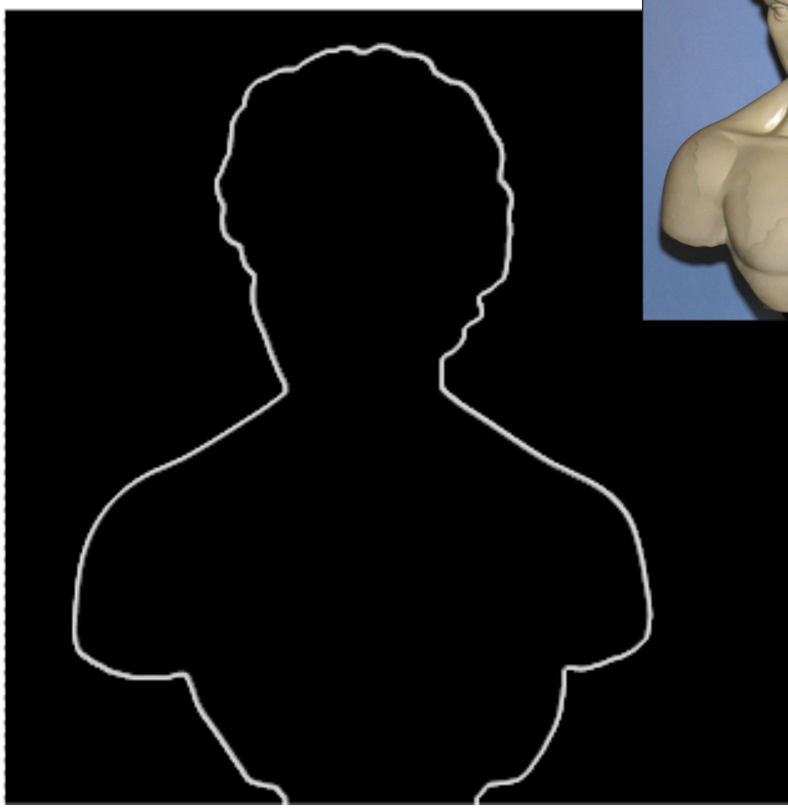


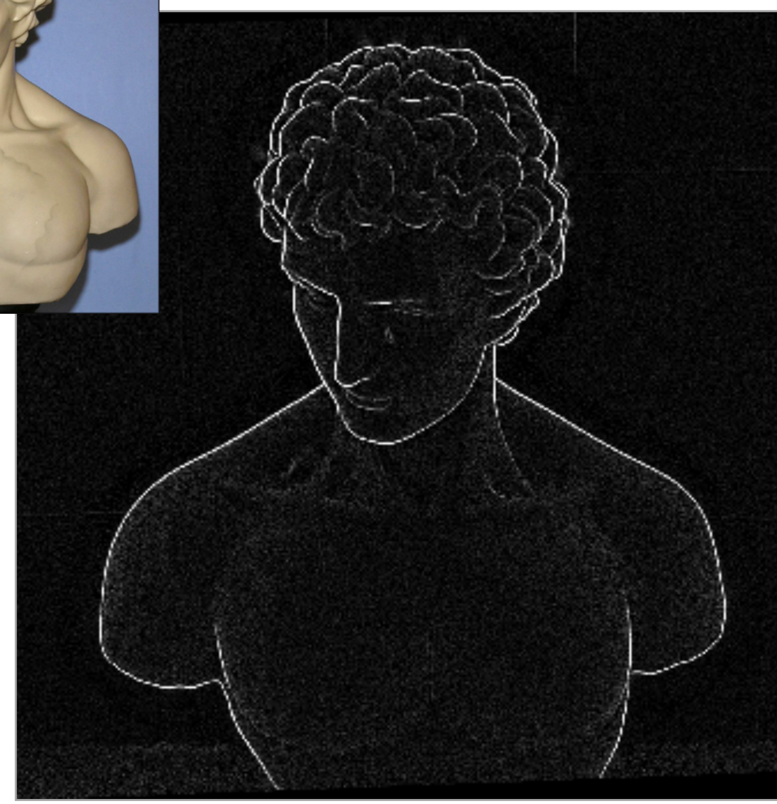




Beyond Silhouettes: Surface Reconstruction using Multi-Flash Photography

D. Crispell, D. Lanman, P. Sibley, Y. Zhao and G. Taubin [3DPVT 2006]

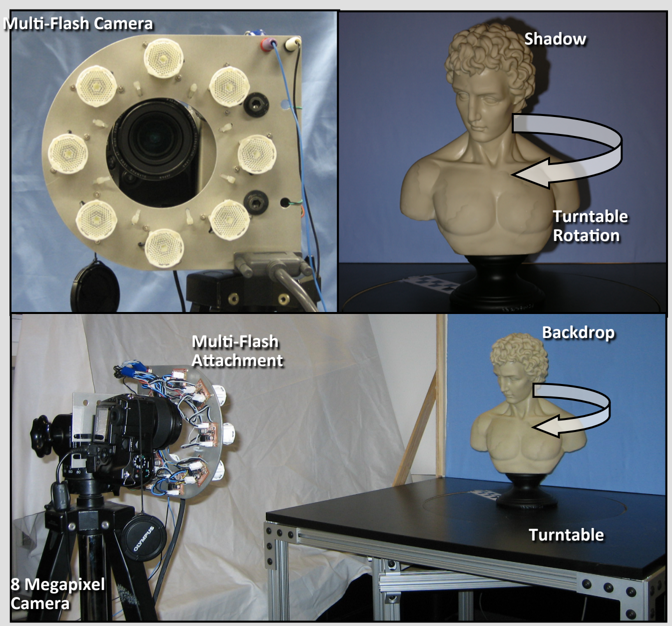




Multi-Flash 3D Photography: Capturing the Shape and Appearance of 3D Objects

A new approach for reconstructing 3D objects using shadows cast by depth discontinuities, as detected by a multi-flash camera. Unlike existing stereo vision algorithms, this method works *even with plain surfaces*, including unpainted ceramics and architecture.

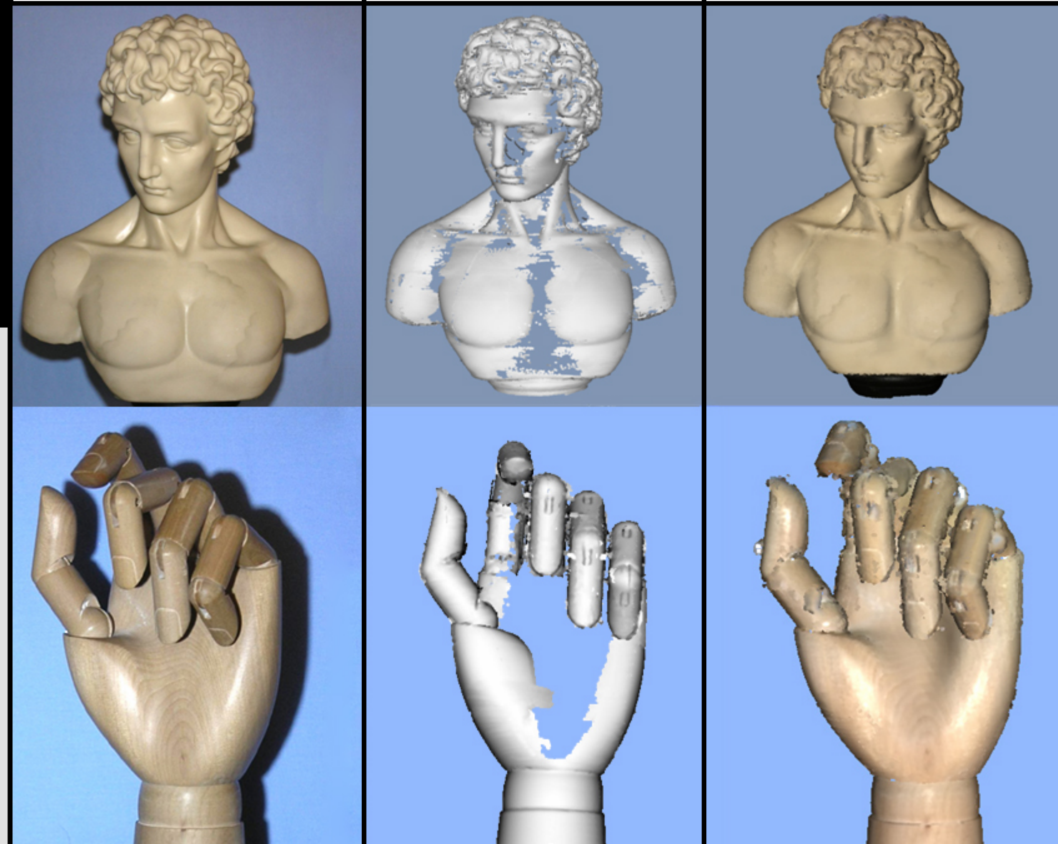
Data Capture: A turntable and a digital camera are used to acquire data from 670 viewpoints. For each viewpoint, we capture a set of images using illumination from four different flashes. Future embodiments will include a small, inexpensive **handheld multi-flash camera**.



Multi-Flash Turntable Sequence: Input Image

Estimated Shape: 3D Point Cloud

Recovered Appearance: Phong BRDF Model



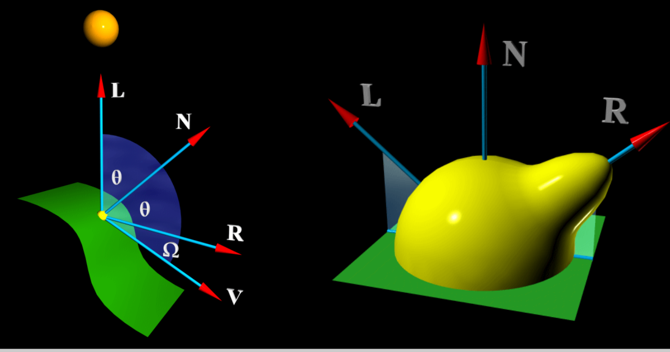
Recovering a Smooth Surface

The reconstructed point cloud can possess errors, including gaps and noise. To minimize these effects, we find an implicit surface which interpolates the 3D points. This method can be applied to any 3D point cloud, including those generated by laser scanners.

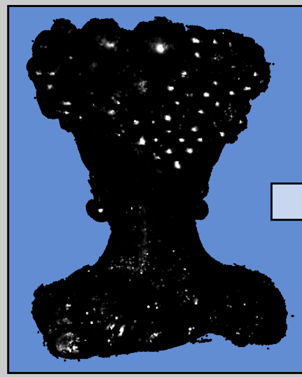
Multi-Flash 3D Photography: Photometric Reconstruction

Using the implicit surface, we can determine which points are visible from each viewpoint. To model the material properties of the surface, we fit a per-point Phong BRDF model to the set of visible reflectance observations (using a total of 67 viewpoints).

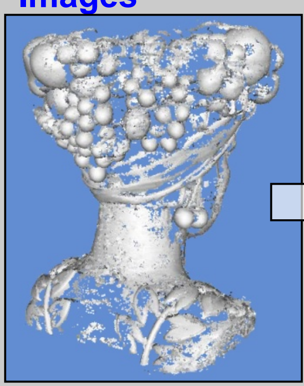
Ambient **Diffuse** **Specular**



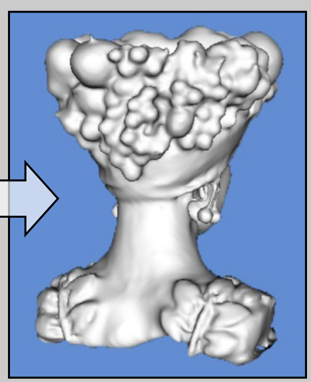
Multi-Flash Turntable Sequence Images



Phong (Specular)



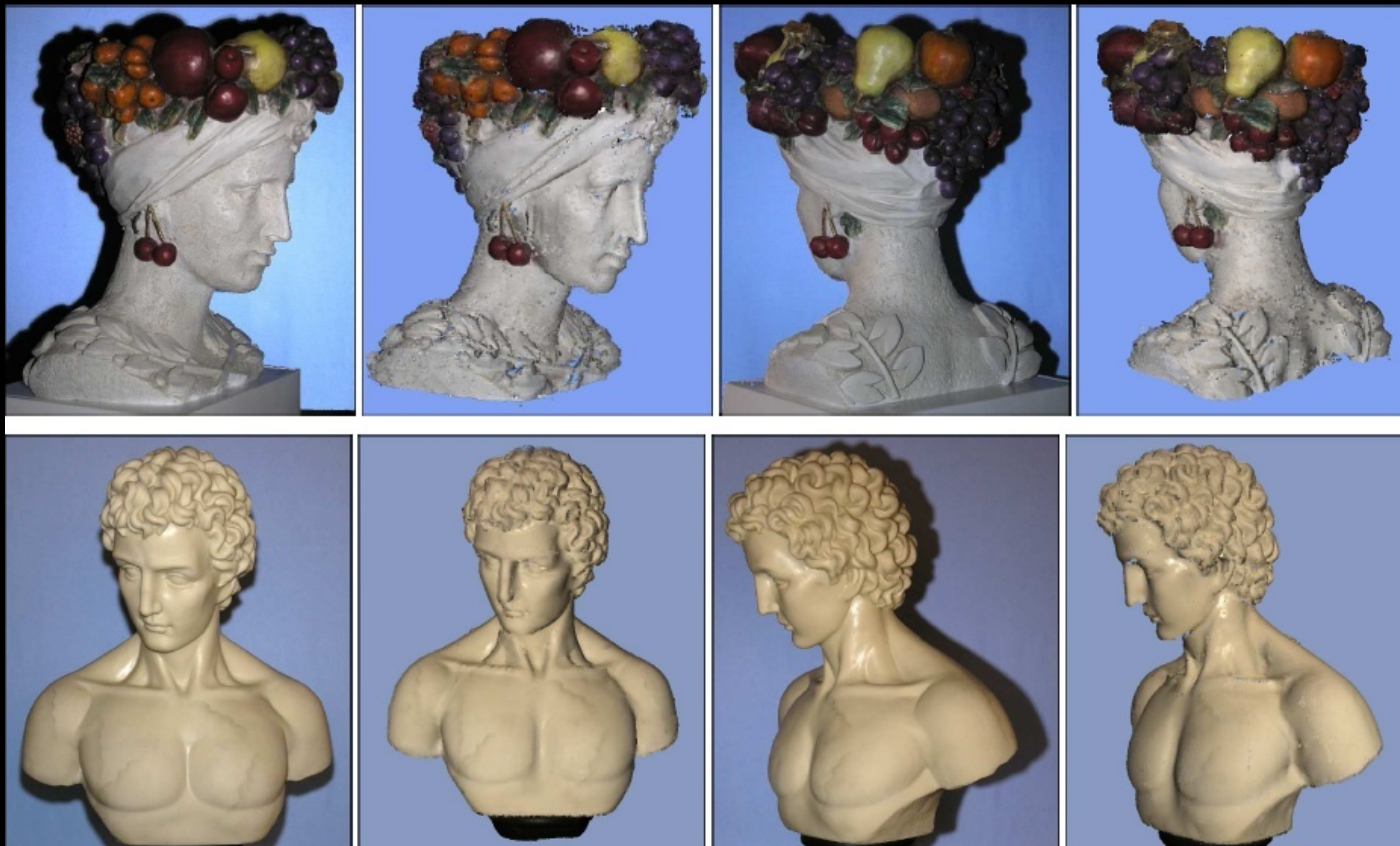
3D Point Cloud

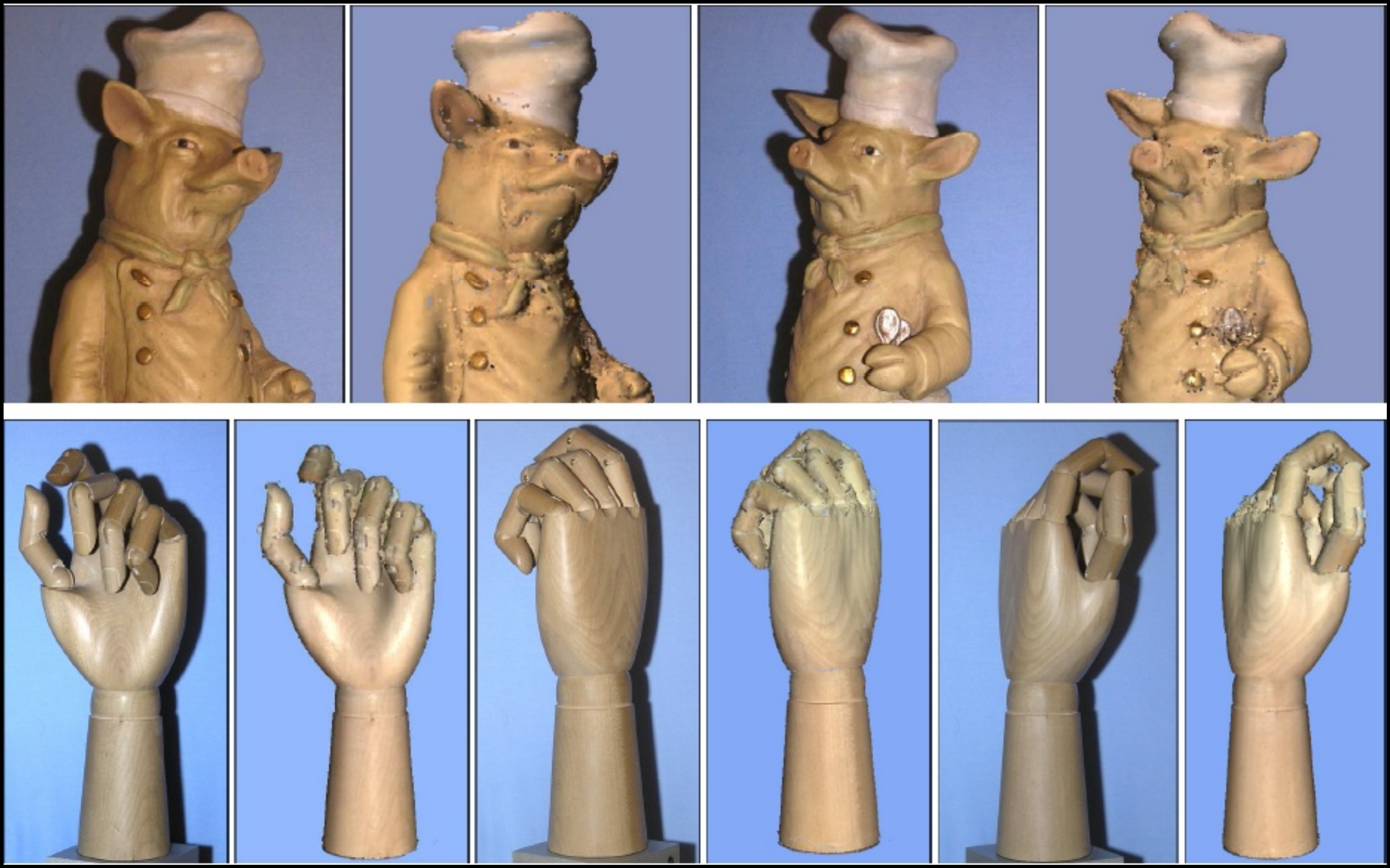


Implicit Surface

Phong (Diffuse)

