Active 3D Scanning

COS 429

Princeton University

3D Scanning

The accuracy and completeness of models produced with multi-view stereo of stereo is limited

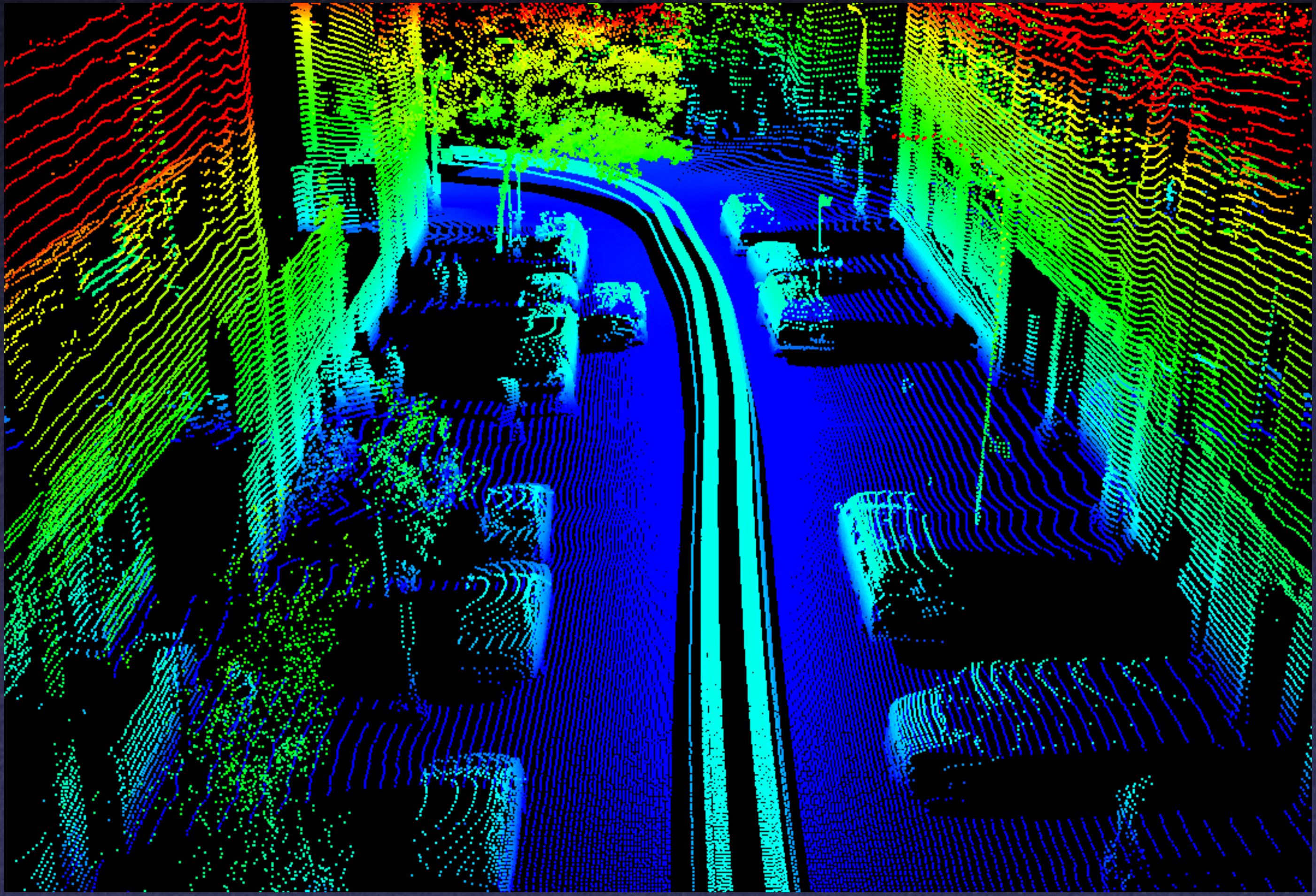
Multiview Stereo

Snavely et al. & Furukawa et al.

Multiview Stereo

Snavely et al. & Furukawa et al.

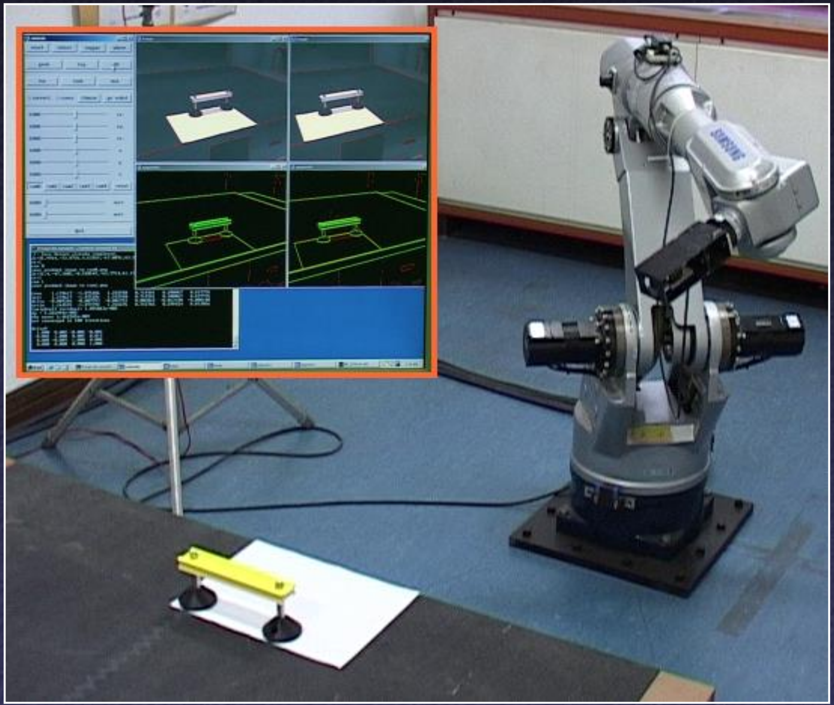
3D Scanning



3D Scanning Applications

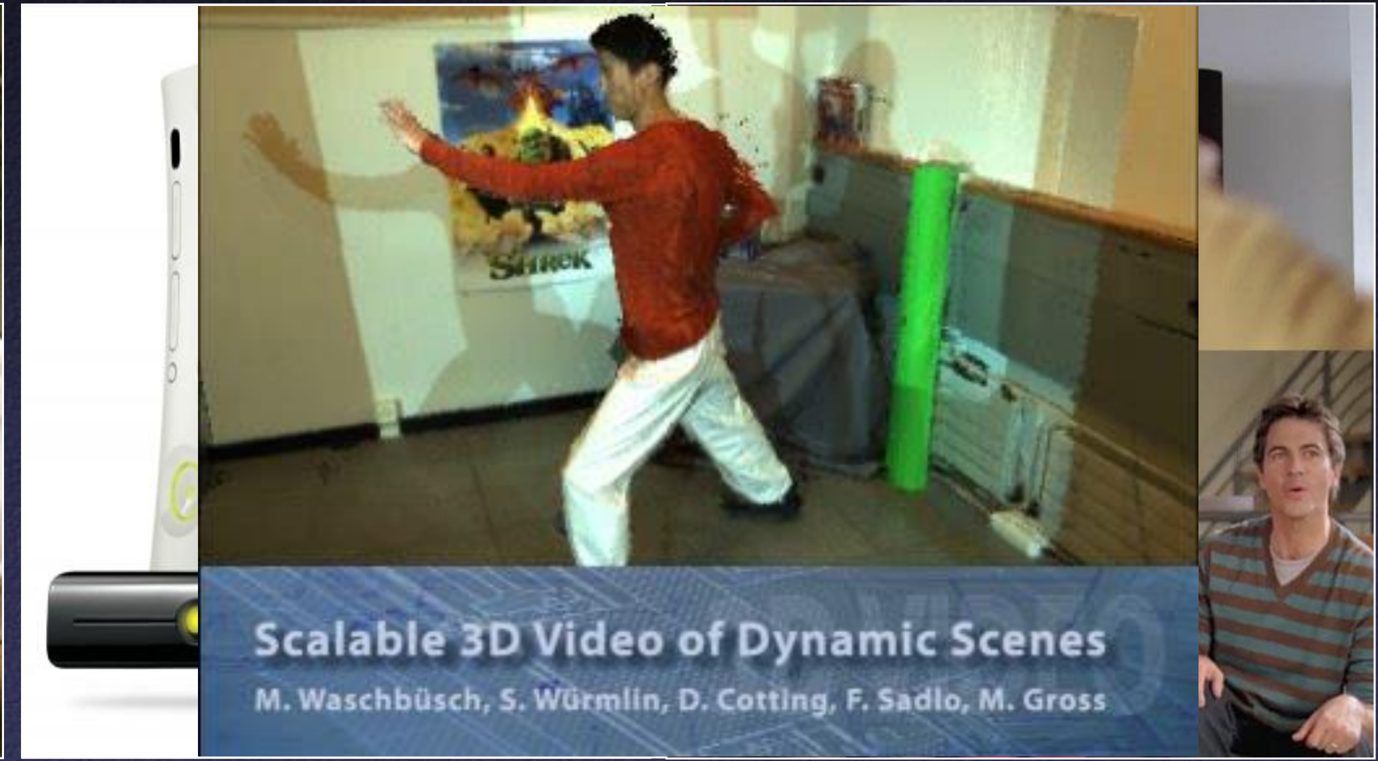
- Computer graphics
- Product inspection
- Robot navigation
- As-built floorplans
- Product design
- Archaeology
- Clothes fitting
- Art history