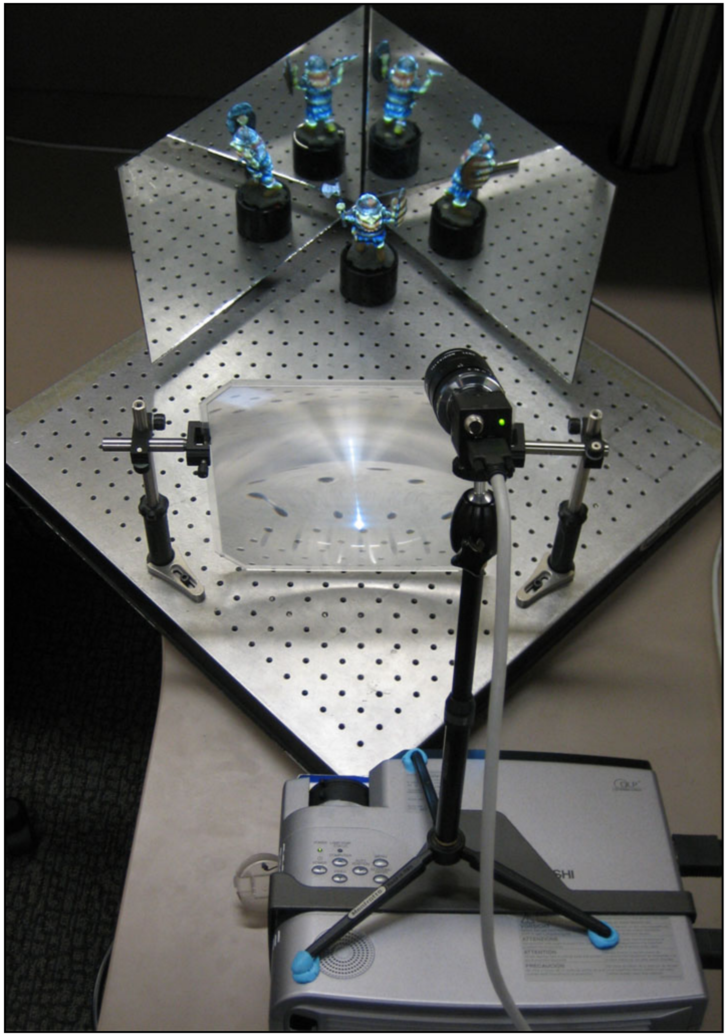
Estimated Phong Appearance Model





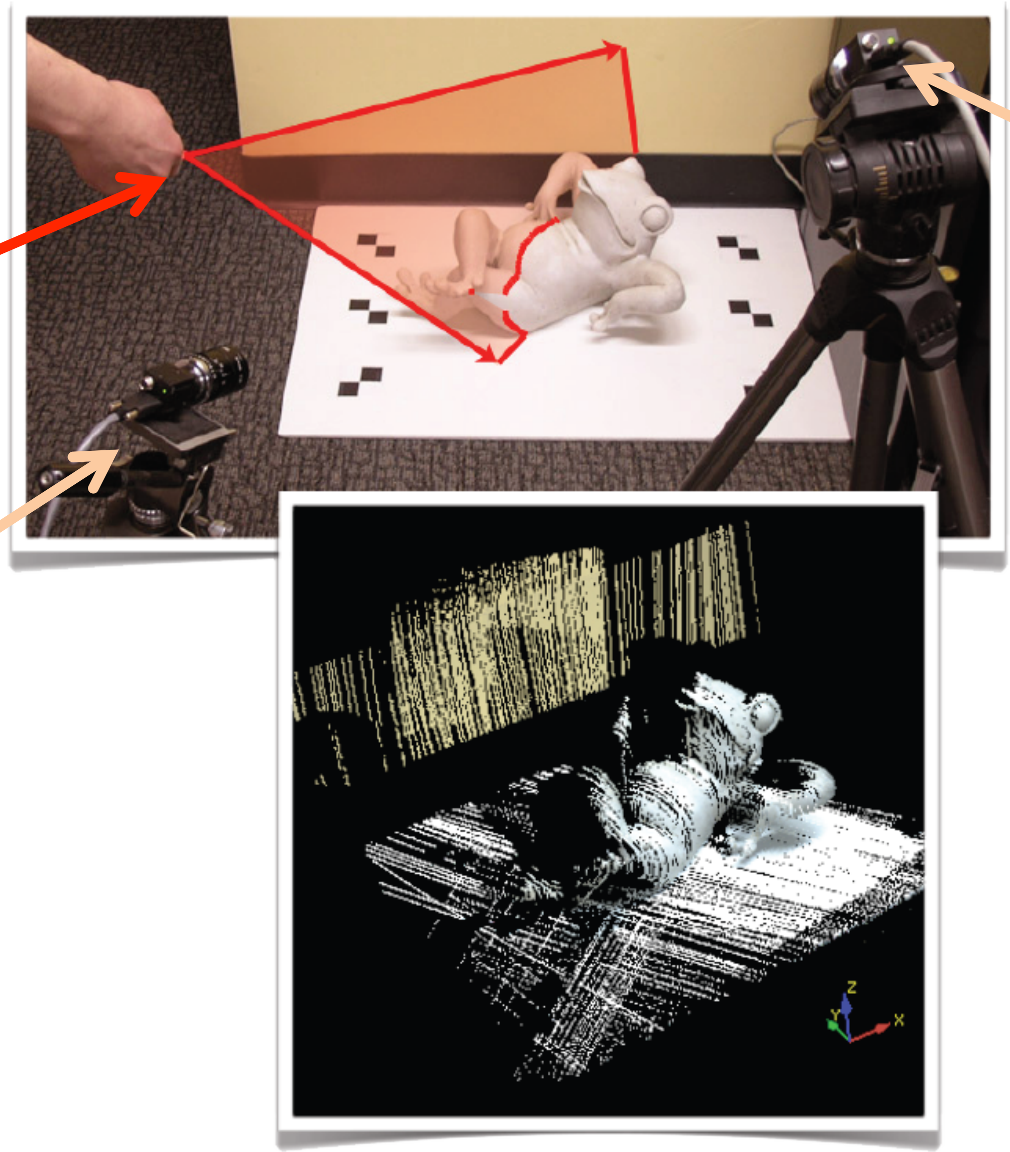
Surround Structured Lighting:
3-D Scanning with Orthographic Illumination

D. Lanman, D. Crispell, G. Taubin [CVIU 2009]

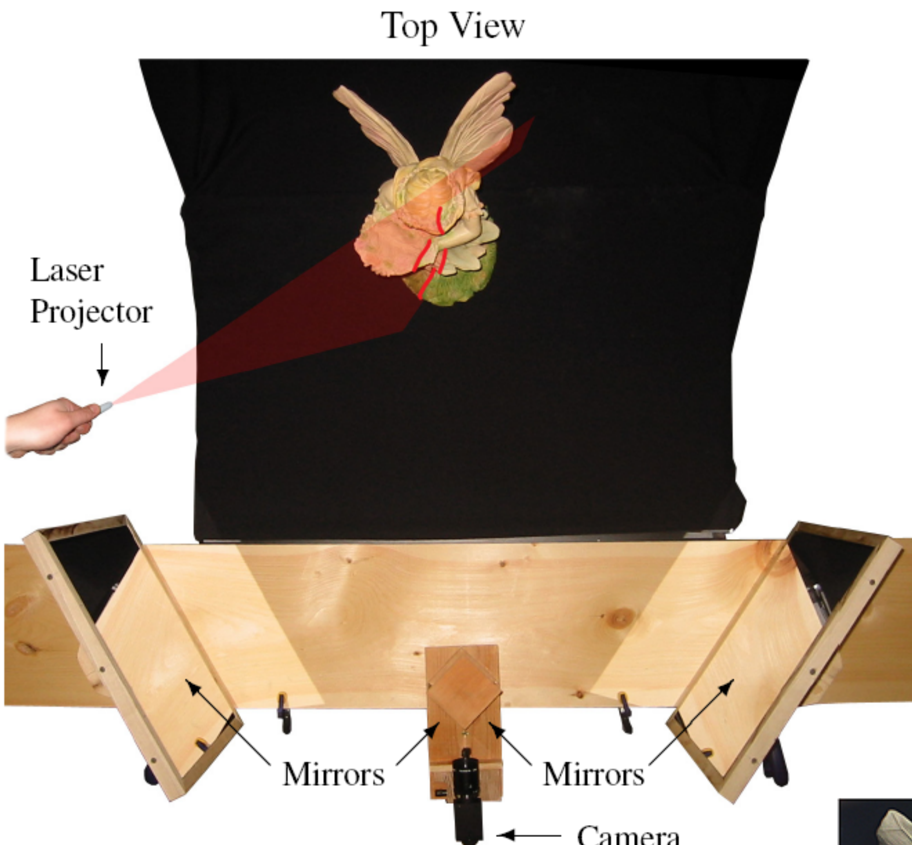


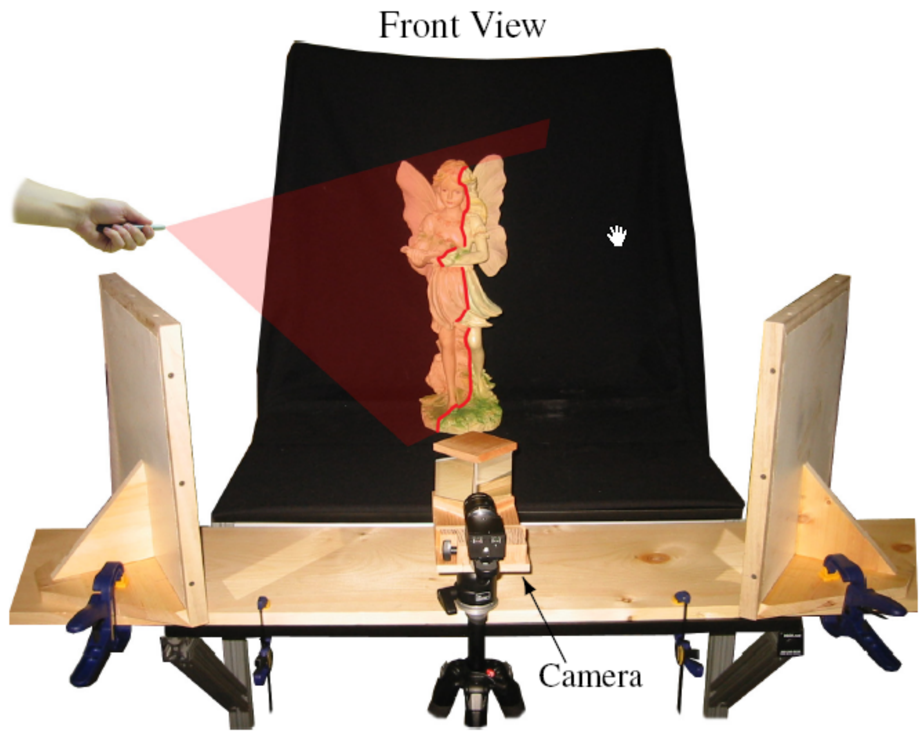
3D Slit Scanning with Planar Constraints

M. Leotta, A. Vandergon, and G. Taubin [CGF 2008]



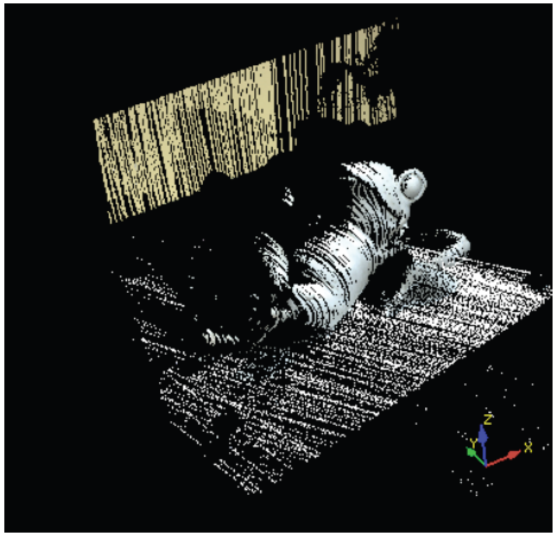
Catadioptric Stereo Implementation



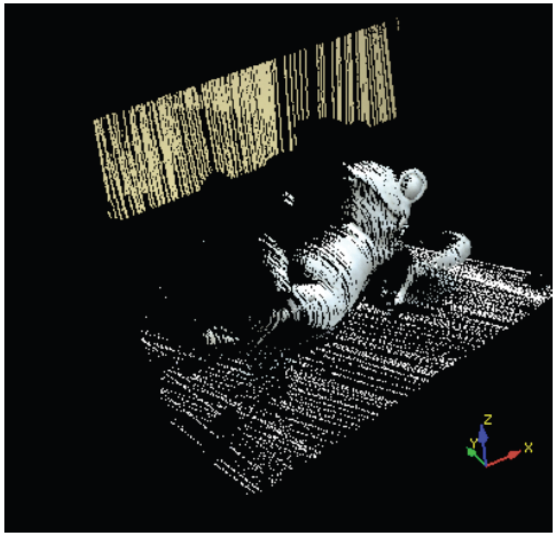


Can Estimate Points Visible From One Camera

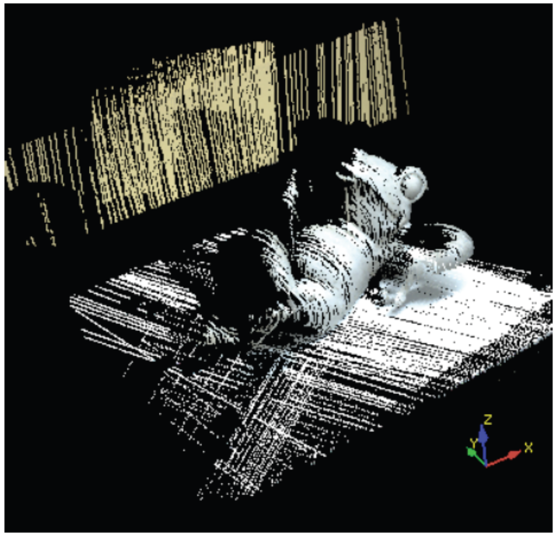
50,986 points



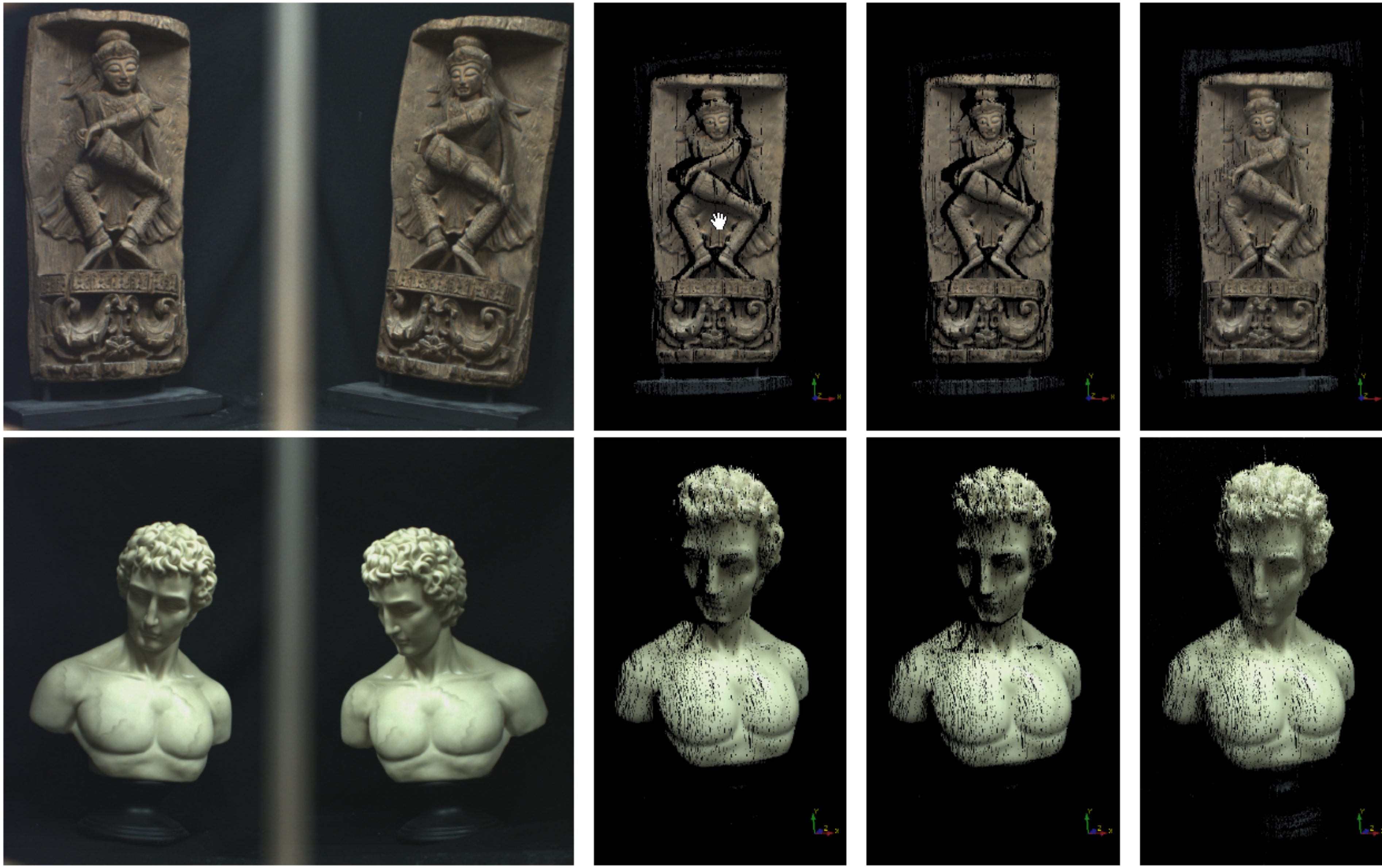
47,271 points in both views



104,488 total points



(a) Camera View (b) Triangulated (c) Planar Optimal (d) All Points



Schedule for this week and next

- **Introduction to 3D Scanning**
- The Mathematics of 3D Triangulation
- 3D Scanning with Swept-Planes | Slit scanner
- Camera and Swept-Plane Light Source Calibration

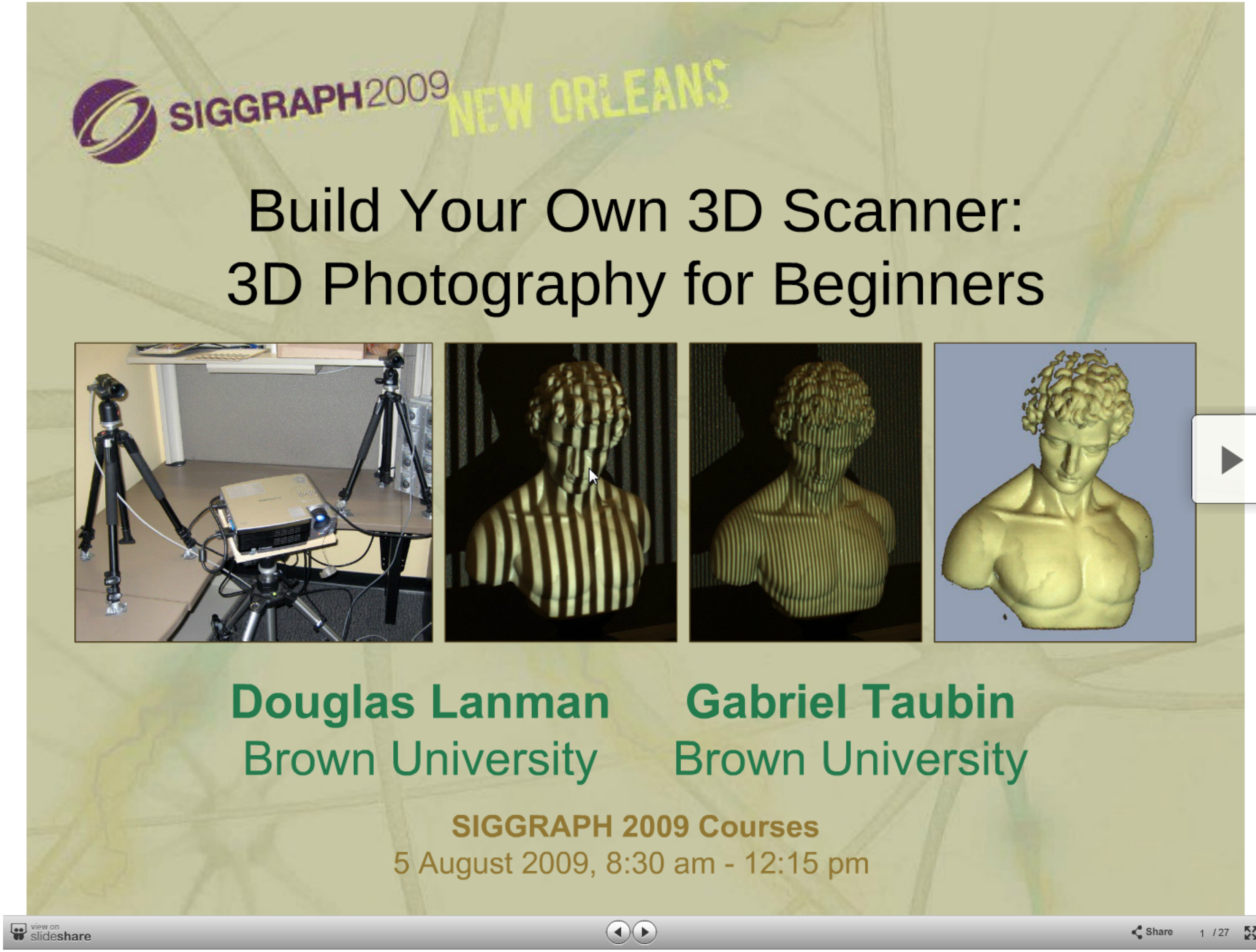
Lecture Notes and Additional Resources

- Download Course Notes from
- **http://mesh.brown.edu/byo3d**
- Or just Google search for BYO3D

- Courses on 3D Photography taught at Brown University
- **http://mesh.brown.edu/3DP**

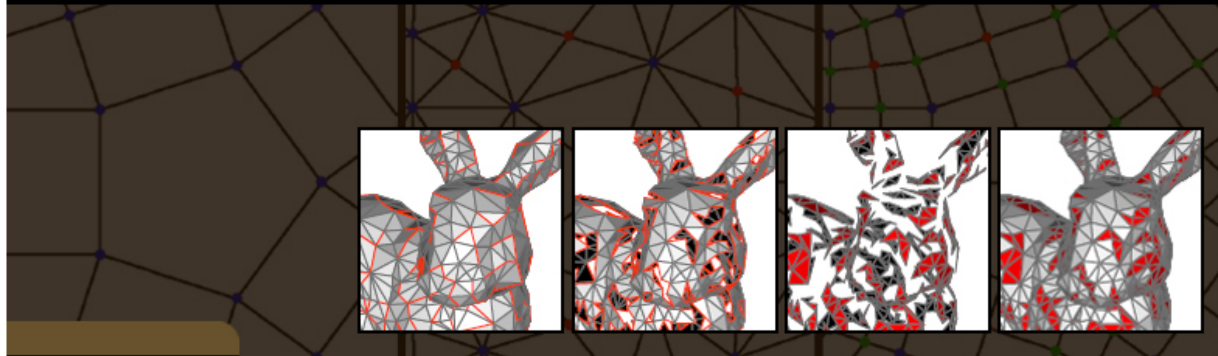
- This Course
- **http://mesh.brown.edu/3DP-FCEN-2013**

http://mesh.brown.edu/byo3d/



SIGGRAPH 2009 and SIGGRAPH Asia 2009 Courses

Build Your Own 3D Scanner: Optical Triangulation for Beginners



- Course Info
- Speaker Bios
- Syllabus
- Course Notes
- Slides
- Source Code
- Links

Announcements

Room 511.

More Info...

Tues July 17 2009:

See this course at SIGGRAPH 2009 on Wed August 5 from 8:30 AM - 12:15 PM in Room 260-262.

More Info...

Abstract

Over the last decade, digital photography has entered the mainstream with inexpensive, miniaturized cameras for consumer use. Digital projection is poised to make a similar breakthrough, with a variety of vendors offering small, low-cost projectors. As a result, active imaging is a topic of renewed interest in the computer graphics community. In particular, low-cost homemade 3D scanners are now within reach of students and hobbyists with a modest budget.

This course provides a beginner with the necessary mathematics, software, and practical details to leverage projector-camera systems in their own 3D scanning projects. An example-driven approach is used throughout; each new concept is illustrated using a practical scanner implemented with off-the-shelf parts. The course concludes by detailing how these new ...ches are used in rapid prototyping, entertainment, cultural heritage, and web-based ...tions.

...erequisites

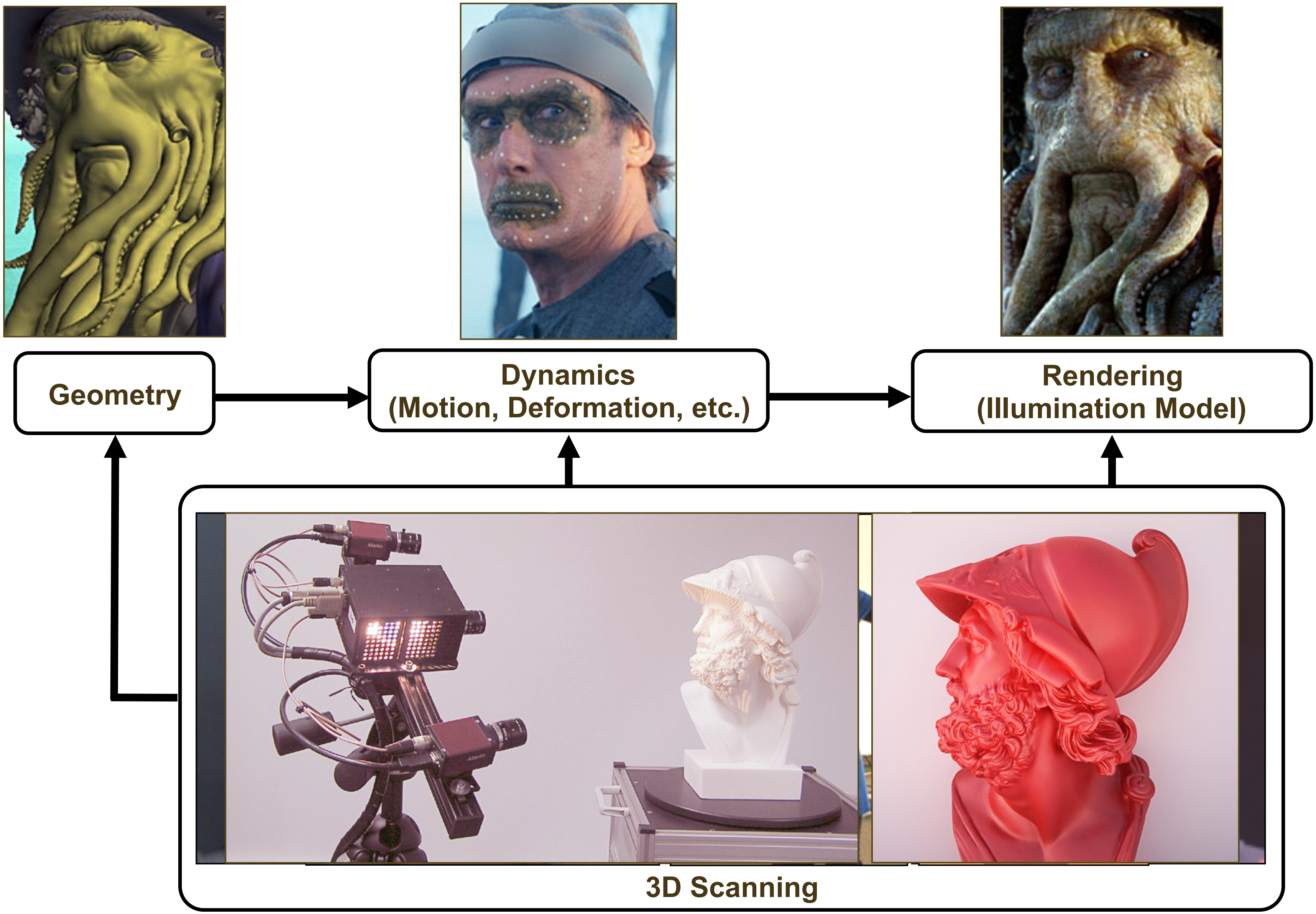
Attendees should have a basic undergraduate-level knowledge of linear algebra. While executables are provided for beginners, attendees with prior knowledge of Matlab, C/C++, and Java programming will be able to directly examine and modify the provided source code.

About this Website

This website serves as an addendum to the course material. Updated versions of the course notes, slides, and source code are distributed here. In addition, links to recent do-it-yourself projects in 3D scanning, as well as late-breaking academic works, are maintained. We encourage course attendees to contact the organizers so we can post links to your own projects, as well as hear your feedback about how the course could be improved.

http://mesh.brown.edu/byo3d

Introduction to 3D Scanning

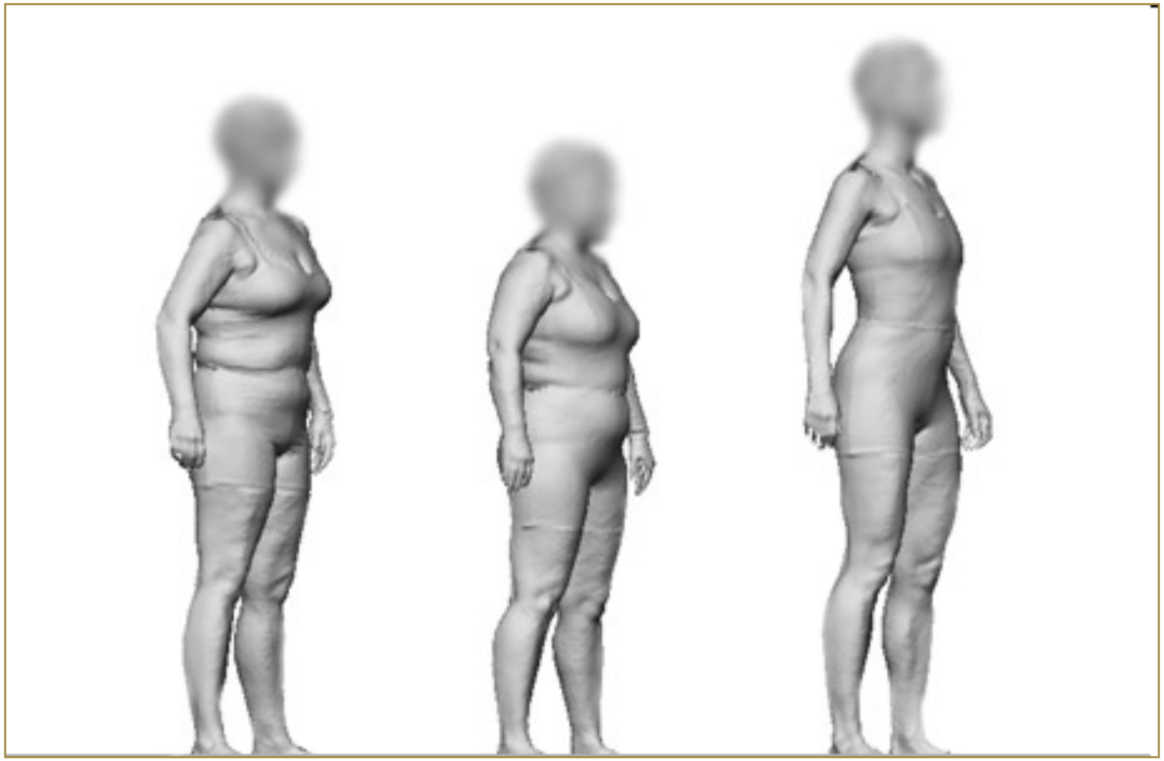


Applications of 3D Scanning:
Entertainment and Consumer Applications

- Import sculptures into a 3D modeling/rendering pipeline
- Capture geometric (and photometric) properties for relighting
- Fit clothes, track 3D interaction, free-viewpoint video (3D TV), etc.

Andreas Wenger et al. Performance Relighting and Reflectance Transformation with Time-Multiplexed Illumination. ACM SIGGRAPH, 2005

Applications of 3D Scanning:
Entertainment and Consumer Applications

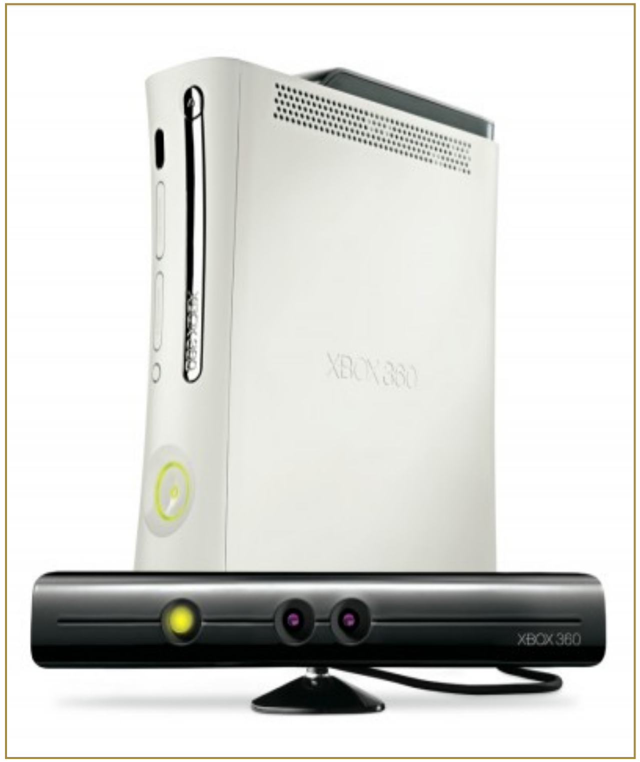


- Import sculptures into a 3D modeling/rendering pipeline
- Capture geometric (and photometric) properties for relighting
- Fit clothes, track 3D interaction, free-viewpoint video (3D TV), etc.

Applications of 3D Scanning:
Entertainment and Consumer Applications

- Import sculptures into a 3D modeling/rendering pipeline
- Capture geometric (and photometric) properties for relighting
- Fit clothes, track 3D interaction, free-viewpoint video (3D TV), etc.

Applications of 3D Scanning:
Entertainment and Consumer Applications



- Import sculptures into a 3D modeling/rendering pipeline
- Capture geometric (and photometric) properties for relighting
- Fit clothes, track 3D interaction, free-viewpoint video (3D TV), etc.

Applications of 3D Scanning:
Entertainment and Consumer Applications

- Import sculptures into a 3D modeling/rendering pipeline
- Capture geometric (and photometric) properties for relighting
- Fit clothes, track 3D interaction, free-viewpoint video (3D TV), etc.

Andreas Wenger et al. Performance Relighting and Reflectance Transformation with Time-Multiplexed Illumination, ACM SIGGRAPH, 2005

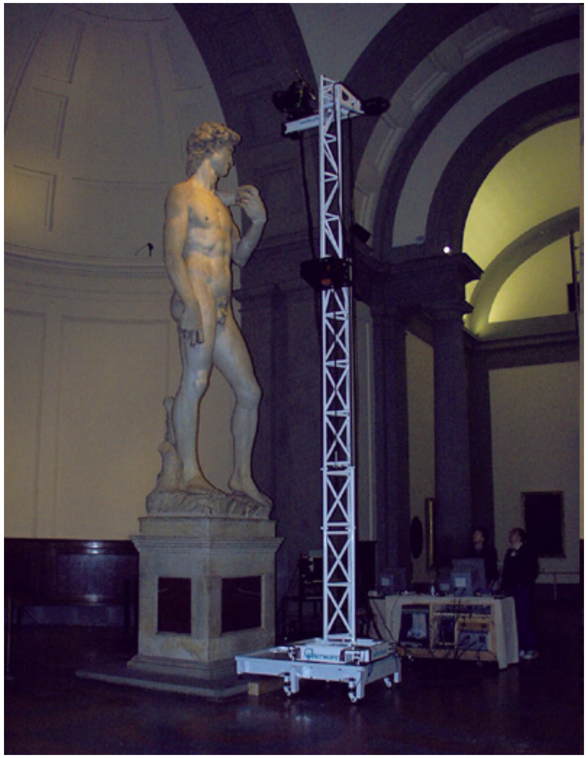
M. Waschbüsch et al. Scalable 3D Video of Dynamic Scenes. *The Visual Computer*, 2005

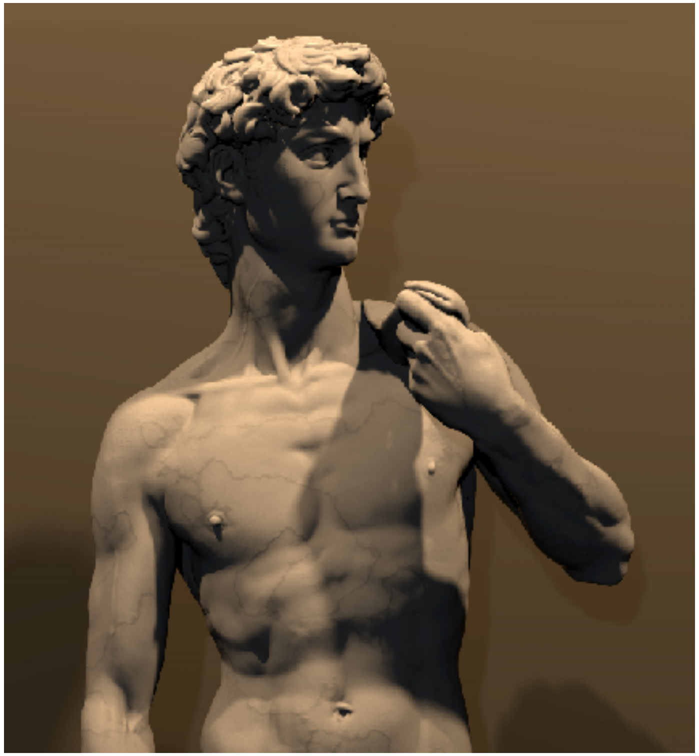
Applications of 3D Scanning: Entertainment and Consumer Applications

- Import sculptures into a 3D modeling/rendering pipeline
- Capture geometric (and photometric) properties for relighting
- Fit clothes, track 3D interaction, free-viewpoint video (3D TV), etc.

M. Waschbüsch et al. Scalable 3D Video of Dynamic Scenes. *The Visual Computer*, 2005.

Applications of 3D Scanning: Historical Preservation

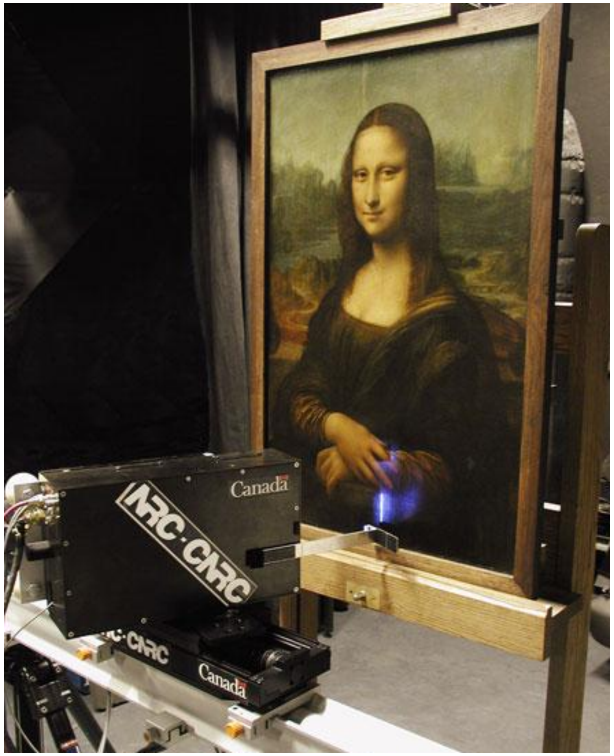




- Preserve/restore deteriorating works and unite dispersed collections
- Facilitate academic study (tooling, lighting, pentimenti, revision history)
- Replicate collections (souvenirs, retain repatriated works, etc.)