Robotics

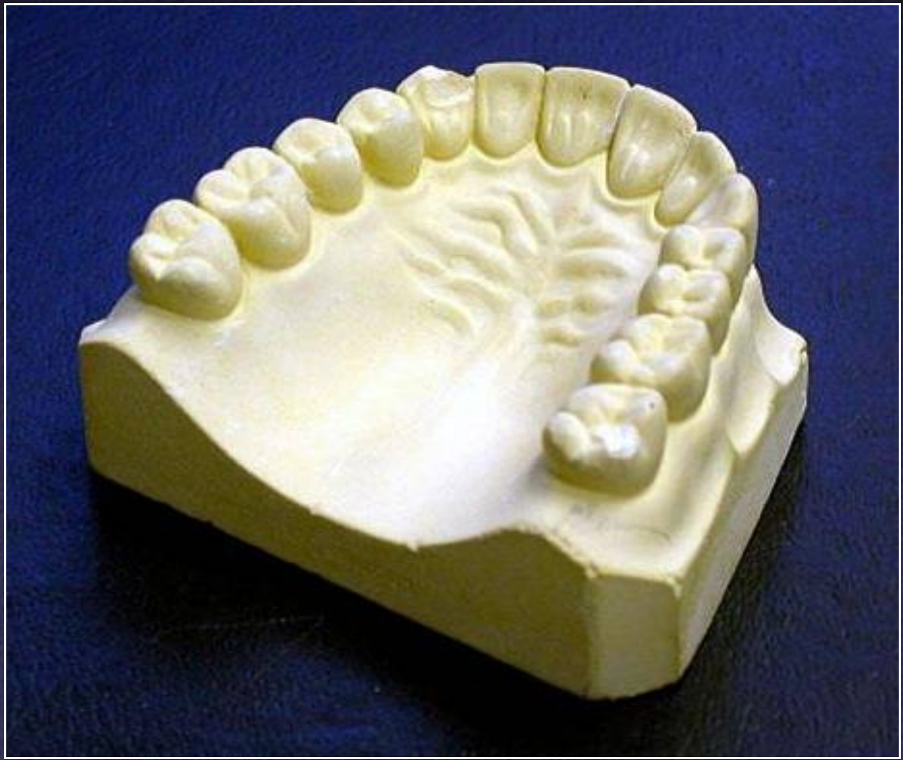


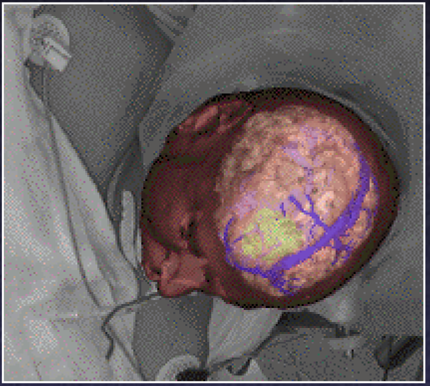
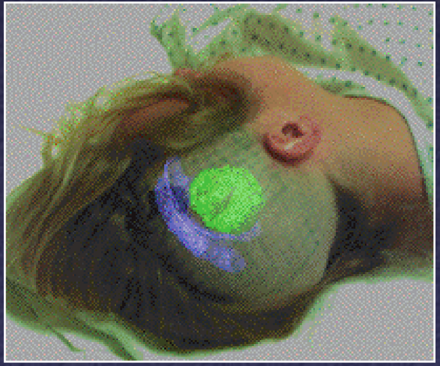
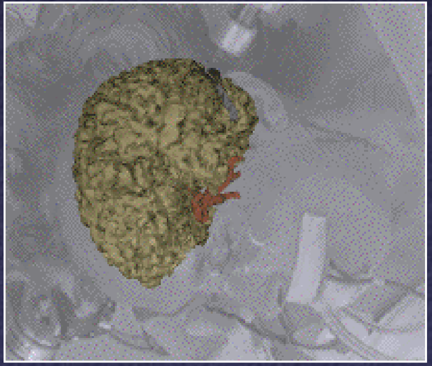
Digital Inspection