M. Levoy et al. The Digital Michelangelo Project: 3D Scanning of Large Statues. ACM SIGGRAPH, 2000

Applications of 3D Scanning:
Historical Preservation



- Preserve/restore deteriorating works and unite dispersed collections
- Facilitate academic study (tooling, lighting, pentimenti, revision history)
- Replicate collections (souvenirs, retain repatriated works, etc.)

L. Borgeat et al. Visualizing and Analyzing the Mona Lisa. *IEEE Computer Graphics and Applications*, 2007

Applications of 3D Scanning: Historical Preservation

- Preserve/restore deteriorating works and unite dispersed collections
- Facilitate academic study (tooling, lighting, pentimenti, revision history)
- Replicate collections (souvenirs, retain repatriated works, etc.)

P. Debevec. Making "The Parthenon". Intl. Sym. on Virtual Reality, Archaeology, and Cultural Heritage, 2005

Applications of 3D Scanning:
Historical Preservation

- Preserve/restore deteriorating works and unite dispersed collections
- Facilitate academic study (tooling, lighting, pentimenti, revision history)
- Replicate collections (souvenirs, retain repatriated works, etc.)

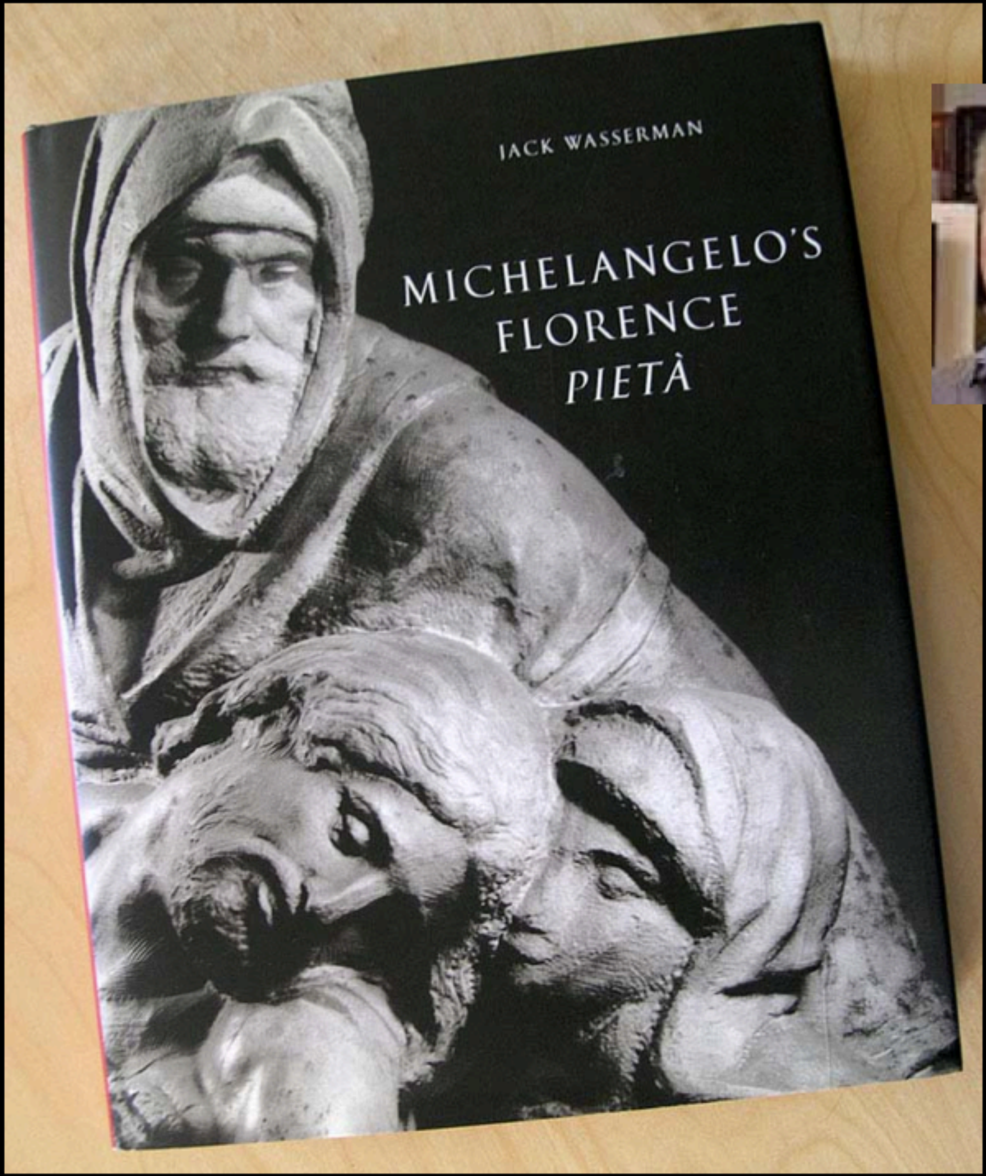
P. Debevec. Making "The Parthenon". Intl. Sym. on Virtual Reality, Archaeology, and Cultural Heritage, 2005

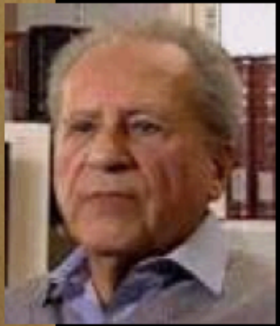
IBM Pietà 3D Scanning Project : 1998-2000

http://www.research.ibm.com/pieta

Remapping Unique Texture

Wasserman’s Pietà Book

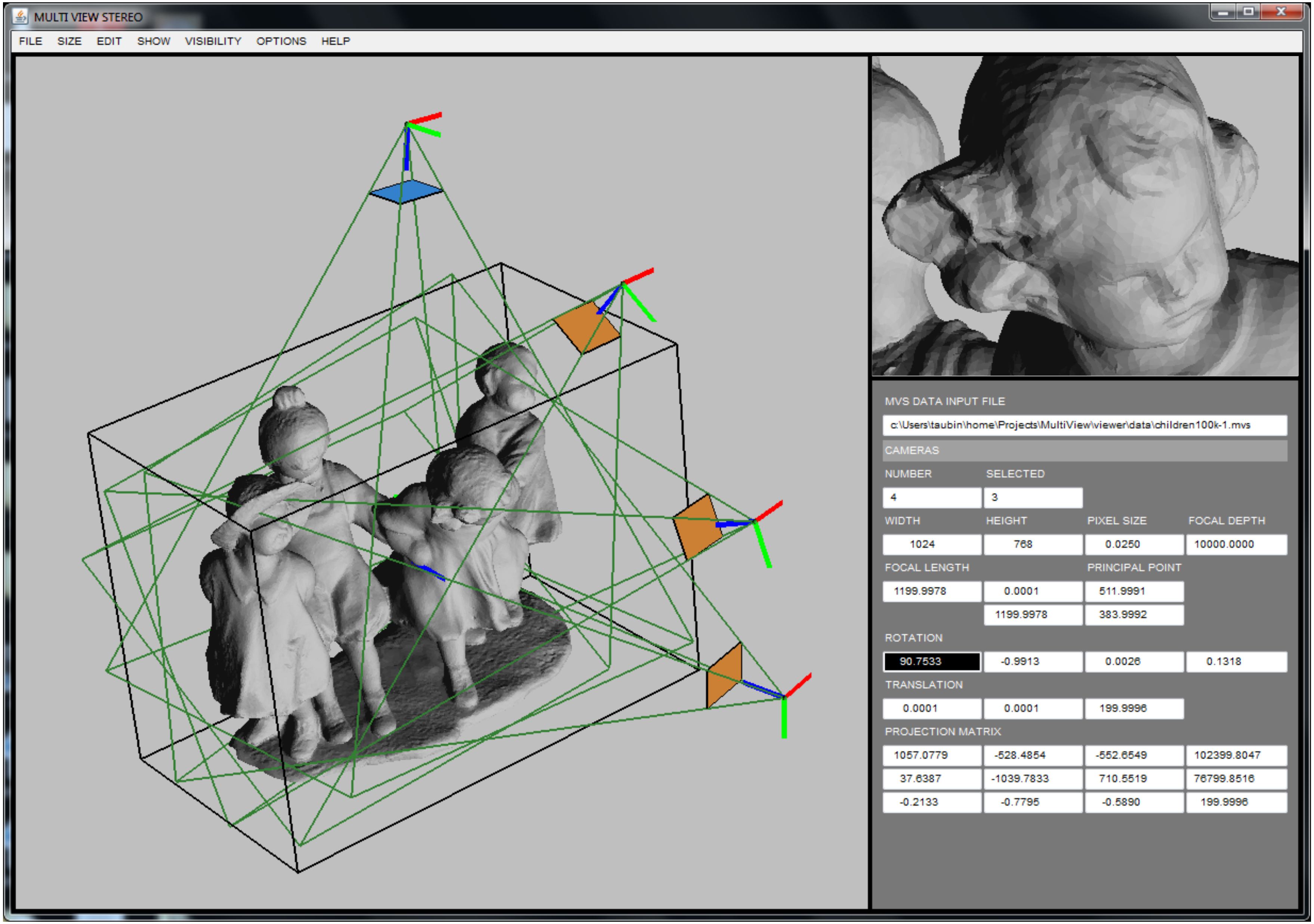




Princeton University Press 2003

Capturing ~800 scans (1998)

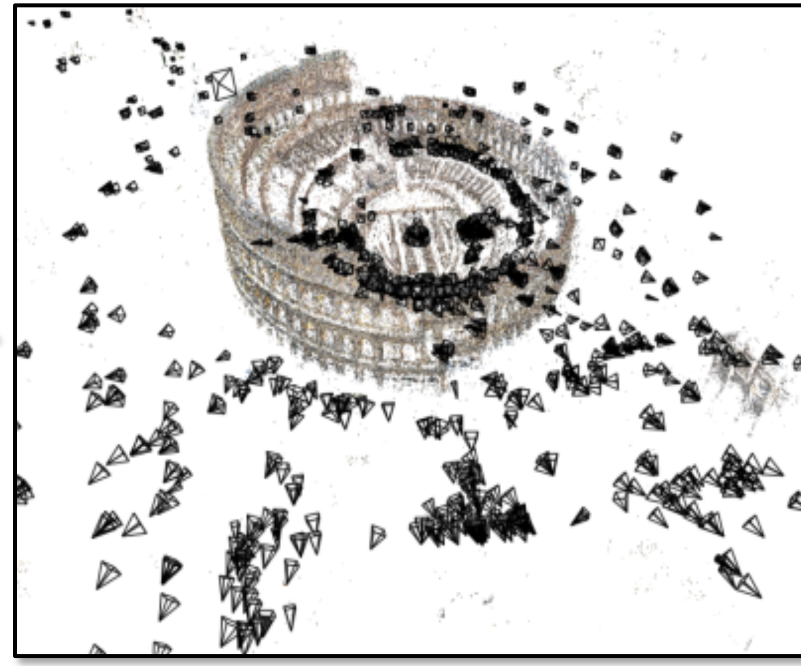
Surface Reconstruction from Multi-View Data



http://phototour.cs.washington.edu/bundler/

+ **MVS software**

Patch-based **M**ulti-**V**iew **S**tereo (PMVS)
http://grail.cs.washington.edu/software/pmvs/



[Snavely et. al. 2006]

[Furukawa and Ponce 2008]

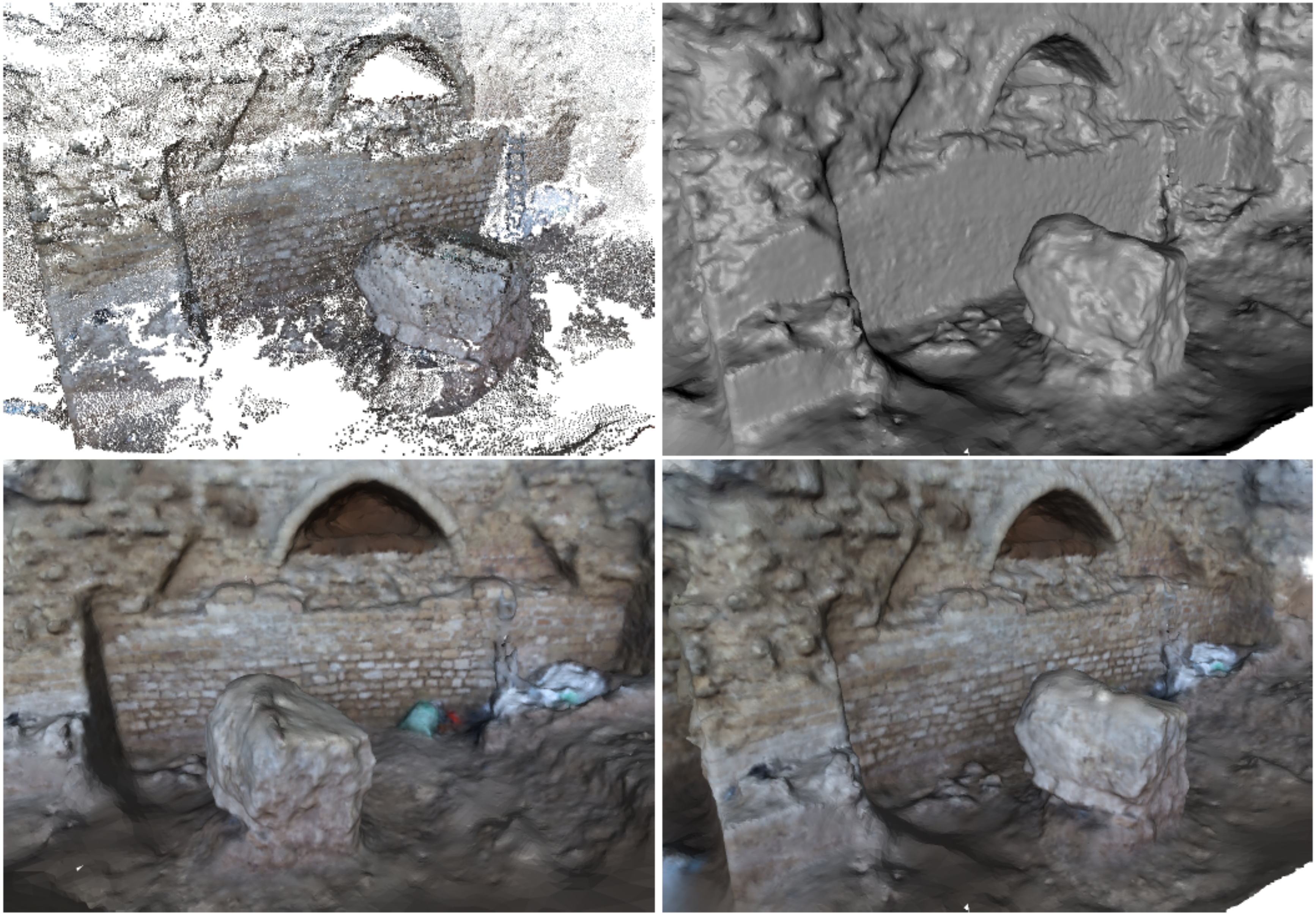
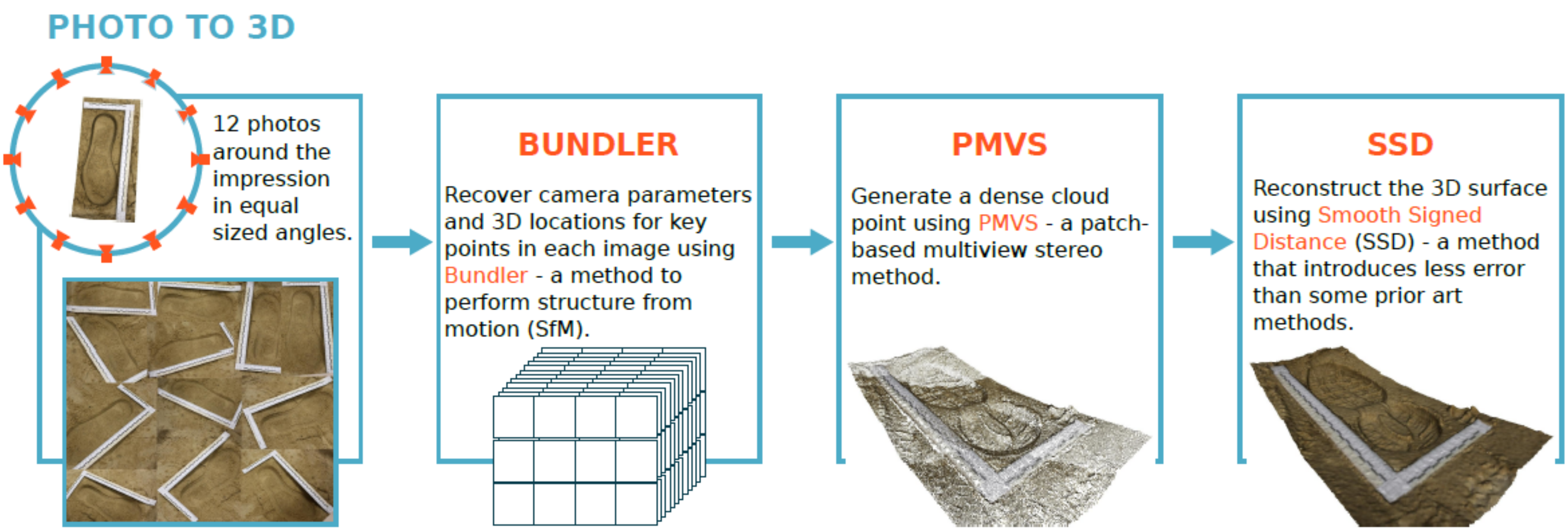


Fig. 1 Reconstruction of the side of a castle model: The input point cloud (top-left), Surface reconstructed by the proposed algorithm(top-right), Two views from the surface and color map reconstructed by the proposed algorithm (bottom).

Fig. 6 Reconstruction of a brick with cuneiform, Mesopotamian, 859-840 BCE, clay, Overall 35 x 35 x 11 cm, Williams College Museum of Art, Williamstown, MA, Gift of Professor Edgar J. Banks and Dr. John Henry Haynes, Class of 1876,(20.1.33.A). Top row: the input point cloud (left), and surface geometry (right) reconstructed by the proposed algorithm. Middle row: Two views from surface and color map reconstructed by the proposed algorithm. Bottom row: 6 examples from the set of 21 images that are used for shape acquisition.

Accurate 3D Footwear Impression Recovery From Photographs,
F. A. Andalo, F. Calakli, G. Taubin, and S. Goldenstein,
International Conference on Imaging for Crime Detection and Prevention (ICDP-2011).



Comparable to 3D Laser Scanner


EXPO

EXPERIMENTAL RESULTS

3D SCANNER

SHOE SOLES

d_g : Haursdoff distance map between the scanned shoe print and the scanned shoe sole.

d_m : Haursdoff distance map between our 3D model and the scanned shoe sole.

Shoeprint #	$\overline{d_g}$	$\overline{d_m}$	$\overline{d_m} - \overline{d_g}$
1	9.996	10.002	0.006
2	8.157	8.660	0.503
3	8.715	9.480	0.765
4	8.816	9.114	0.298

(mm)

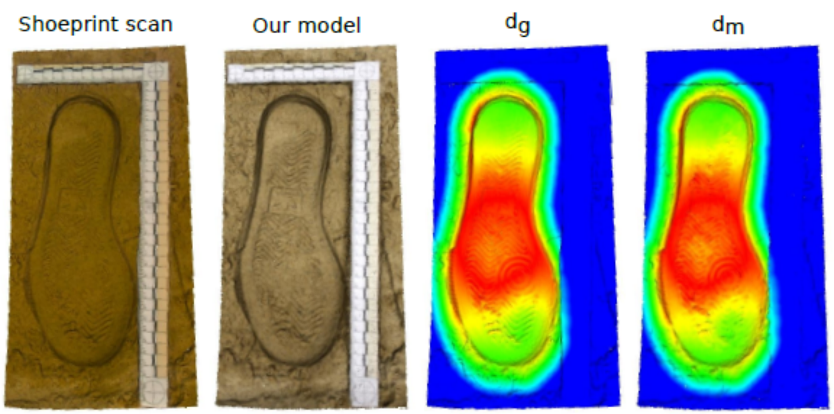
CONCLUSIONS

We presented a pipeline to recover footwear impressions from crime scenes using multiview stereo, which has not been considered for this kind of application until now.

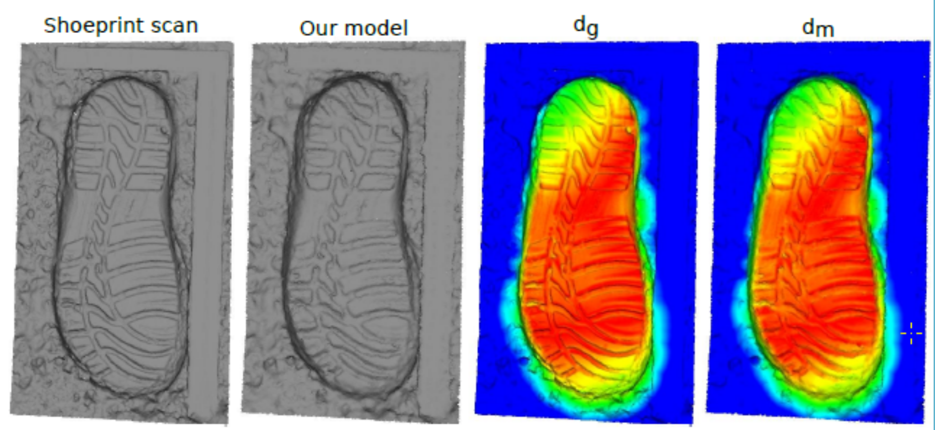
Despite the simplicity, the obtained surfaces are comparable with 3D scanning.

Future work: more experiments - number of images, angle between images, comparison with casting.

EXAMPLES

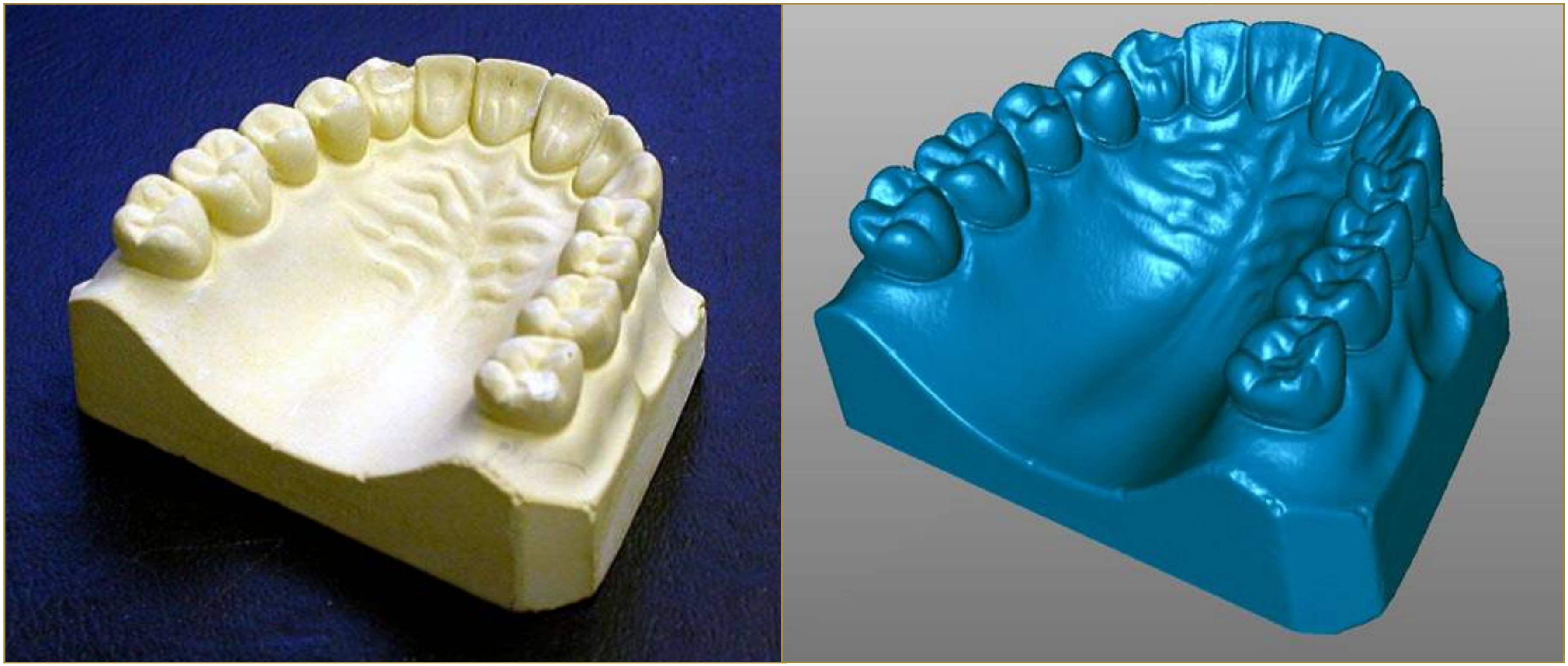


1st Shoeprint



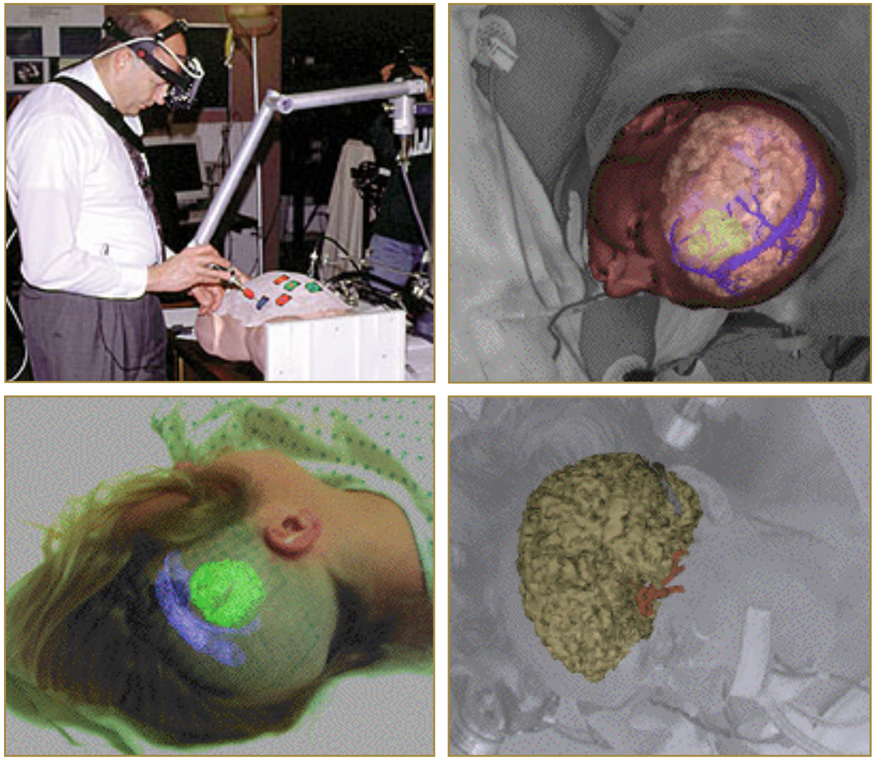
3rd Shoeprint

Applications of 3D Scanning:
Medical Imaging and Surgical Planning



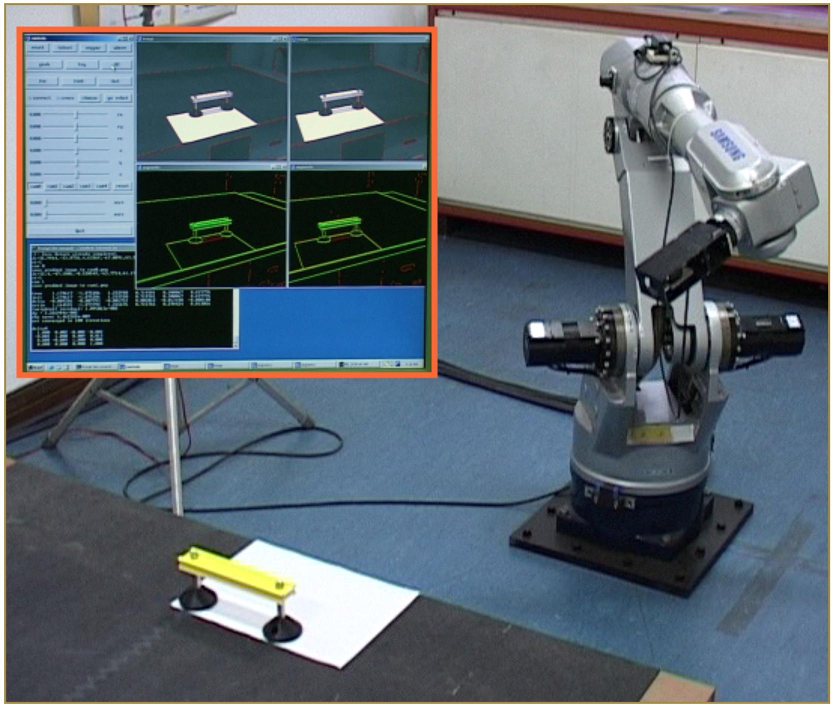
- Medical imaging (X-ray, CT, MRI, etc.) and surgical planning
- Measuring dimensions (dental impressions and hip replacement surgery)
- Tele-surgery (augmented virtual reality, video see-through, etc.)

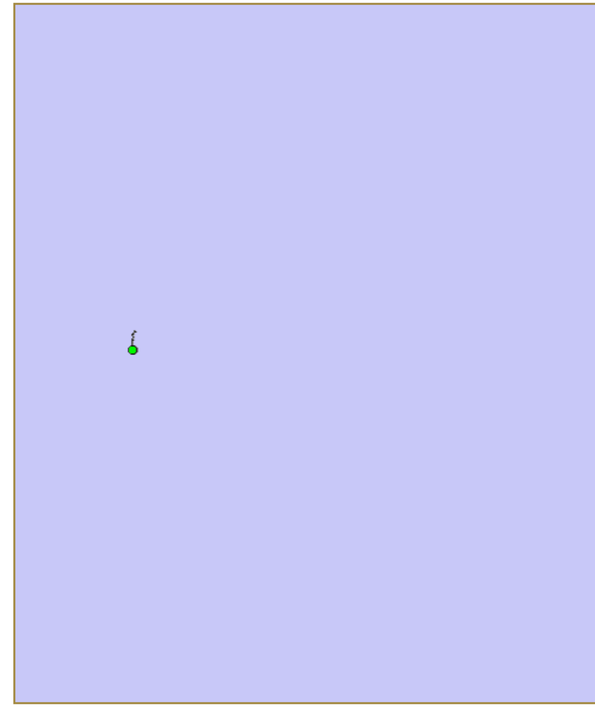
Applications of 3D Scanning: Medical Imaging and Surgical Planning



- Medical imaging (X-ray, CT, MRI, etc.) and surgical planning
- Measuring dimensions (dental impressions and hip replacement surgery)
- Tele-surgery (augmented virtual reality, video see-through, etc.)

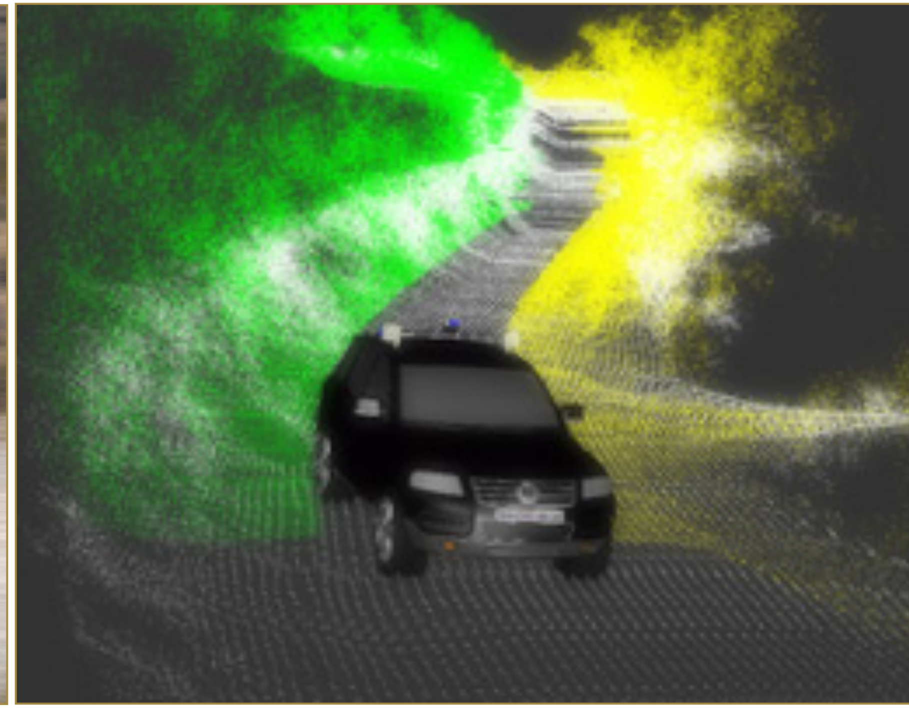
Applications of 3D Scanning:
Robotics (Interaction and Navigation)





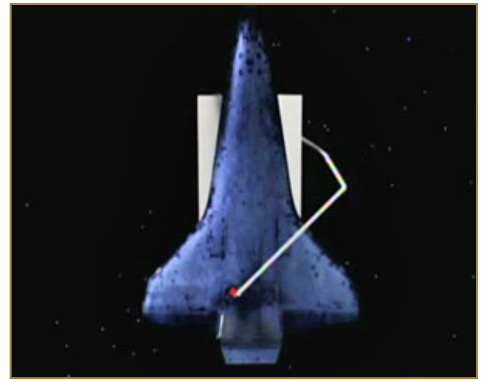
- Motion planning (manipulation, gripping, pushing/pulling, etc.)
- Simultaneous localization and mapping (SLAM)
- Autonomous navigation (DARPA Grand/Urban Challenge)

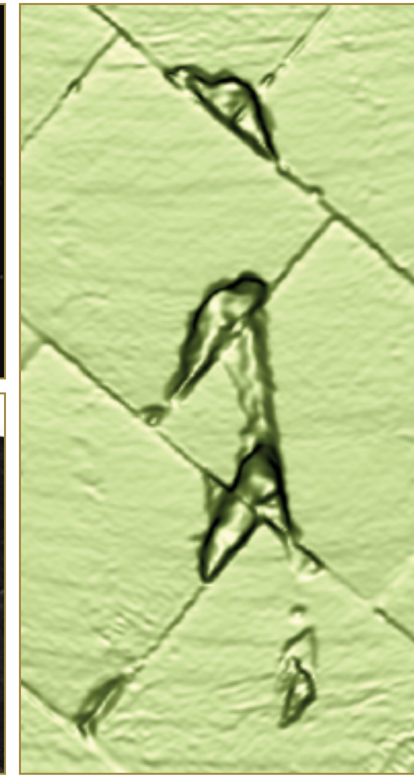
Applications of 3D Scanning:
Robotics (Interaction and Navigation)



- Motion planning (manipulation, gripping, pushing/pulling, etc.)
- Simultaneous localization and mapping (SLAM)
- Autonomous navigation (DARPA Grand/Urban Challenge)

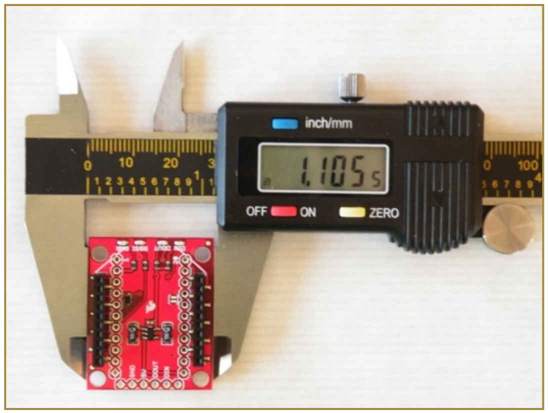
Applications of 3D Scanning:
Inspection and Reverse Engineering

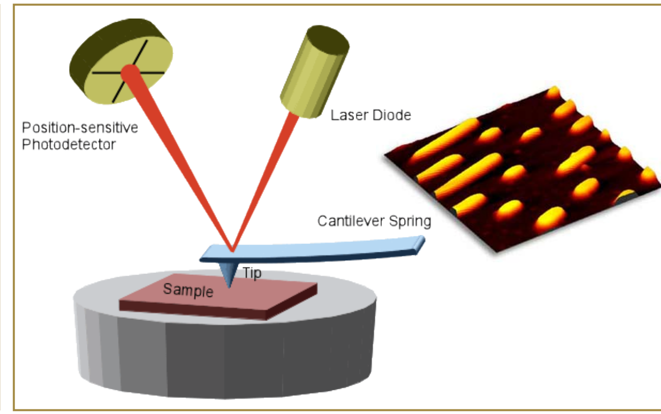




- Manufacturing and process control (tolerances and alignment)
- Reverse engineering (repairing antiques and replicating designs)
- Remote inspection (inaccessible or dangerous environments)

Taxonomy of 3D Scanning:
Direct Contact





Contact —— Direct Measurements
(rulers, calipers, pantographs, coordinate measuring machines (CMM), AFM)

Non-Contact

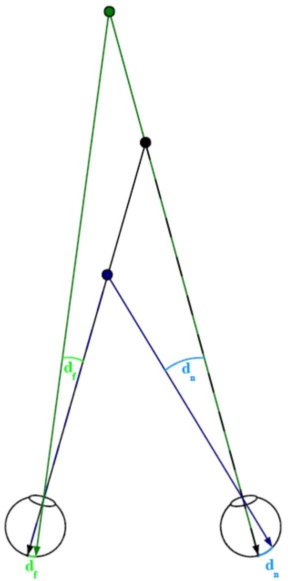
Taxonomy adapted from Szymon Rusinkiewicz

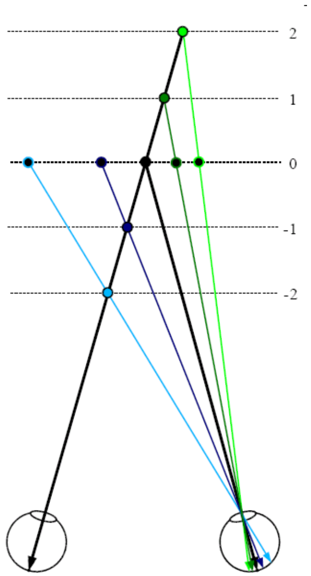
Real-Time High-Definition Stereo on GPGPU using Progressive Multi-Resolution Adaptive Windows

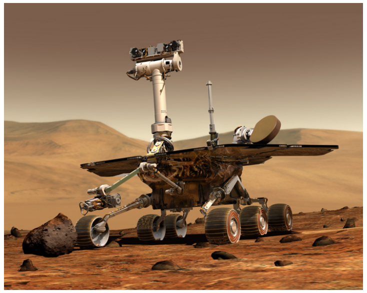
Y. Zhao, and G. Taubin, Image and Vision Computing 2011.