Entertainment

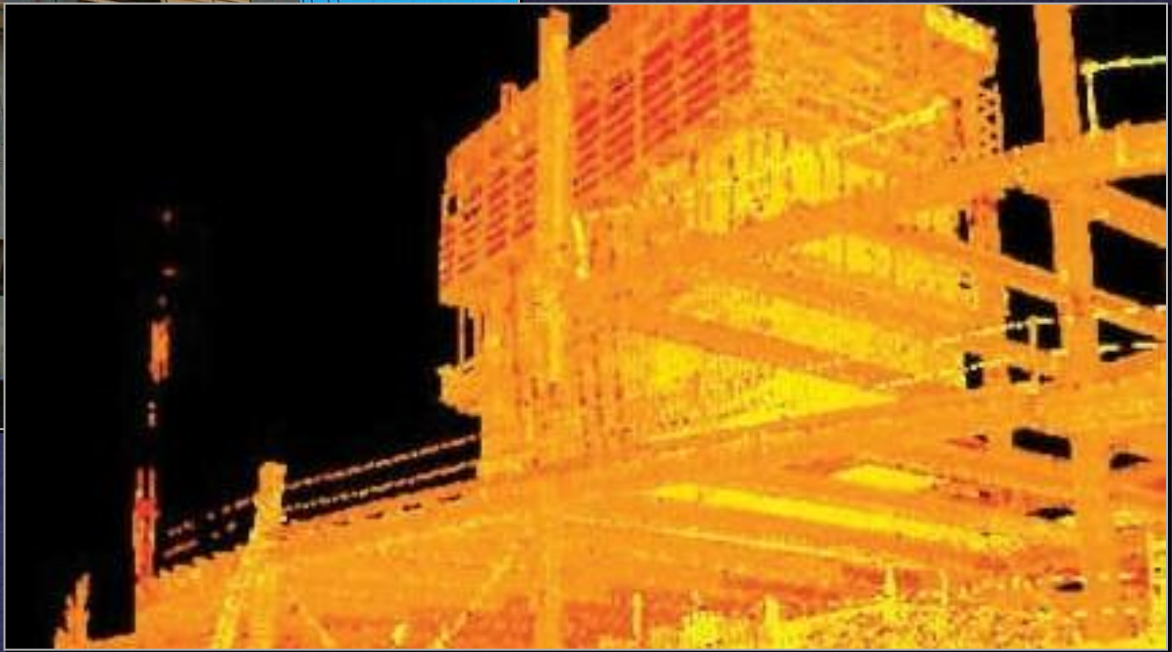


Medical Imaging & Surgical Planning

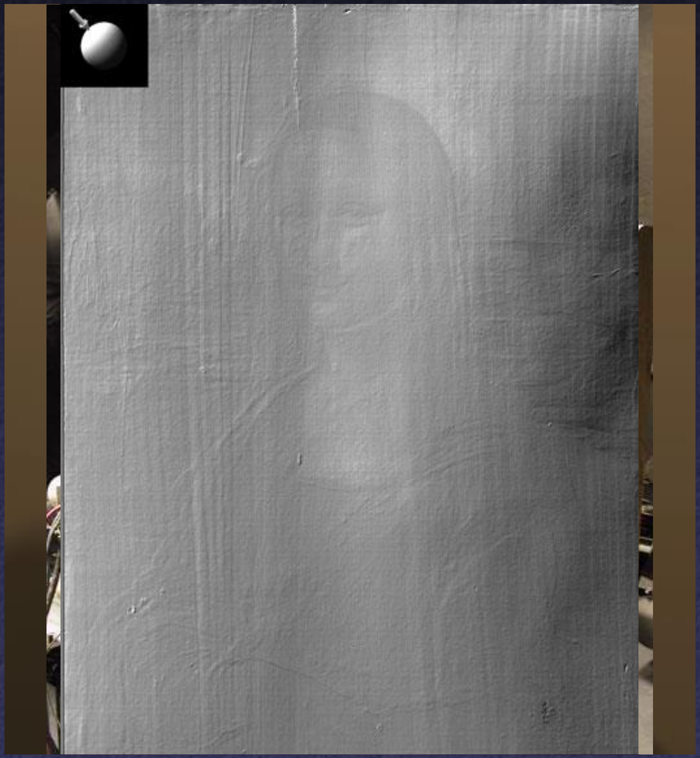


Architecture & Building



Historical Preservation

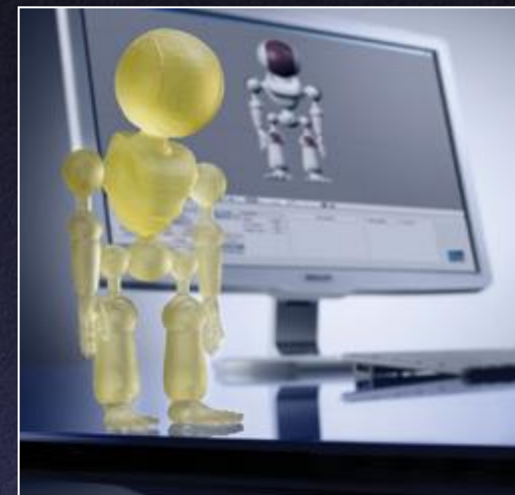


L. Borgeat et al. Visualizing and Analyzing the Mona Lisa. *IEEE Computer Graphics and Applications*, 2007

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

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

3D Printing



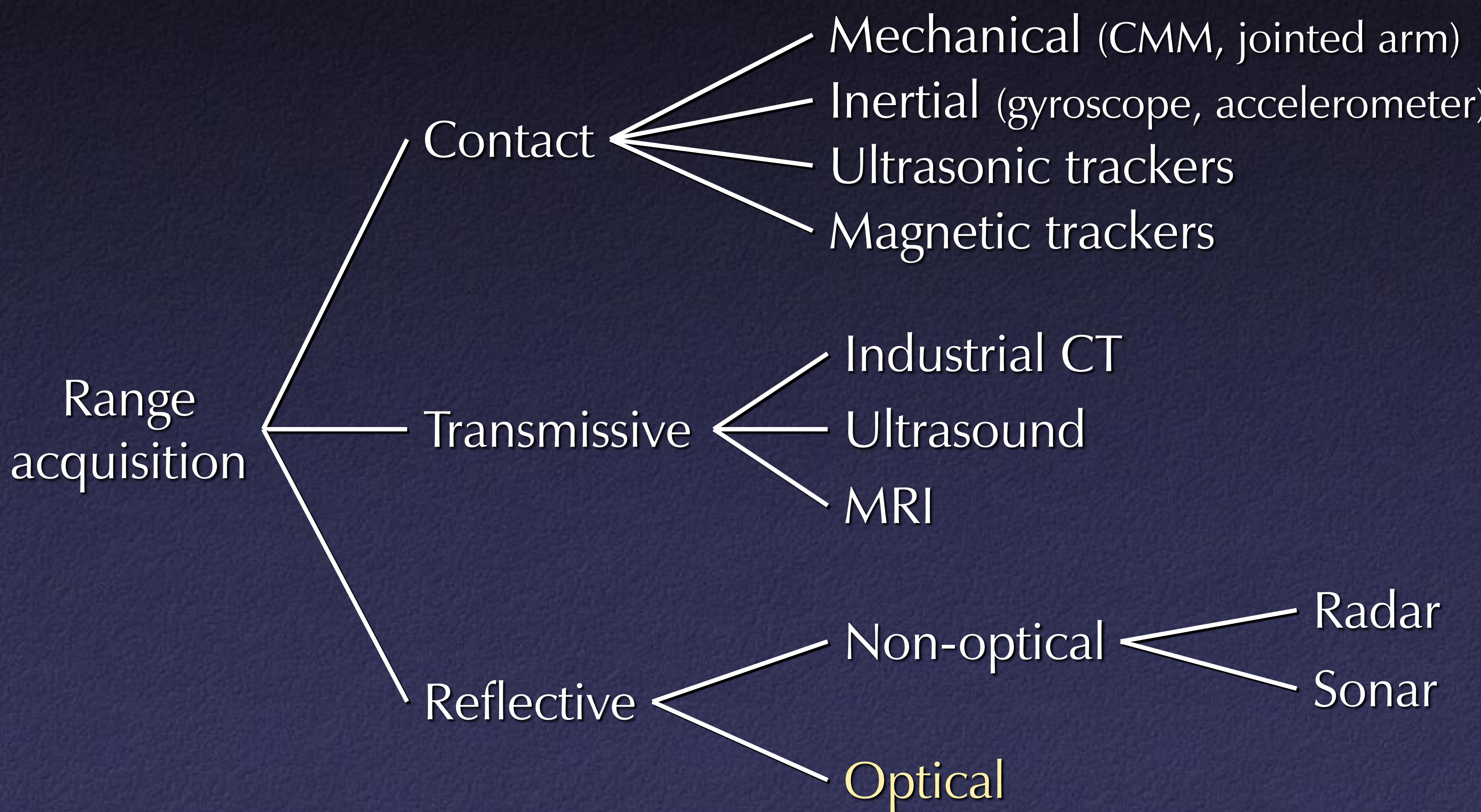
Outline

- 3D scanning methods
- 3D scan processing
- Example applications

Outline

- 3D scanning methods ⟵
- 3D scan processing
- Example applications

3D Scanning Taxonomy



Touch Probes

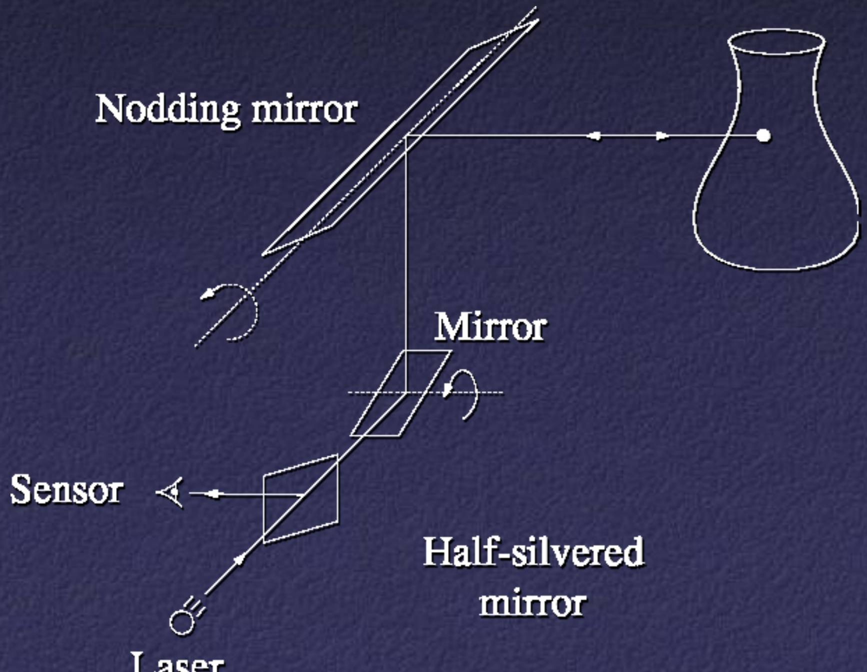
- Jointed arms with angular encoders
- Return position, orientation of tip

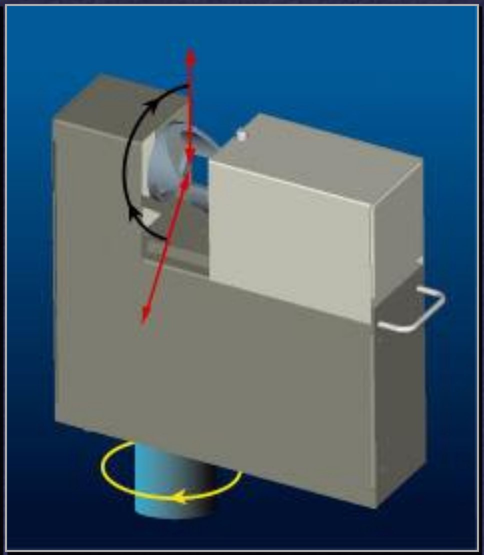
Faro Arm – Faro Technologies, Inc.

Pulsed Time of Flight

- Basic idea: send out pulse of light (usually laser), time how long it takes to return

$$d = \frac{1}{2} c \Delta t$$

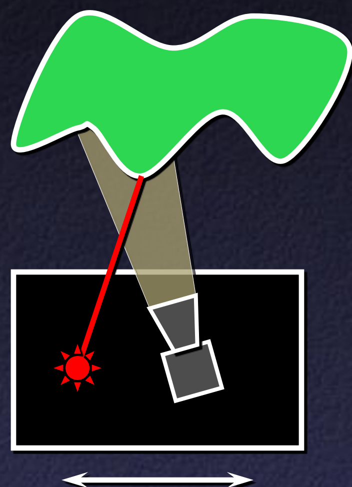


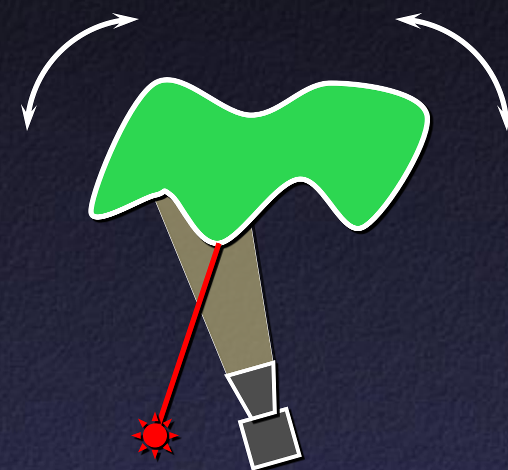


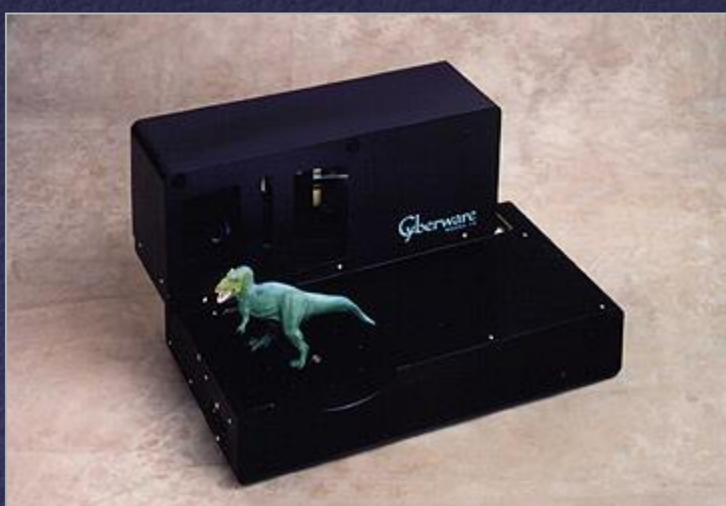
Pulsed Time of Flight

- Advantages:
  - Large working volume (up to 100 m.)
- Disadvantages:
  - Not-so-great accuracy (at best ~5 mm.)
    - Requires getting timing to ~30 picoseconds
    - Does not scale with working volume
- Often used for scanning buildings, rooms, archeological sites, etc.

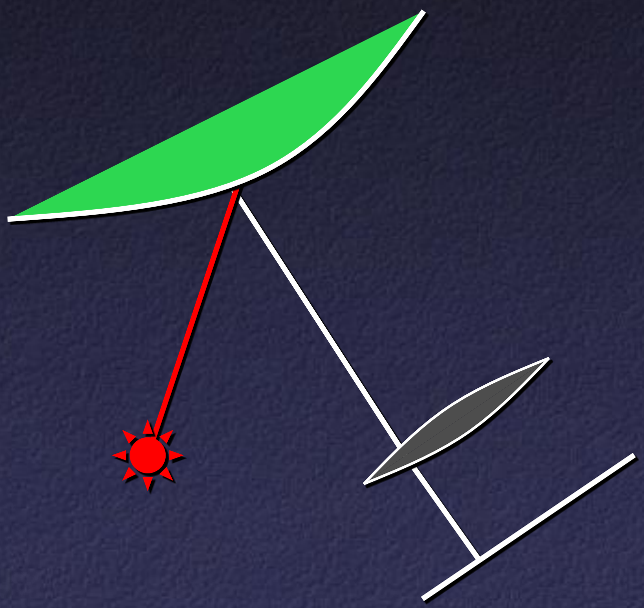
Triangulation







Triangulation



Point Triangulation

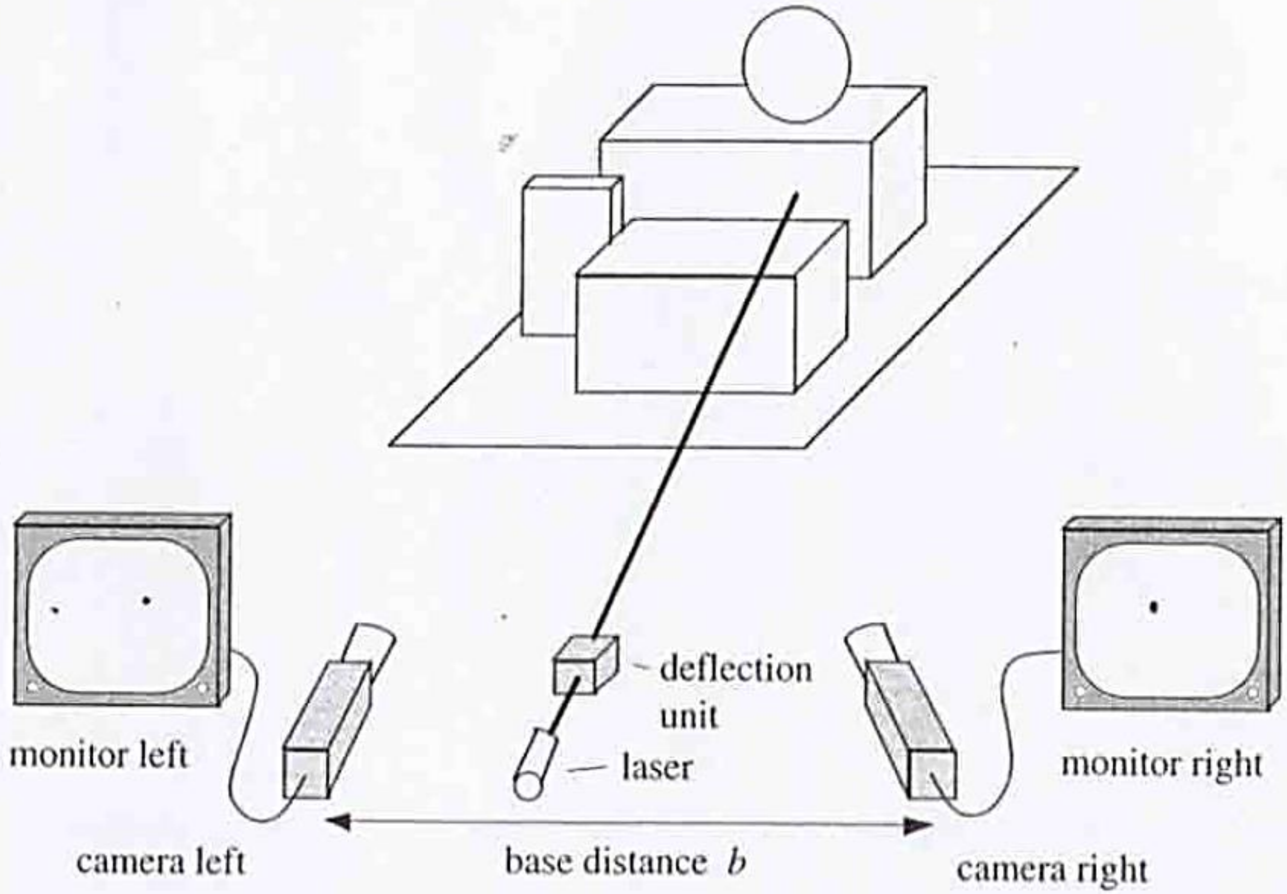
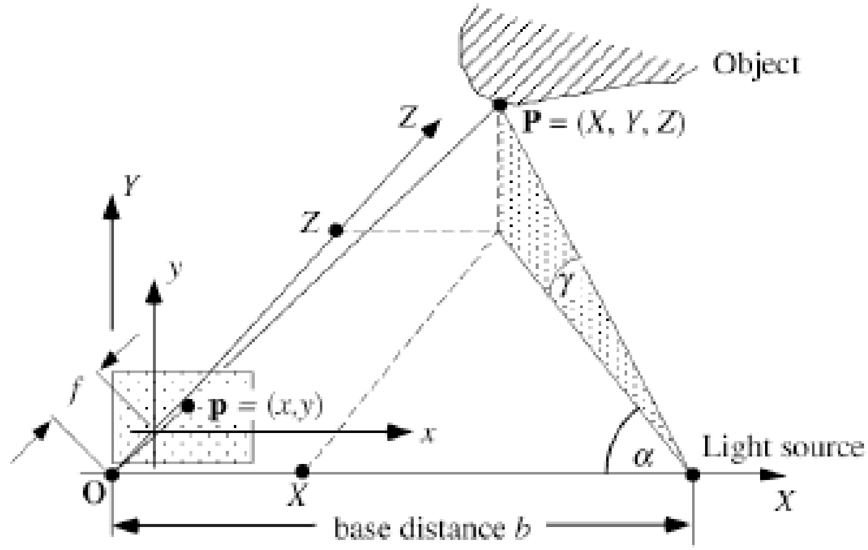


Figure 9.5: General arrangement for a method based on light spot stereo analysis.

Point Triangulation



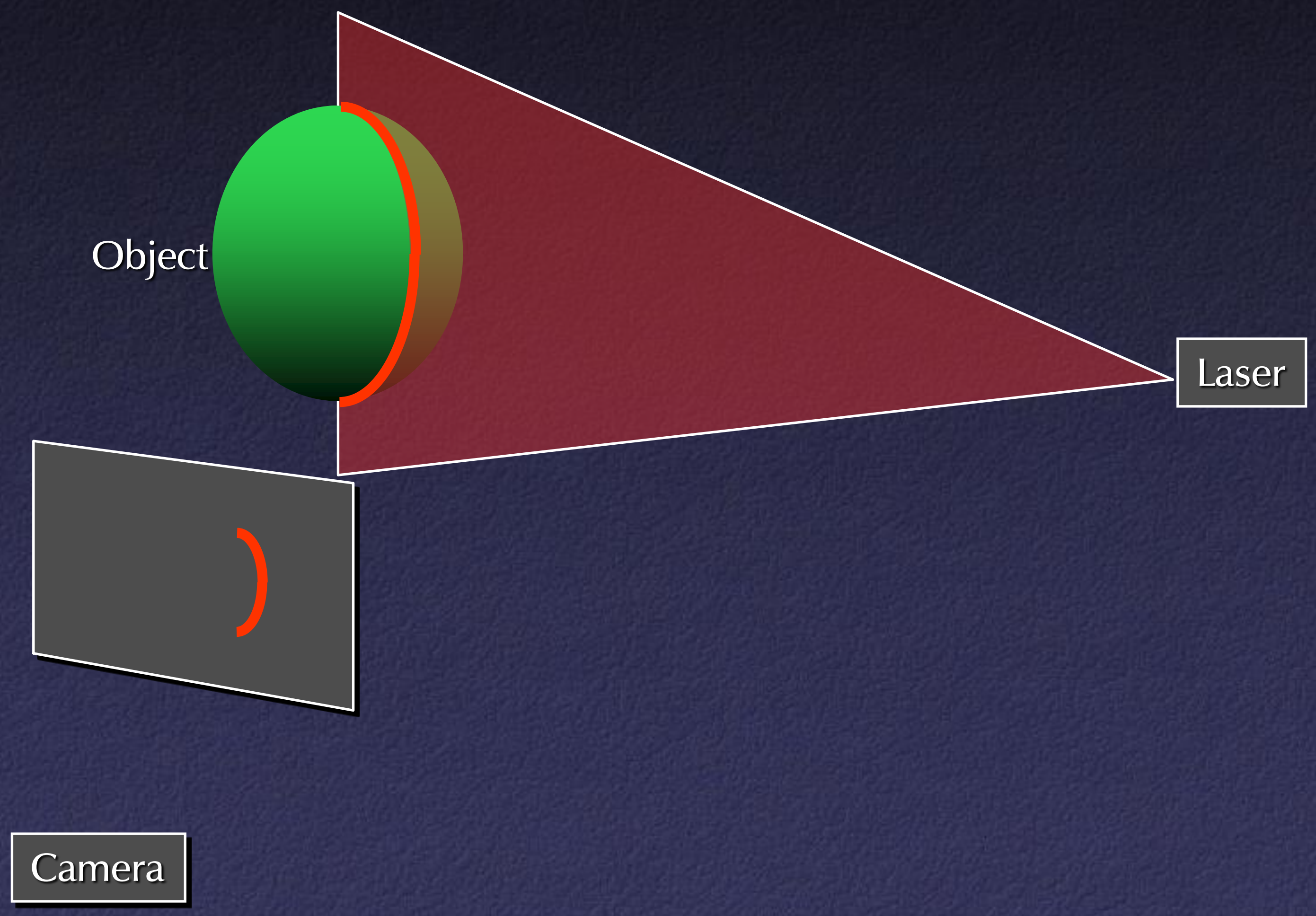
The ray theorem (of central projection) tells us that $\frac{X}{x} = \frac{Z}{f} = \frac{Y}{y}$, and from the trigonometry of right triangles we know that $\tan\alpha = \frac{Z}{b-X}$. It follows that

$$Z = \frac{X}{x} \cdot f = \tan\alpha \cdot (b - X) \quad \text{and} \quad X \cdot \left(\frac{f}{x} + \tan\alpha\right) = \tan\alpha \cdot b$$