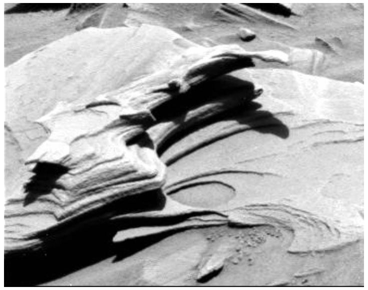
Screen shots of our real-time stereo system working on the field

Taxonomy of 3D Scanning:
Stereo/Multi-view Photography





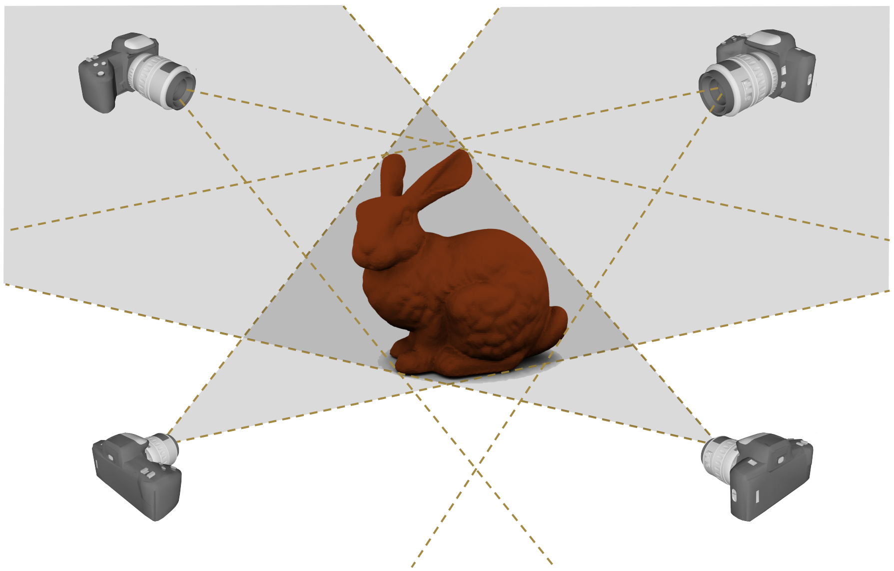


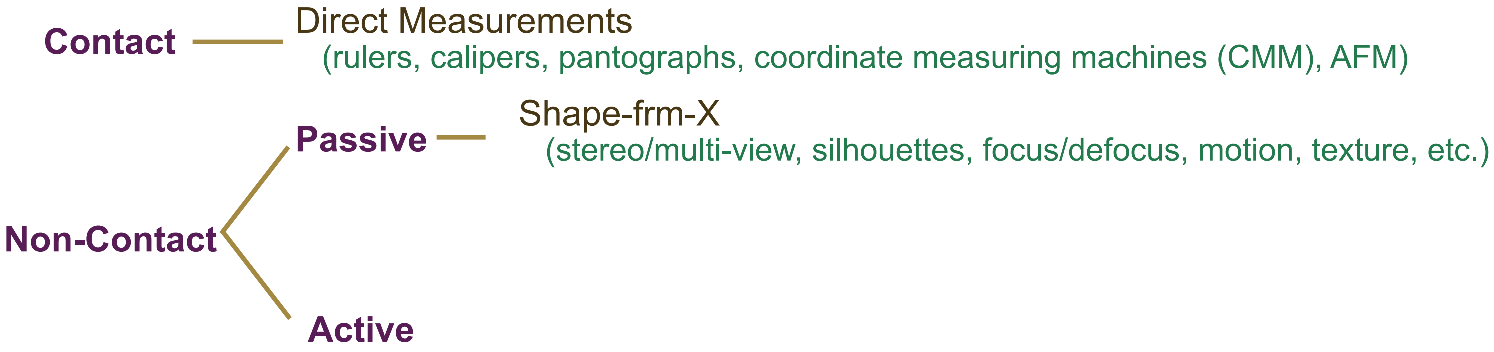


Contact — Direct Measurements
(rulers, calipers, pantographs, coordinate measuring machines (CMM), AFM)

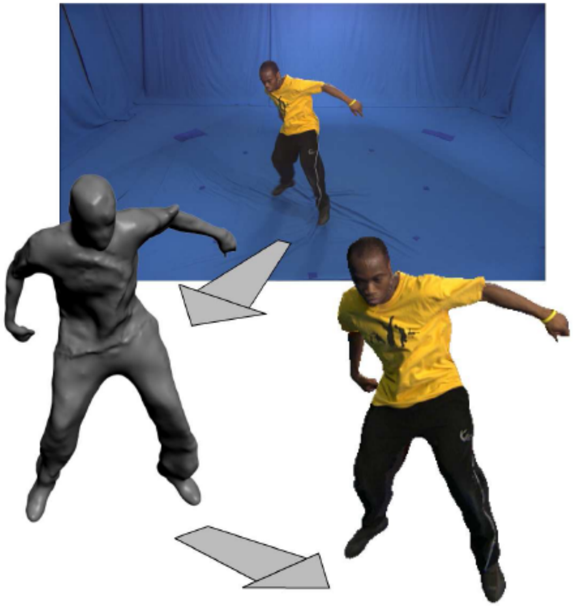
Non-Contact
- **Passive** — Shape-from-X
  (stereo/multi-view, silhouettes, focus/defocus, motion, texture, etc.)
- **Active**

Taxonomy of 3D Scanning:
Shape-from-Silhouettes





Taxonomy of 3D Scanning:
Shape-from-Silhouettes

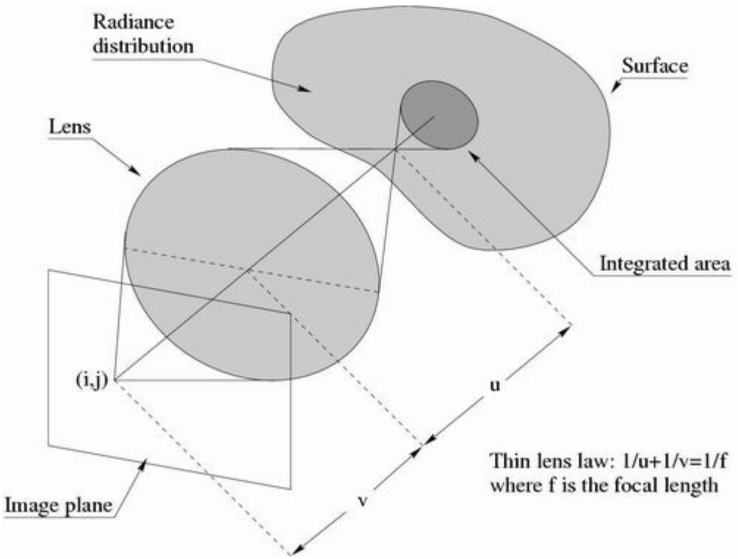


Contact — Direct Measurements
(rulers, calipers, pantographs, coordinate measuring machines (CMM), AFM)

Non-Contact
- **Passive** — Shape-from-X
  (stereo/multi-view, silhouettes, focus/defocus, motion, texture, etc.)
- **Active**

J. Starck and A. Hilton. Surface Capture for Performance-Based Animation. *IEEE Computer Graphics and Applications*, 2007

Taxonomy of 3D Scanning:
Shape-from-Focus/Defocus

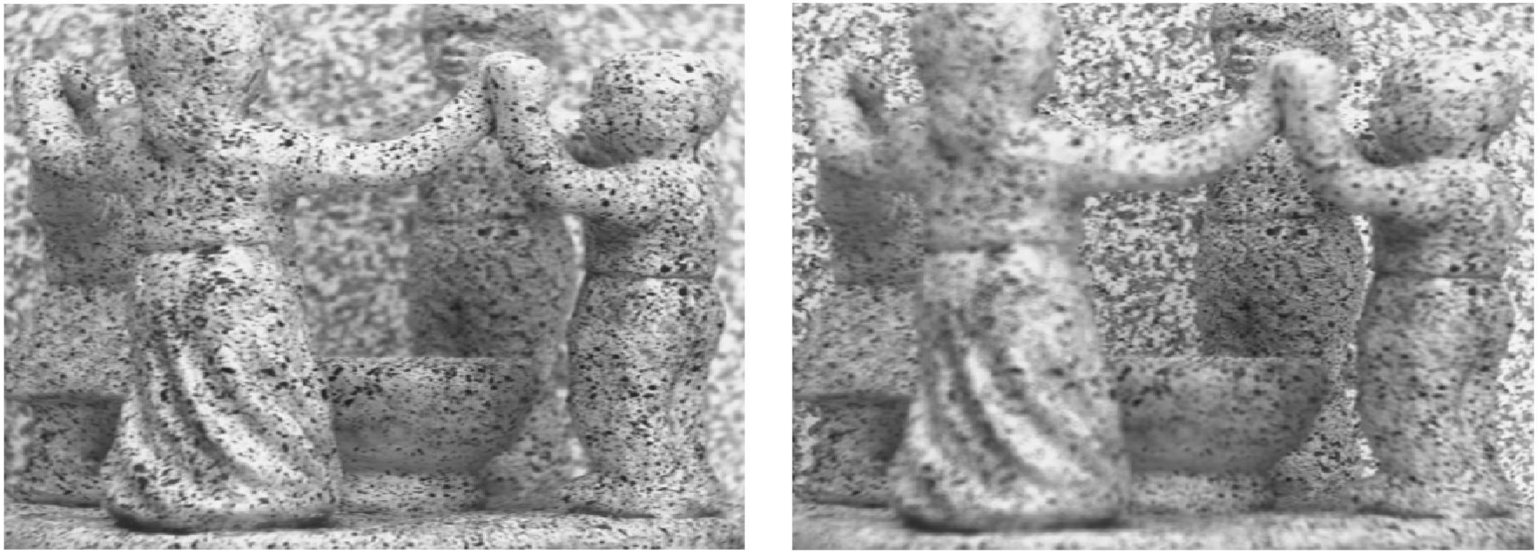


Contact — Direct Measurements
(rulers, calipers, pantographs, coordinate measuring machines (CMM), AFM)

Non-Contact
- **Passive** — Shape-from-X
  (stereo/multi-view, silhouettes, focus/defocus, motion, texture, etc.)
- **Active**

M. Watanabe and S. Nayar. Rational filters for passive depth from defocus. *Intl. J. of Comp. Vision*, 27(3):203-225, 1998

Taxonomy of 3D Scanning:
Shape-from-Focus/Defocus

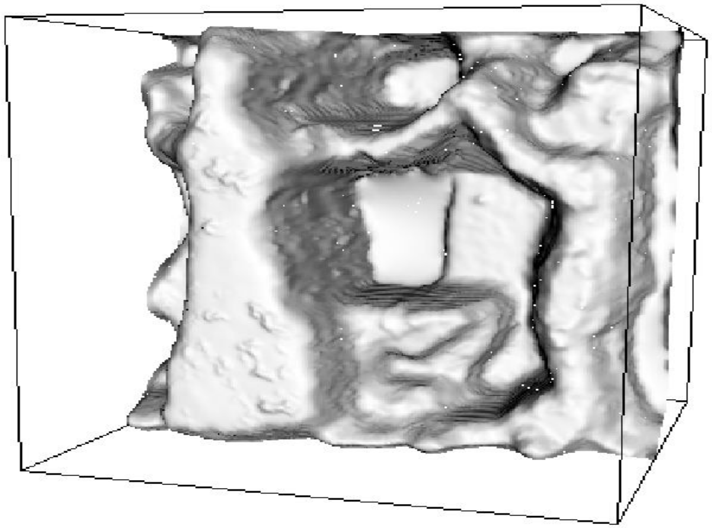


Contact — Direct Measurements
(rulers, calipers, pantographs, coordinate measuring machines (CMM), AFM)

Non-Contact
- **Passive** — Shape-from-X
(stereo/multi-view, silhouettes, focus/defocus, motion, texture, etc.)
- **Active**

M. Watanabe and S. Nayar. Rational filters for passive depth from defocus. *Intl. J. of Comp. Vision*, 27(3):203-225, 1998

Taxonomy of 3D Scanning:
Shape-from-Focus/Defocus

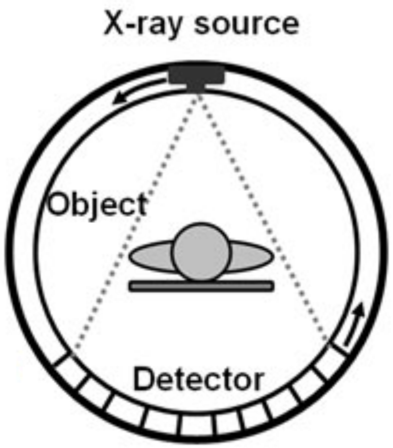


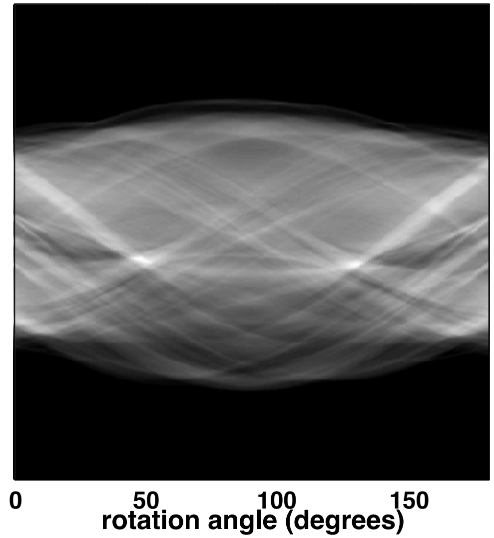
Contact — Direct Measurements
(rulers, calipers, pantographs, coordinate measuring machines (CMM), AFM)

Non-Contact
- Passive — Shape-from-X
  (stereo/multi-view, silhouettes, focus/defocus, motion, texture, etc.)
- Active

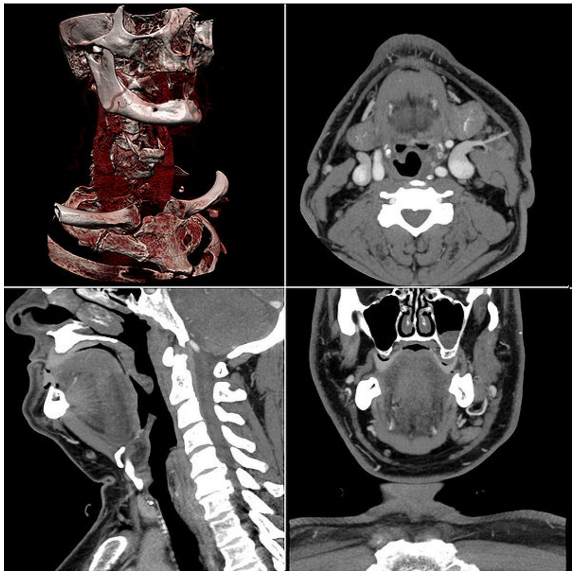
M. Watanabe and S. Nayar. Rational filters for passive depth from defocus. *Intl. J. of Comp. Vision*, 27(3):203-225, 1998

Taxonomy of 3D Scanning:
Computed Tomography (CT)





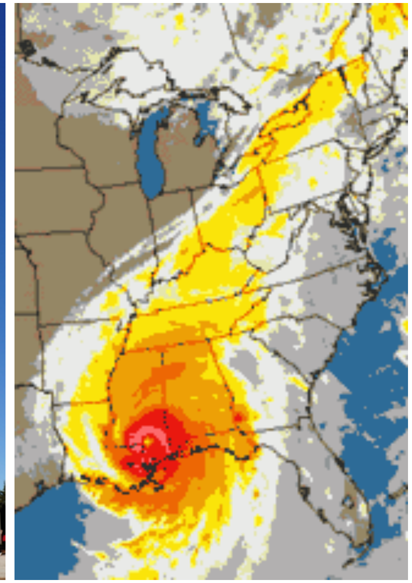
Parallel/Fan-beam Projections

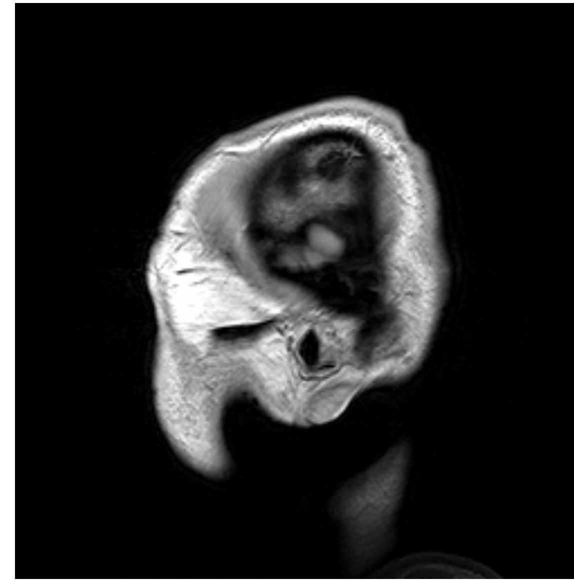


Contact — Direct Measurements
(rulers, calipers, pantographs, coordinate measuring machines (CMM), AFM)

Non-Contact
- **Passive** — Shape-from-X
  (stereo/multi-view, silhouettes, focus/defocus, motion, texture, etc.)
- **Active**
  - **Transmissive**
    - Computed Tomography (CT)
    - Transmissive Ultrasound
  - **Reflective**

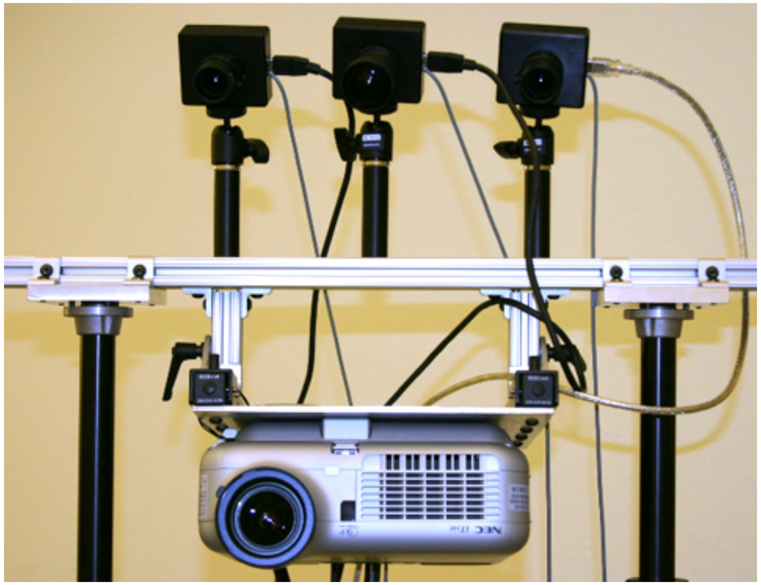
Taxonomy of 3D Scanning:
Non-optical Active Methods