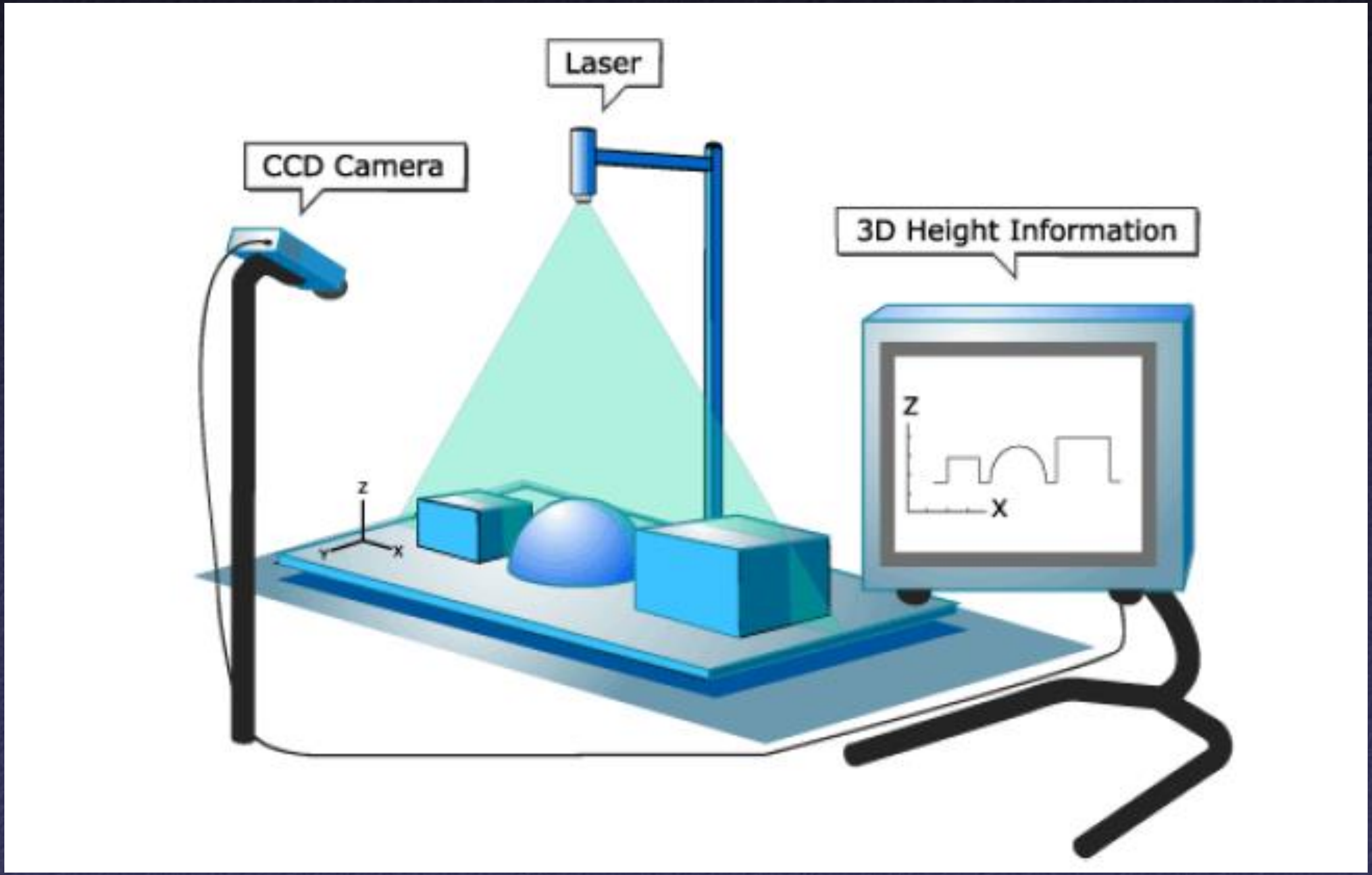
The solution is

$$X = \frac{\tan\alpha \cdot b \cdot x}{f + x \cdot \tan\alpha}, \; Y = \frac{\tan\alpha \cdot b \cdot y}{f + x \cdot \tan\alpha}, \; Z = \frac{\tan\alpha \cdot b \cdot f}{f + x \cdot \tan\alpha}$$