- **Contact** — Direct Measurements
  (rulers, calipers, pantographs, coordinate measuring machines (CMM), AFM)
- **Non-Contact**
  - **Passive** — Shape-from-X
    (stereo/multi-view, silhouettes, focus/defocus, motion, texture, etc.)
  - **Active**
    - **Transmissive**
      - Computed Tomography (CT)
      - Transmissive Ultrasound
    - **Reflective**
      - Non-optical Methods
        (reflective ultrasound, radar, sonar, MRI)

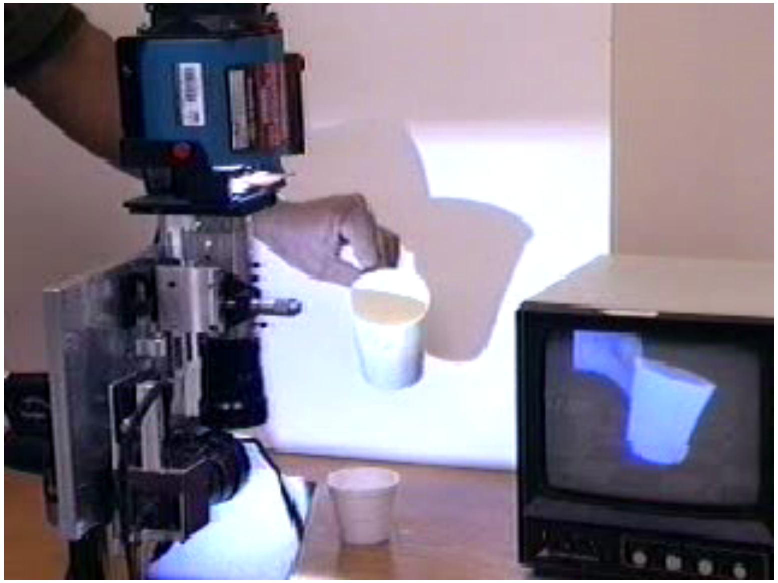
Taxonomy of 3D Scanning:
Active Variants of Passive Methods



- **Contact** — Direct Measurements
  (rulers, calipers, pantographs, coordinate measuring machines (CMM), AFM)
- **Non-Contact**
  - **Passive** — Shape-from-X
    (stereo/multi-view, silhouettes, focus/defocus, motion, texture, etc.)
  - **Active**
    - **Transmissive**
      - Computed Tomography (CT)
      - Transmissive Ultrasound
    - **Reflective**
      - Non-optical Methods
        (reflective ultrasound, radar, sonar, MRI)
      - Active Variants of Passive Methods
        (stereo/focus/defocus using projected patterns)

M. Waschbüsch et al. Scalable 3D Video of Dynamic Scenes.
The Visual Computer, pp. 629-638, 2005

Taxonomy of 3D Scanning:
Active Variants of Passive Methods

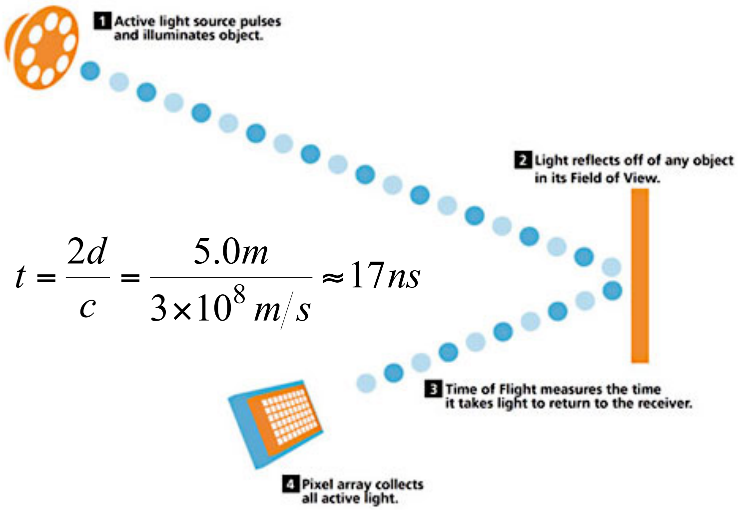


Contact — Direct Measurements
(rulers, calipers, pantographs, coordinate measuring machines (CMM), AFM)

Non-Contact
- **Passive** — Shape-from-X
  (stereo/multi-view, silhouettes, focus/defocus, motion, texture, etc.)
- **Active**
  - **Transmissive**
    - Computed Tomography (CT)
    - Transmissive Ultrasound
  - **Reflective**
    - Non-optical Methods
      (reflective ultrasound, radar, sonar, MRI)
    - Active Variants of Passive Methods
      (stereo/focus/defocus using projected patterns)

M. Watanabe and S. Nayar. Rational Filters for Passive Depth from Defocus. *Intl. J. of Comp. Vision*, 27(3):203-225, 1998

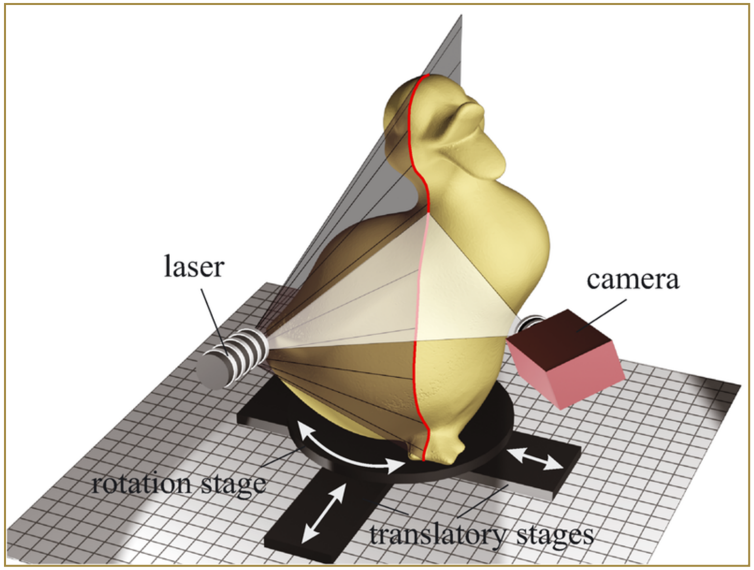
Taxonomy of 3D Scanning: Time-of-Flight

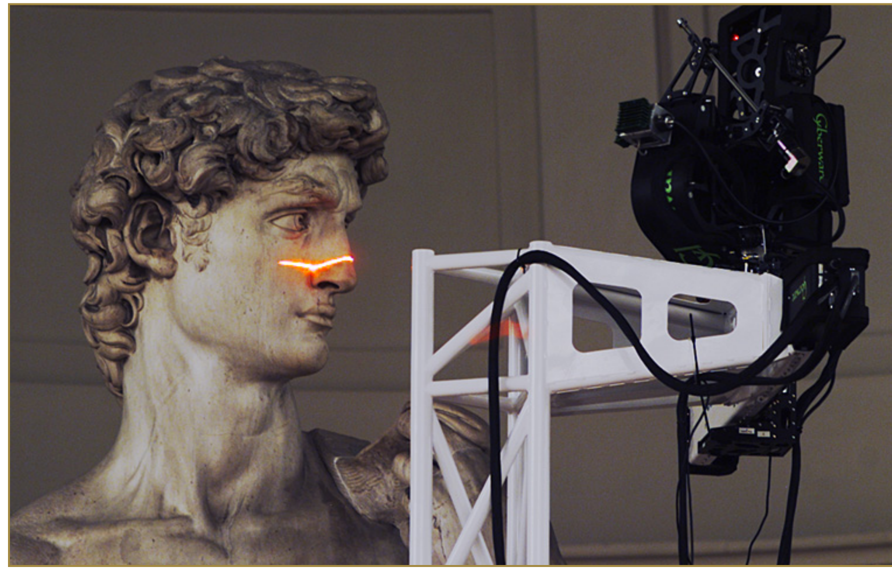


$$t = \frac{2d}{c} = \frac{5.0m}{3\times10^{8}\, m/s} \approx 17ns$$

- **Contact** — Direct Measurements
  (rulers, calipers, pantographs, coordinate measuring machines (CMM), AFM)
- **Non-Contact**
  - **Passive** — Shape-from-X
    (stereo/multi-view, silhouettes, focus/defocus, motion, texture, etc.)
  - **Active**
    - **Transmissive**
      - Computed Tomography (CT)
      - Transmissive Ultrasound
    - **Reflective**
      - Non-optical Methods
        (reflective ultrasound, radar, sonar, MRI)
      - Active Variants of Passive Methods
        (stereo/focus/defocus using projected patterns)
      - Time-of-Flight

Taxonomy of 3D Scanning:
Triangulation with Laser Striping





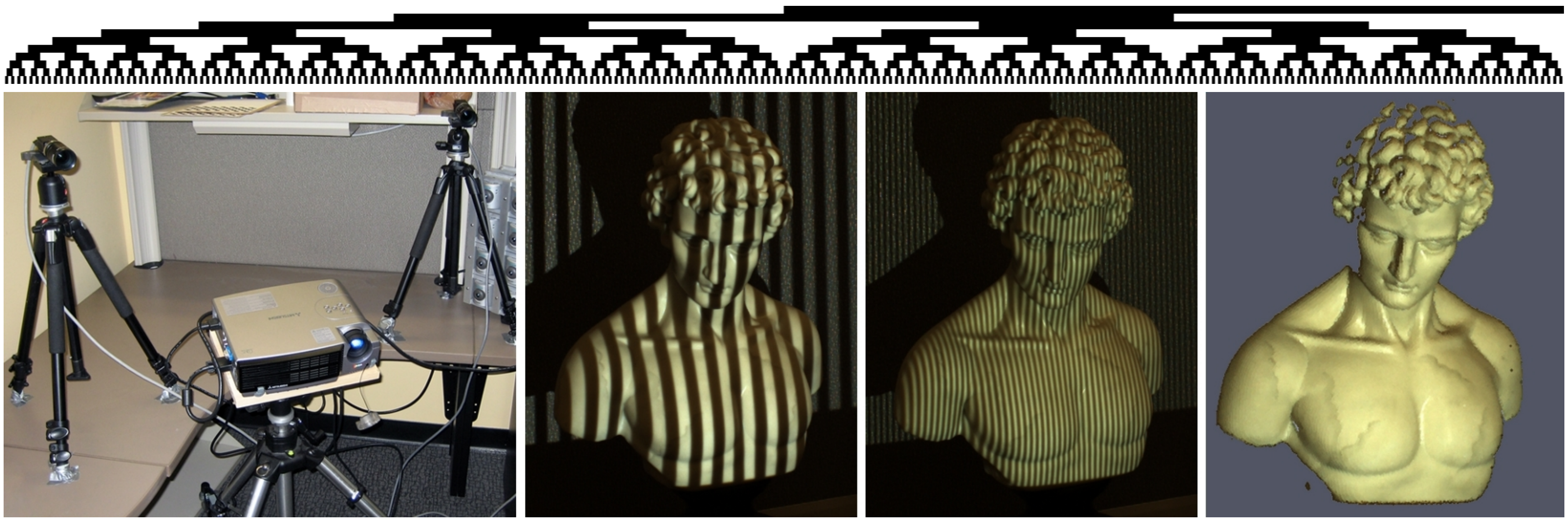
Contact — Direct Measurements
(rulers, calipers, pantographs, coordinate measuring machines (CMM), AFM)

Non-Contact

- **Passive** — Shape-from-X
  (stereo/multi-view, silhouettes, focus/defocus, motion, texture, etc.)
- **Active**
  - **Transmissive**
    - Computed Tomography (CT)
    - Transmissive Ultrasound
  - **Reflective**
    - Non-optical Methods
      (reflective ultrasound, radar, sonar, MRI)
    - Active Variants of Passive Methods
      (stereo/focus/defocus using projected patterns)
    - Time-of-Flight
    - Triangulation
      (laser striping and structured lighting)

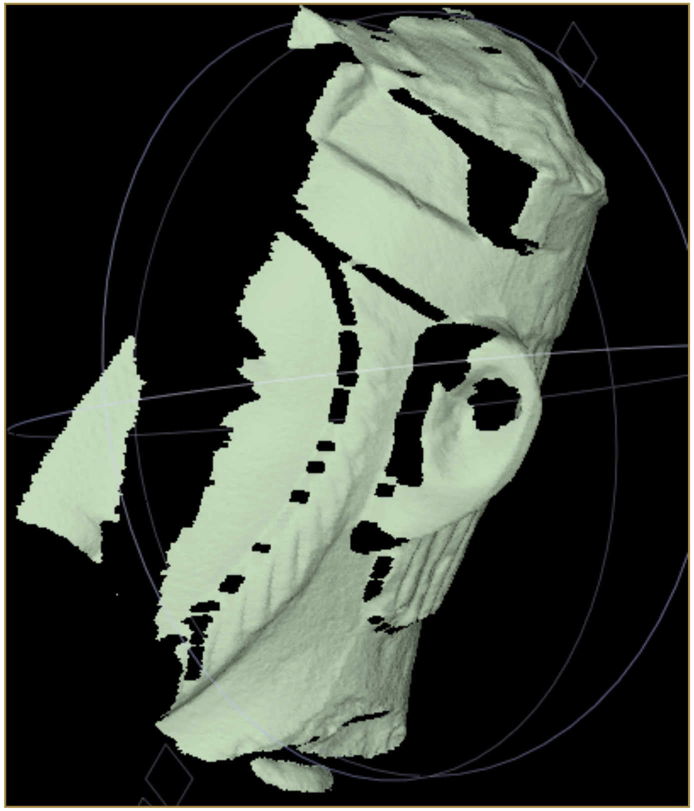
M. Levoy et al. The Digital Michelangelo Project: 3D Scanning of Large Statues. Proc. ACM SIGGRAPH, 2000

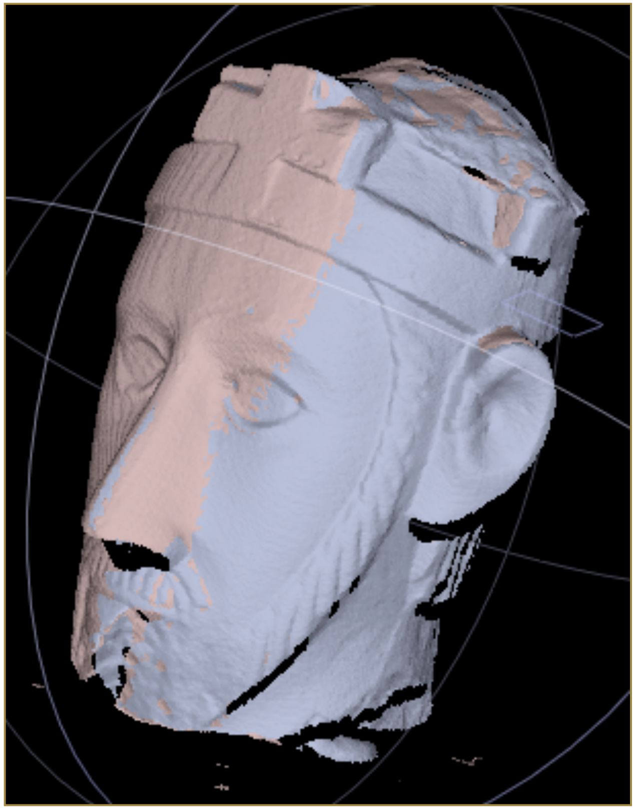
Taxonomy of 3D Scanning:
Triangulation with Structured Lighting



- **Contact** — Direct Measurements
  - (rulers, calipers, pantographs, coordinate measuring machines (CMM), AFM)
- **Non-Contact**
  - **Passive** — Shape-from-X
    - (stereo/multi-view, silhouettes, focus/defocus, motion, texture, etc.)
  - **Active**
    - **Transmissive**
      - Computed Tomography (CT)
      - Transmissive Ultrasound
    - **Reflective**
      - Non-optical Methods
        - (reflective ultrasound, radar, sonar, MRI)
      - Active Variants of Passive Methods
        - (stereo/focus/defocus using projected patterns)
      - Time-of-Flight
      - Triangulation
        - (laser striping and structured lighting)

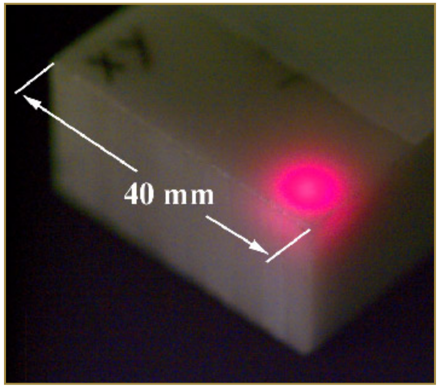
Challenges of Optical 3D Scanning

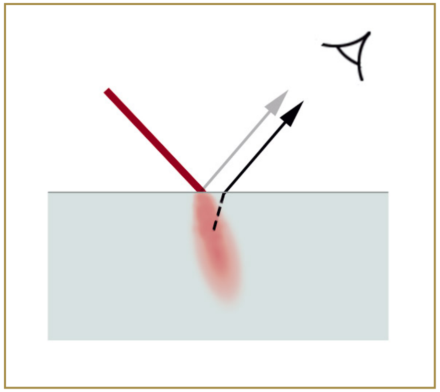


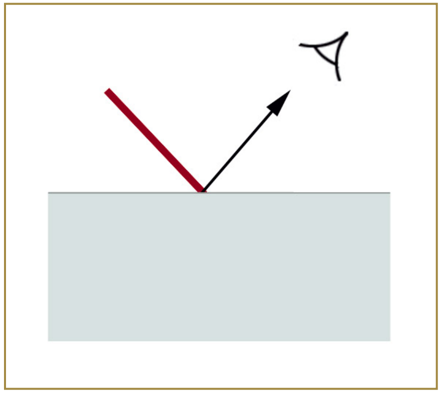


- Must be simultaneously *illuminated* and *imaged* (occlusion problems)
- Non-Lambertian BRDFs (transparency, reflections, subsurface scattering)
- Acquisition time (dynamic scenes), large (or small) features, etc.