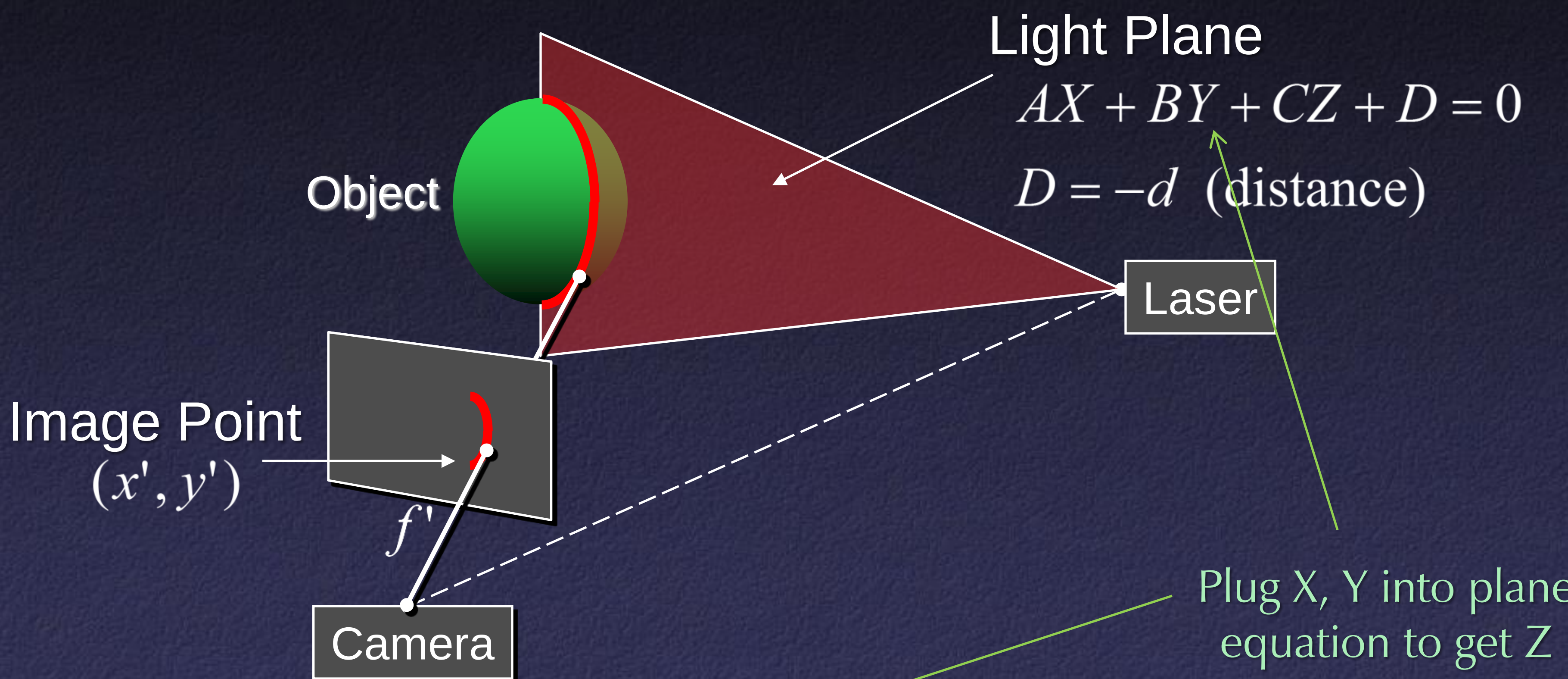
Stripe Triangulation



Stripe Triangulation



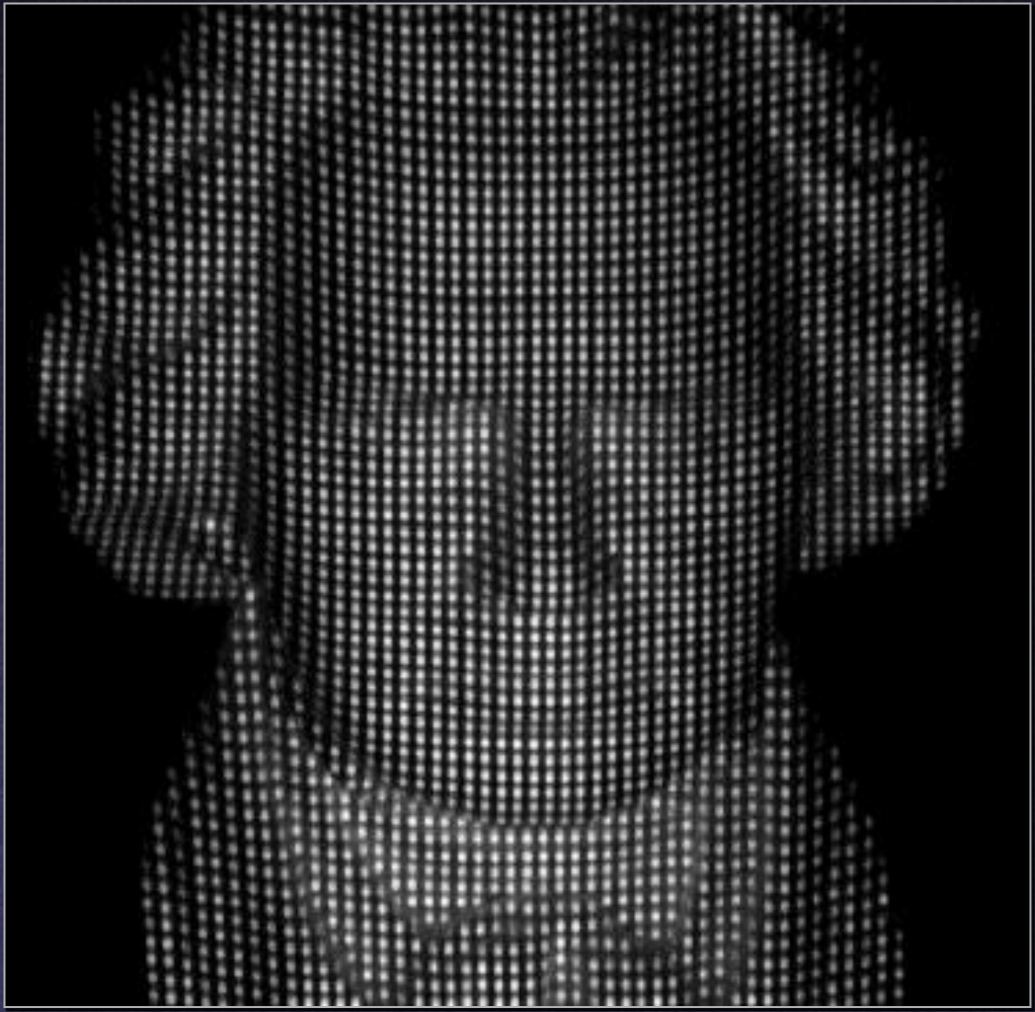
Stripe Triangulation



$$X = x'Z / f'$$
$$Y = y'Z / f'$$
$$Z = \frac{-Df'}{Ax' + By' + Cf'}$$

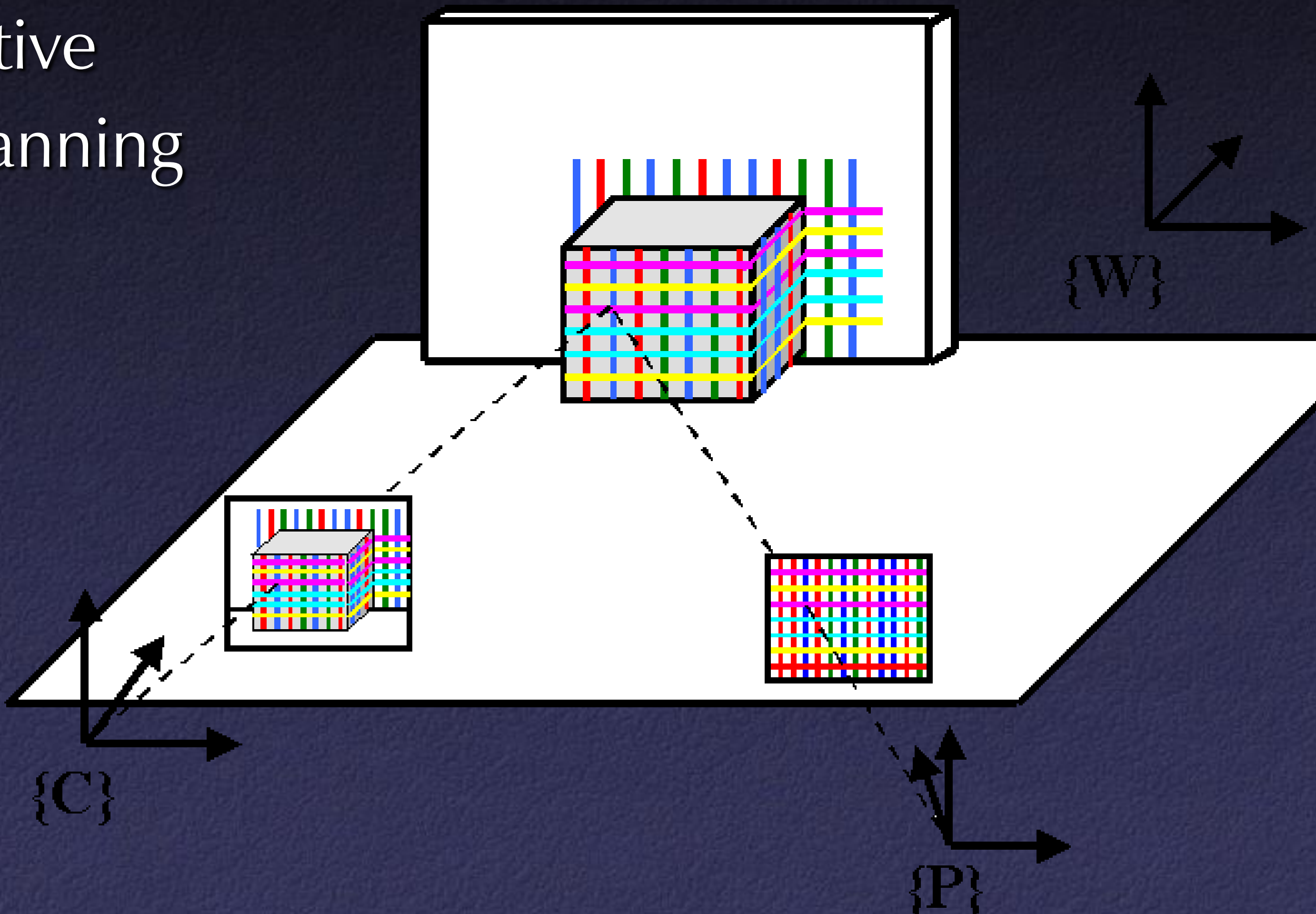
Courtesy S. Narasimhan, CMU

Multi-Stripe Triangulation



Color-Coded Stripe Triangulation

Active Scanning

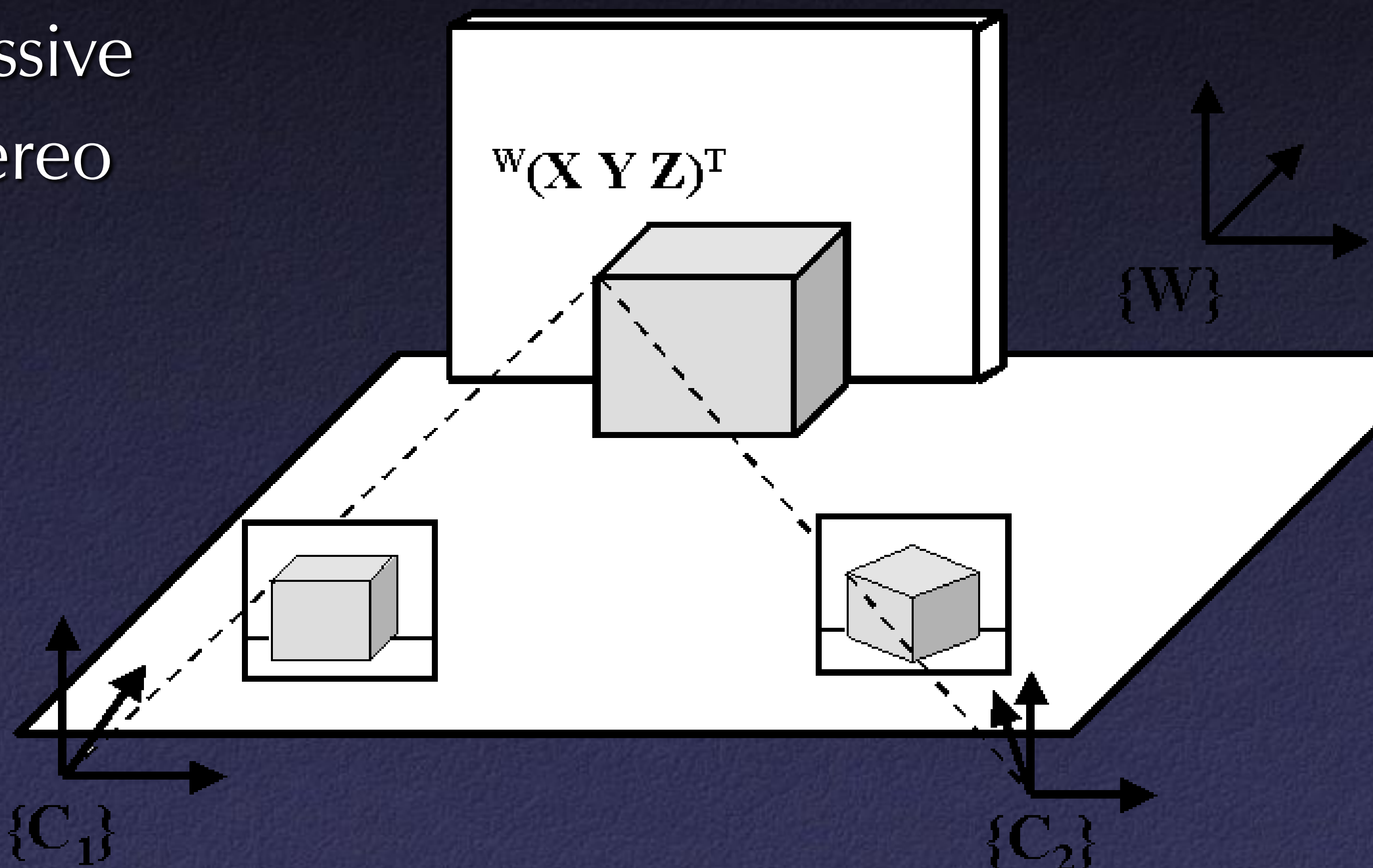


Zhang et al, 3DPVT 2002

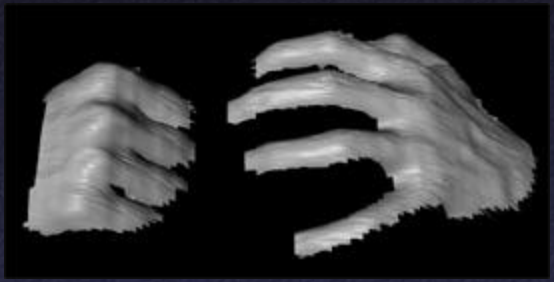
Stereo Triangulation

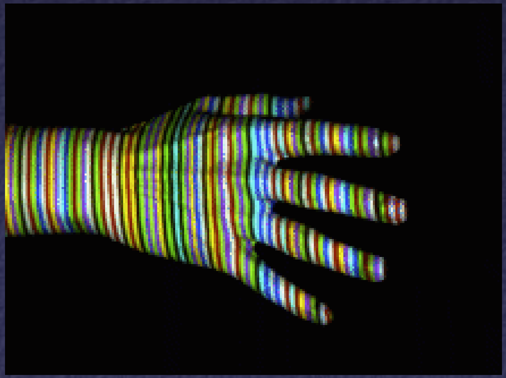