Challenges of Optical 3D Scanning





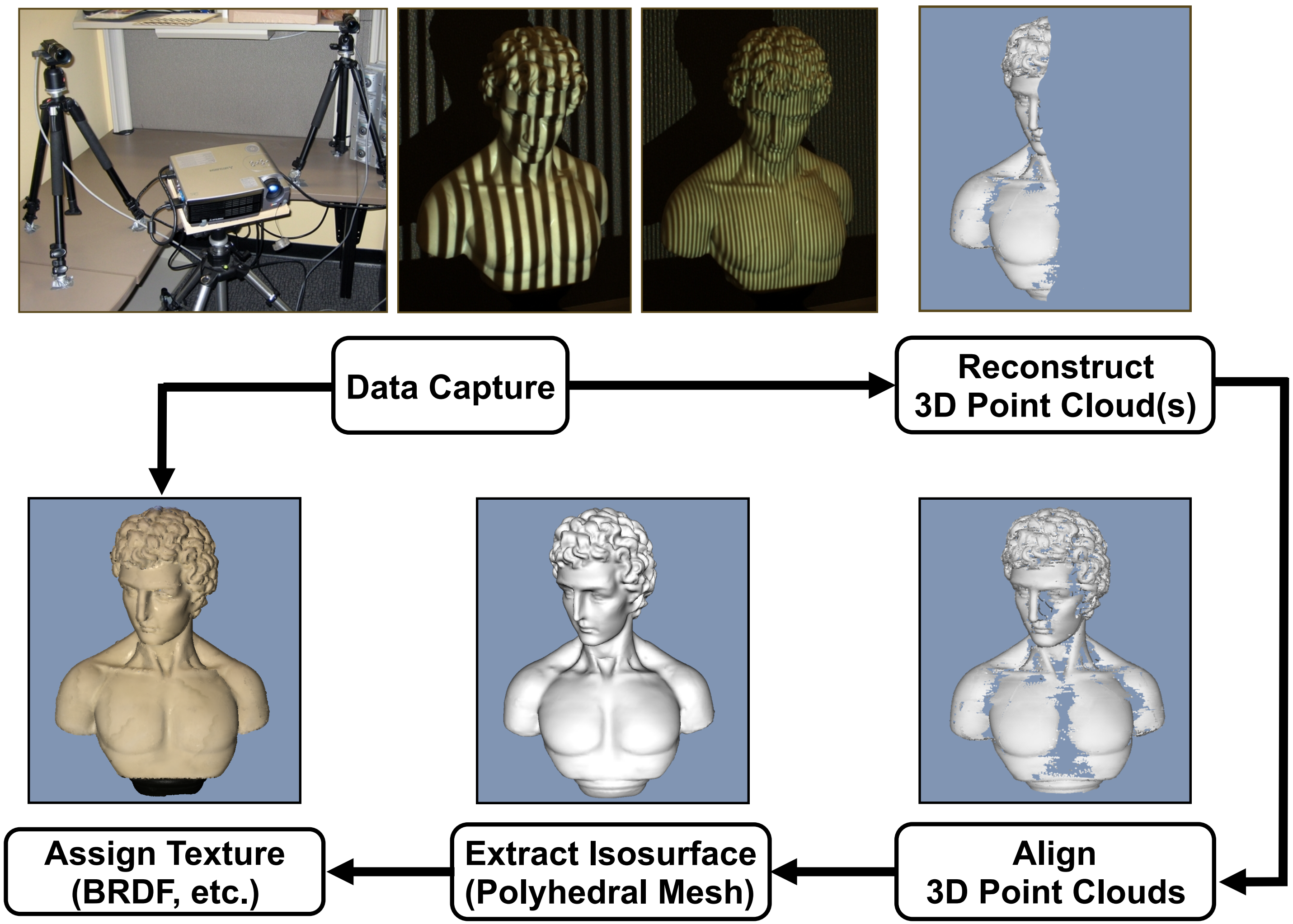


- Must be simultaneously *illuminated* and *imaged* (occlusion problems)
- Non-Lambertian BRDFs (transparency, reflections, subsurface scattering)
- Acquisition time (dynamic scenes), large (or small) features, etc.

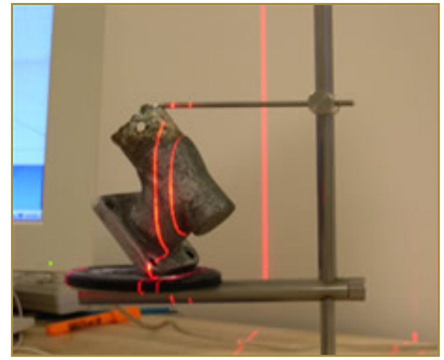
M. Levoy. Why is 3D scanning hard? 3DPVT, 2002

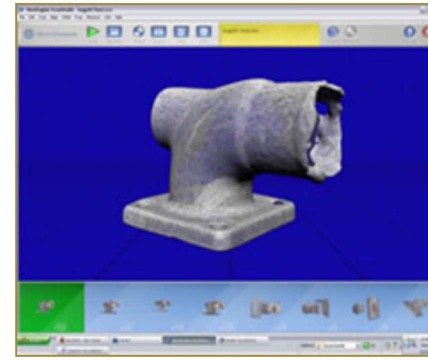
Godin et al. An Assessment of Laser Range Measurement on Marble Surfaces. Intl. Conf. Optical 3D Measurement Techniques, 2001

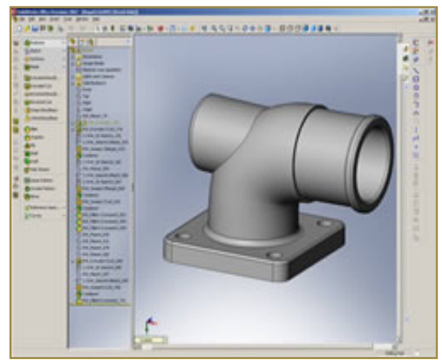
The 3D Scanning Pipeline

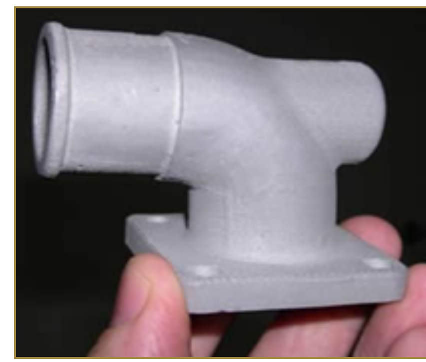


Commercial 3D Scanners









Features, Limitations, and Benefits

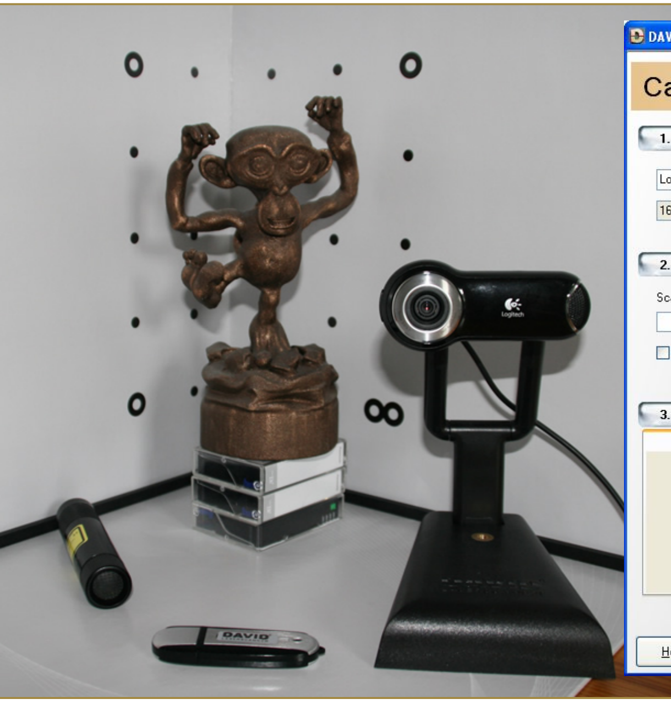
- Most commercial scanners use laser striping + turntables/fiducials
- Cost varies (NextEngine ~$3,000 USD, others more expensive)
- Complete pipeline (including registration and isosurface extraction)

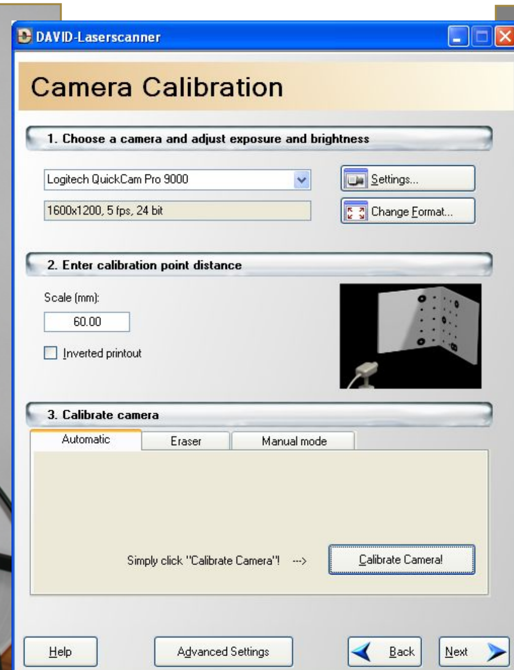
Commercial 3D Scanners

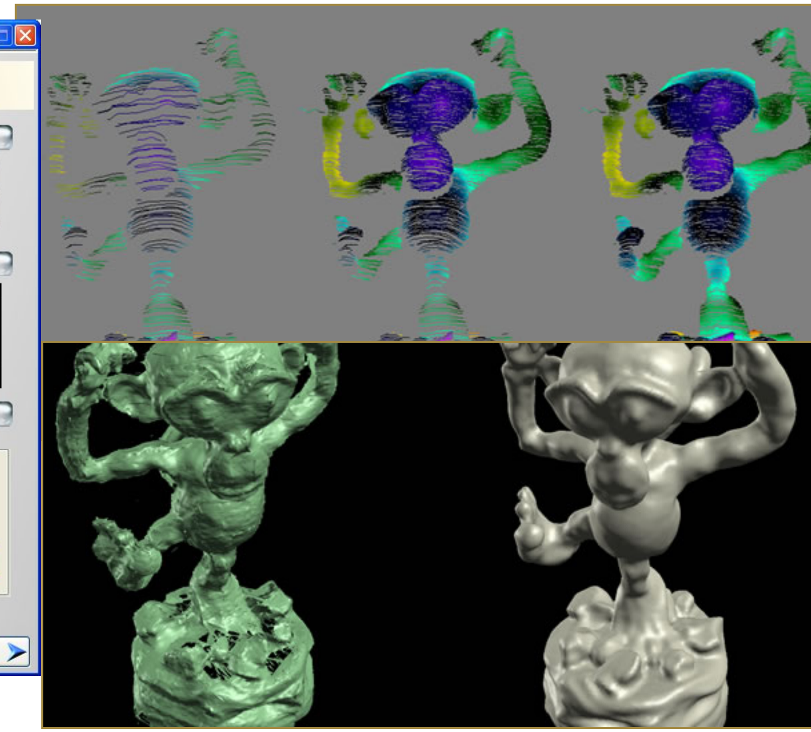
Features, Limitations, and Benefits

- Most commercial scanners use laser striping + turntables/fiducials
- Cost varies (NextEngine ~$3,000 USD, others more expensive)
- Complete pipeline (including registration and isosurface extraction)

Do-It-Yourself (DIY) 3D Scanners



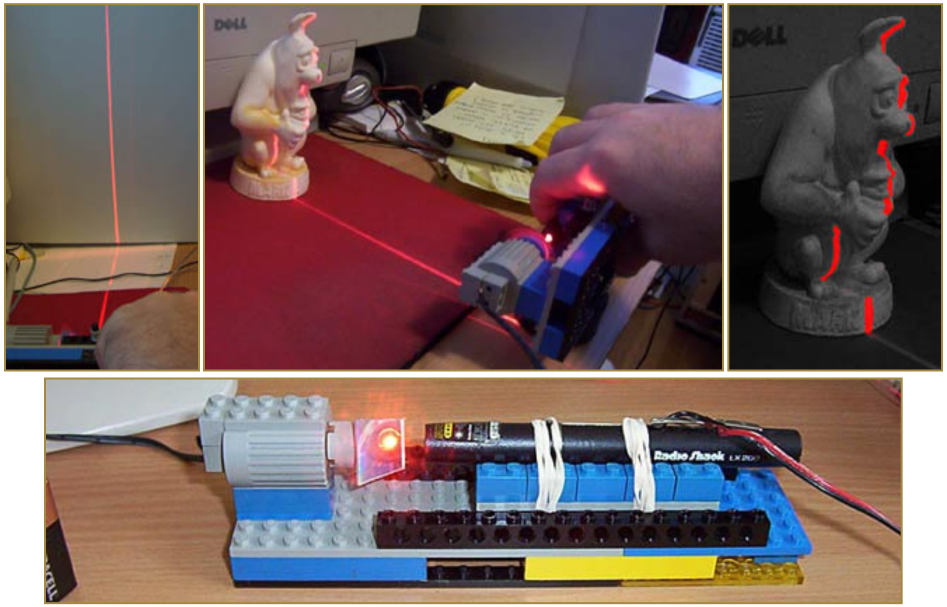


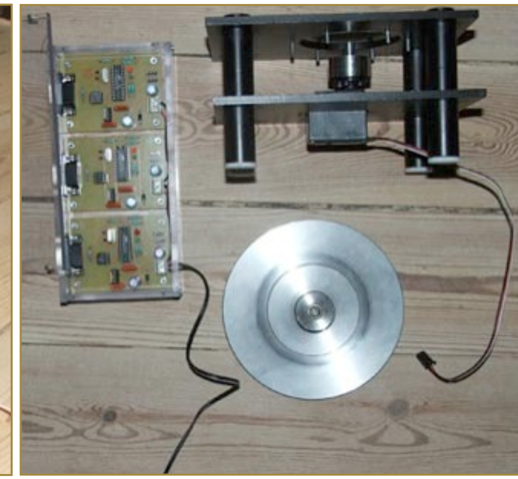


Features, Limitations, and Benefits

- Most DIY scanners also use laser striping + turntables
- Relatively inexpensive (DAVID laser scanner ~$550 USD for starter kit)
- Incomplete pipeline (lacking registration and isosurface extraction)
- Most (but not all) lack proper camera and light source calibration

Do-It-Yourself (DIY) 3D Scanners

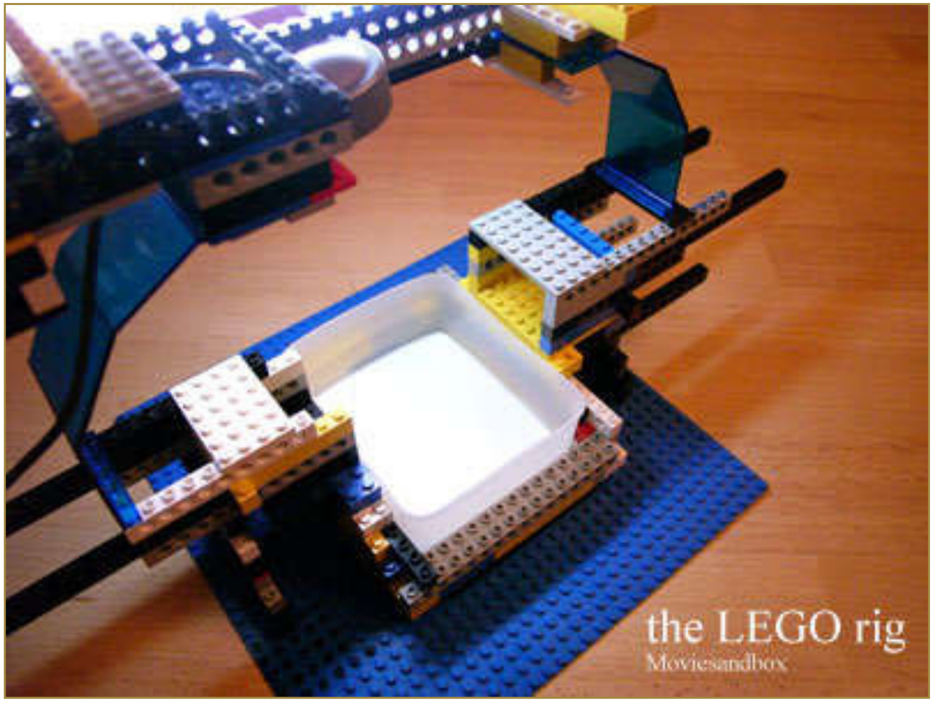




Features, Limitations, and Benefits

- Most DIY scanners also use laser striping + turntables
- Relatively inexpensive (DAVID laser scanner ~$550 USD for starter kit)
- Incomplete pipeline (lacking registration and isosurface extraction)
- Most (but not all) lack proper camera and light source calibration

Do-It-Yourself (DIY) 3D Scanners



Features, Limitations, and Benefits

- Most DIY scanners also use laser striping + turntables
- Relatively inexpensive (DAVID laser scanner ~$550 USD for starter kit)
- Incomplete pipeline (lacking registration and isosurface extraction)
- Most (but not all) lack proper camera and light source calibration

Do-It-Yourself (DIY) 3D Scanners

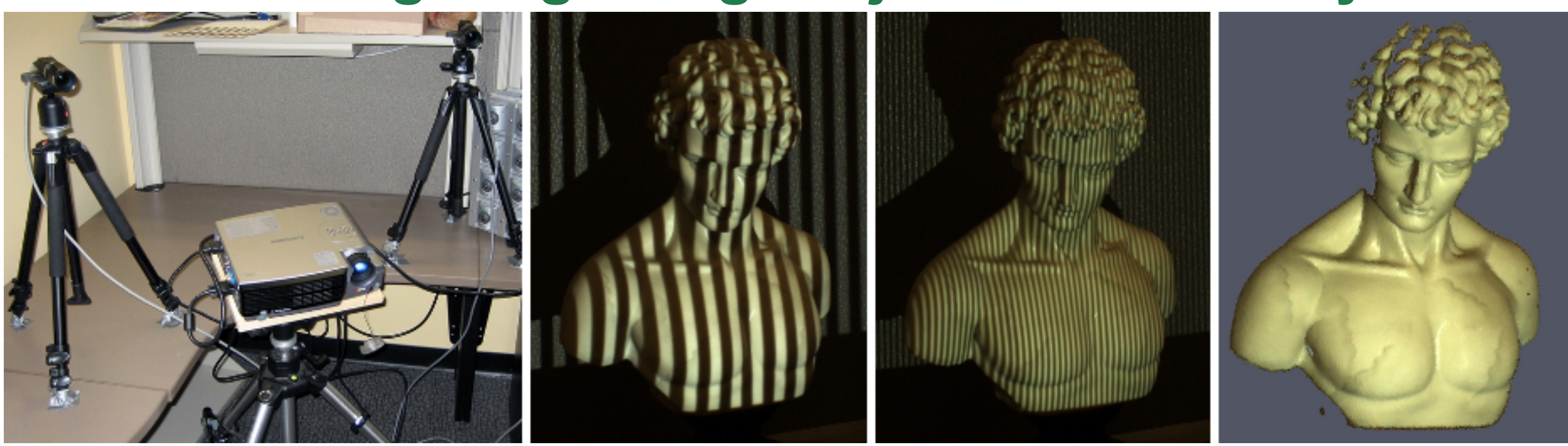
Features, Limitations, and Benefits

- Most DIY scanners also use laser striping + turntables
- Relatively inexpensive (DAVID laser scanner ~$550 USD for starter kit)
- Incomplete pipeline (lacking registration and isosurface extraction)
- Most (but not all) lack proper camera and light source calibration

Topics/Scanners in this Course

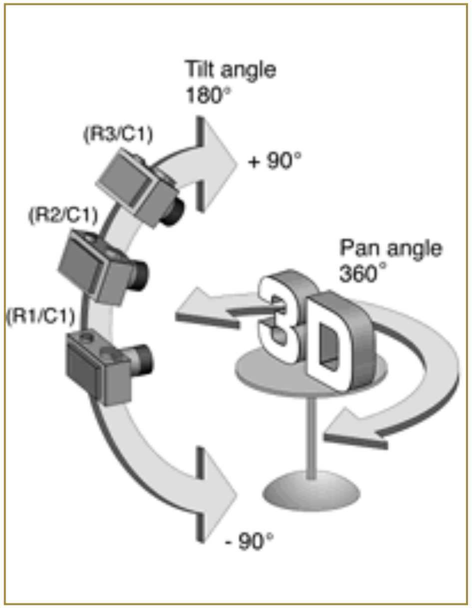
1) Scanning with Swept-Planes

2) Structured Lighting using Projector-Camera Systems



3) Post-processing Pipeline: Registration and Isosurfaces

When not to Scan?



- Scanning is (usually) unnecessary when output is another image!
- Better to use image-based rendering (light fields, QTVR, etc.)

Marc Levoy. Stanford Spherical Gantry. On-line, 2005

Next Class

- Introduction to 3D Scanning
- **The Mathematics of 3D Triangulation**
- 3D Scanning with Swept-Planes | Slit scanner
- Camera and Swept-Plane Light Source Calibration