Passive

Stereo



Color-Coded Stripe Triangulation

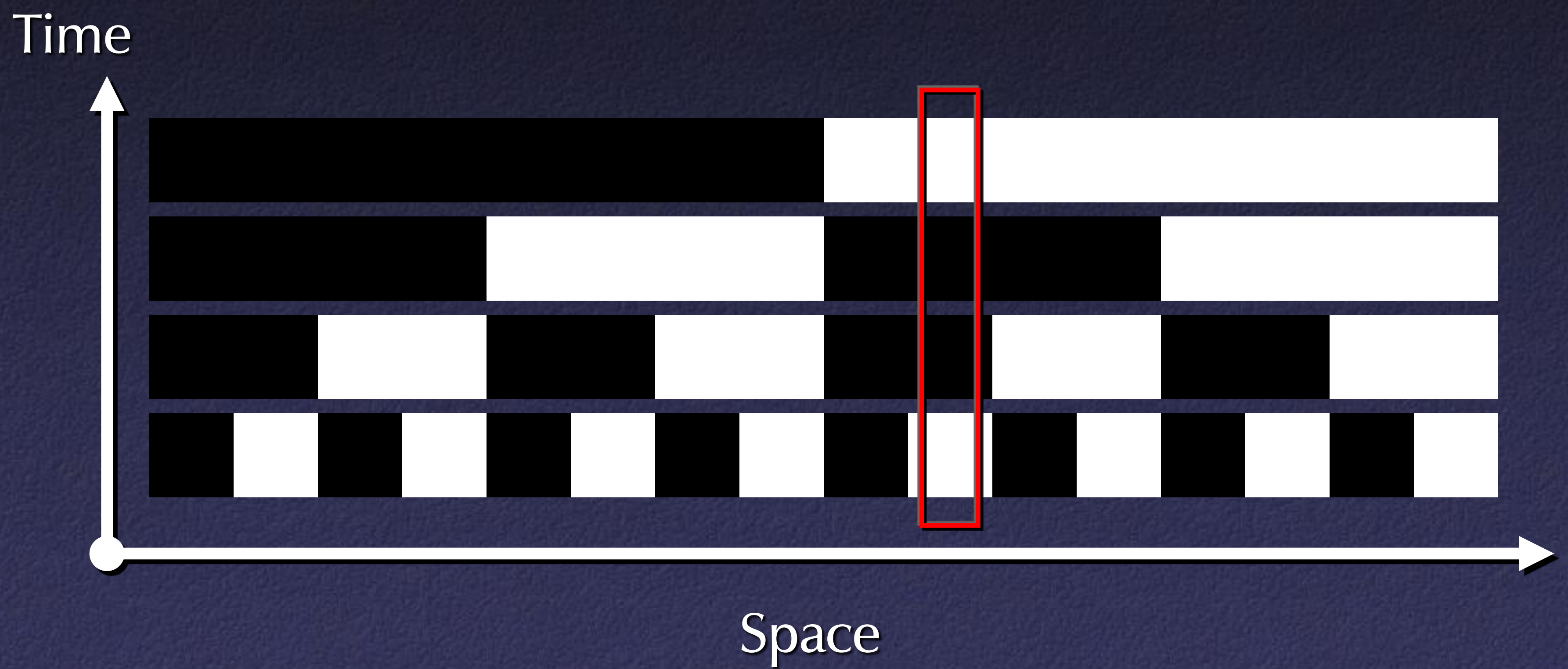




Zhang et al, 3DPVT 2002

Time-Coded Stripe Triangulation

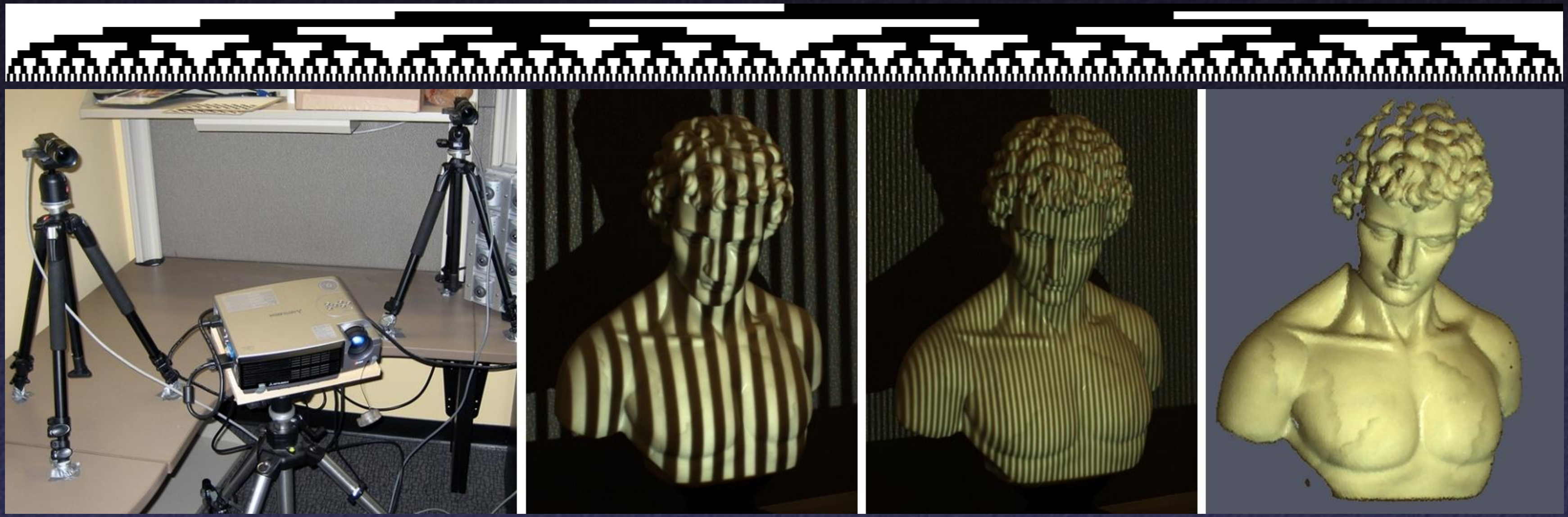
Assign each stripe a unique illumination code over time



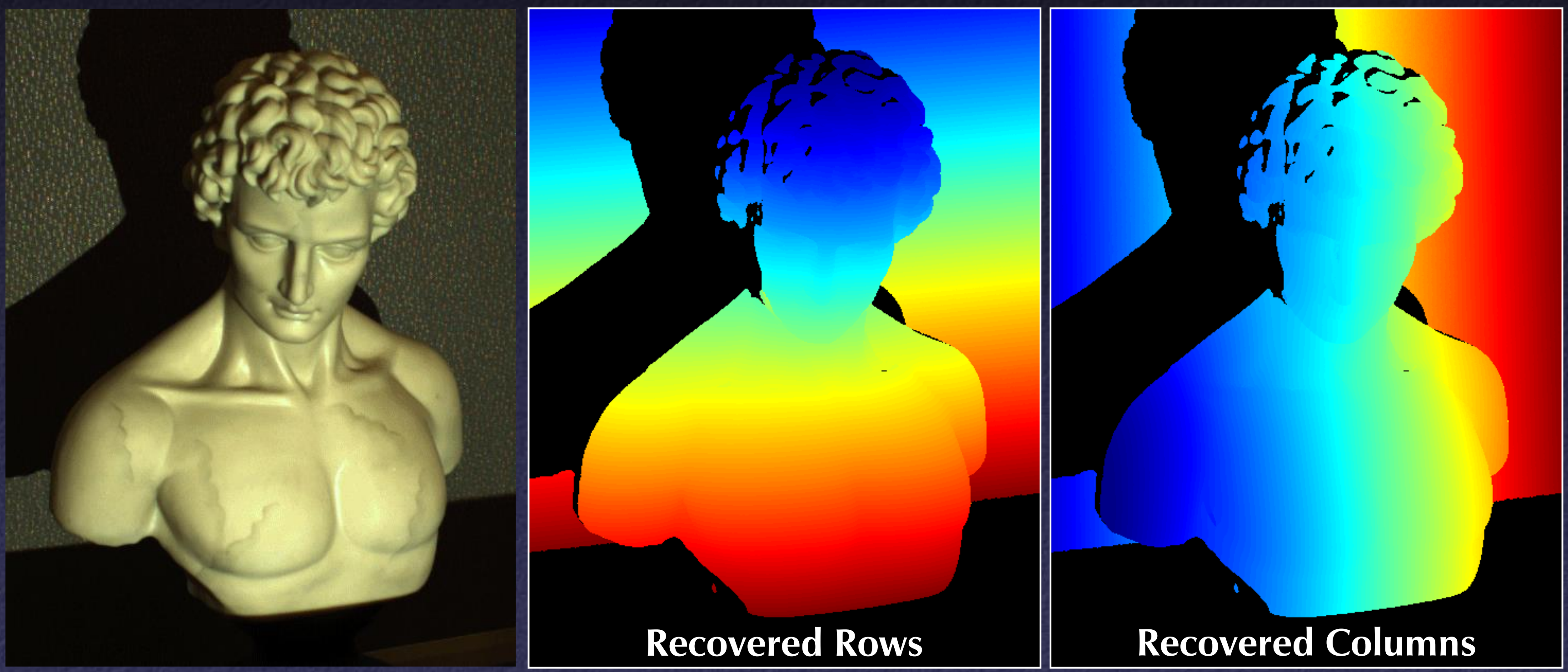
[Posdamer 82]

Time-Coded Stripe Triangulation

Time-Coded Stripe Triangulation

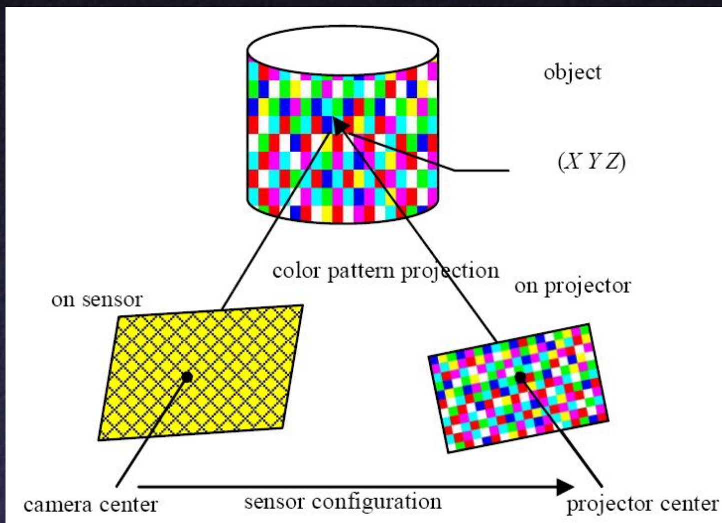


Time-Coded Stripe Triangulation

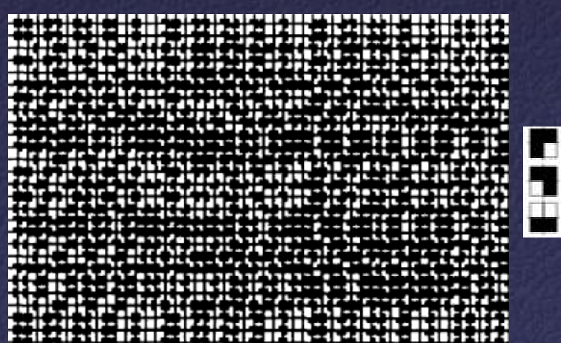


3D Reconstruction using Structured Light [Inokuchi 1984]

Structured Light Patterns

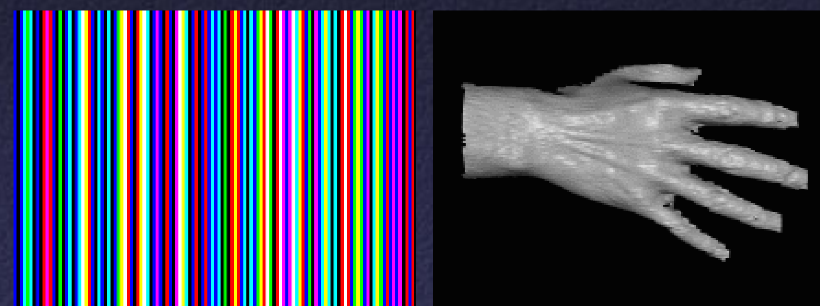


Spatial encoding strategies [Chen et al. 2007]

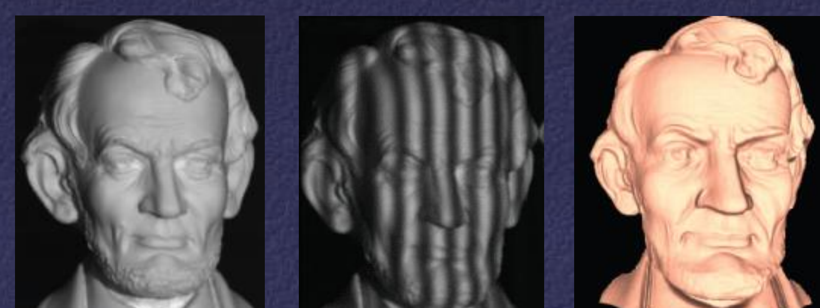


Pseudorandom and M-arrays [Griffin 1992]

“Single-shot” patterns (N-arrays, grids, random, etc.)



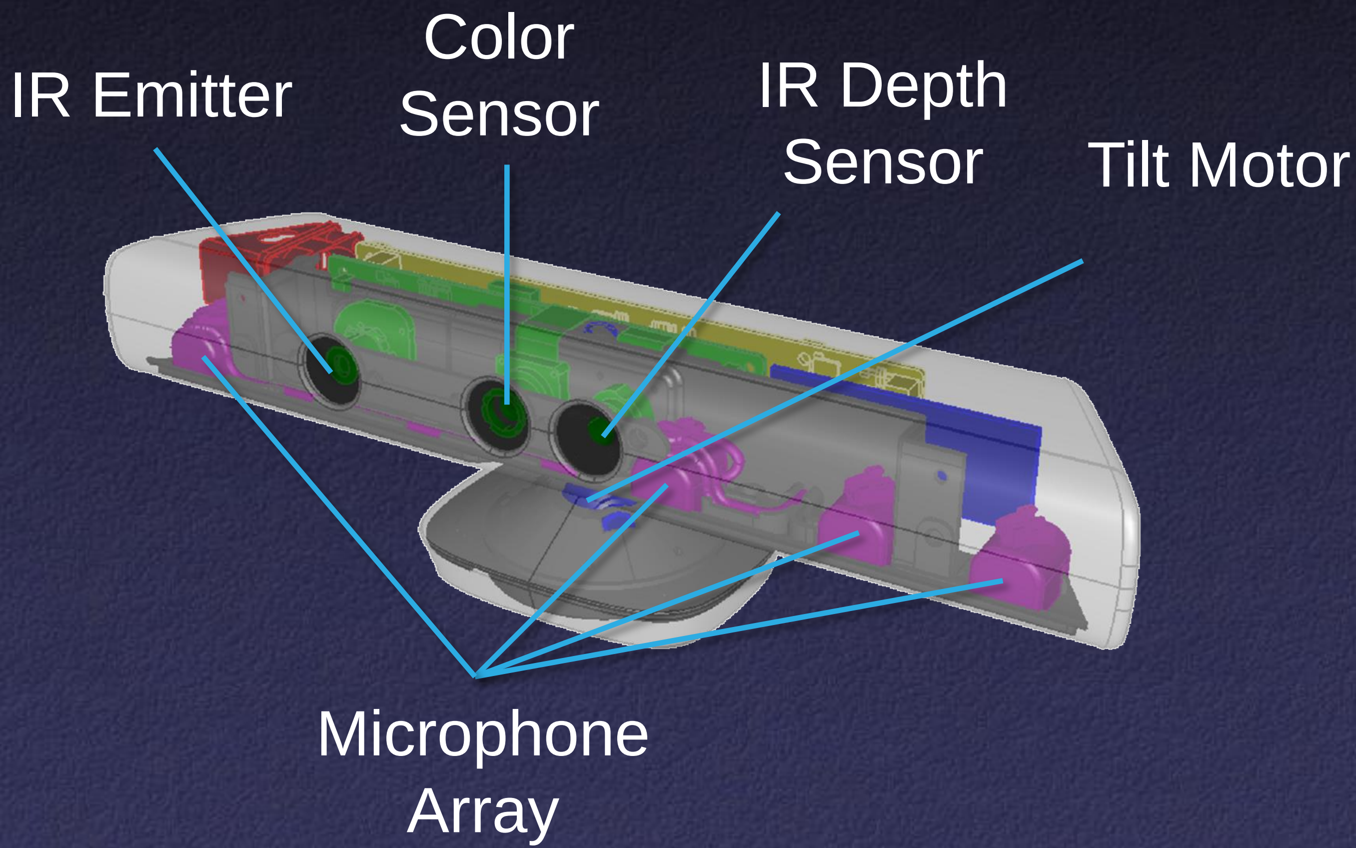
De Bruijn sequences [Zhang et al. 2002]



Phase-shifting [Zhang et al. 2004]

J. Salvi, J. Pagès, and J. Batlle. Pattern Codification Strategies in Structured Light Systems. *Pattern Recognition*, 2004

Kinect


IR Emitter
Color Sensor
IR Depth Sensor
Tilt Motor
Microphone Array

Kinect

Projected IR Pattern

Kinect

Depth Map

RGB Image

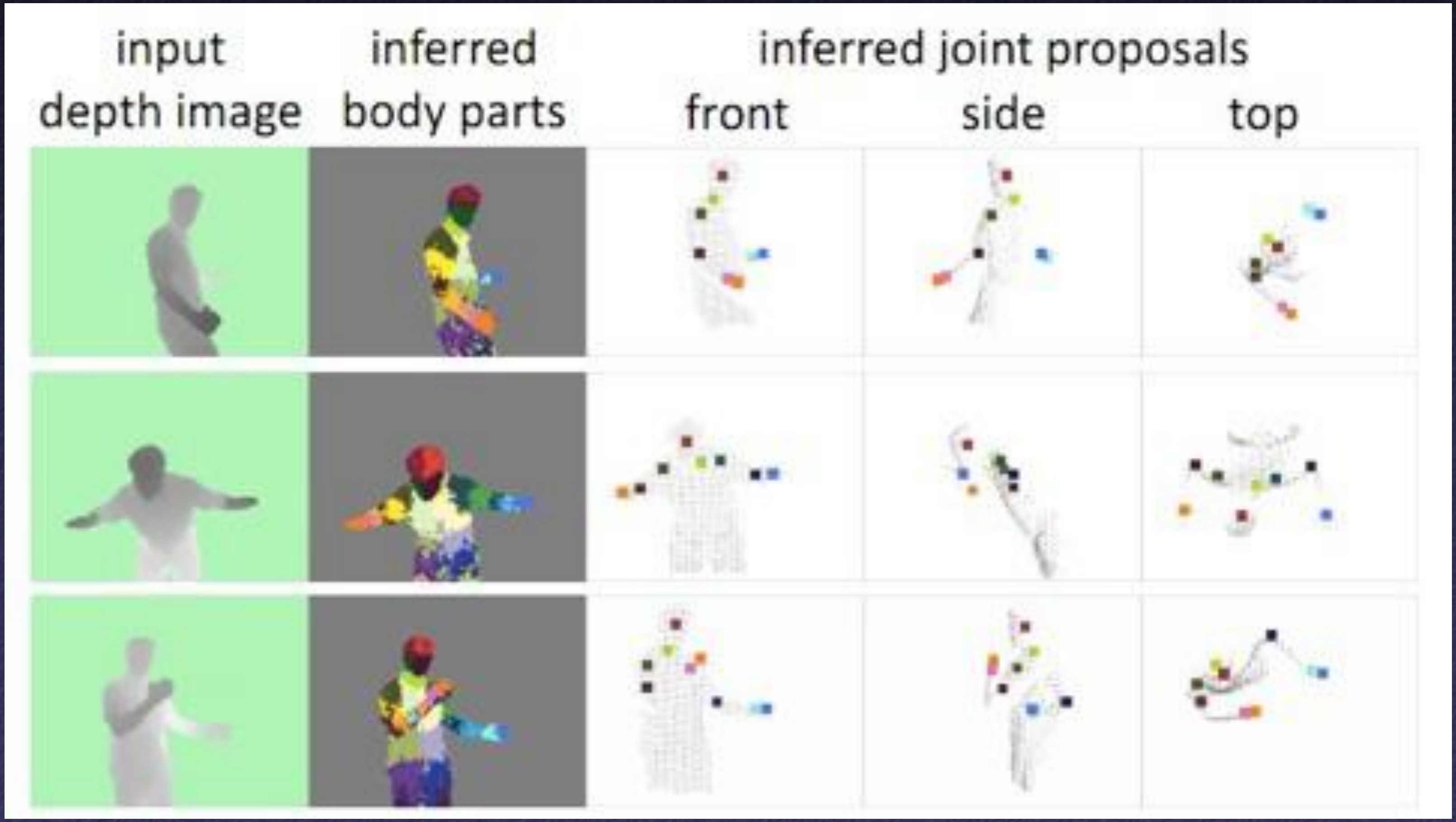
Kinect

http://www.youtube.com/watch?v=uq9SEJxZiUg

Kinect

http://users.dickinson.edu/~jmac/selected-talks/kinect.pdf

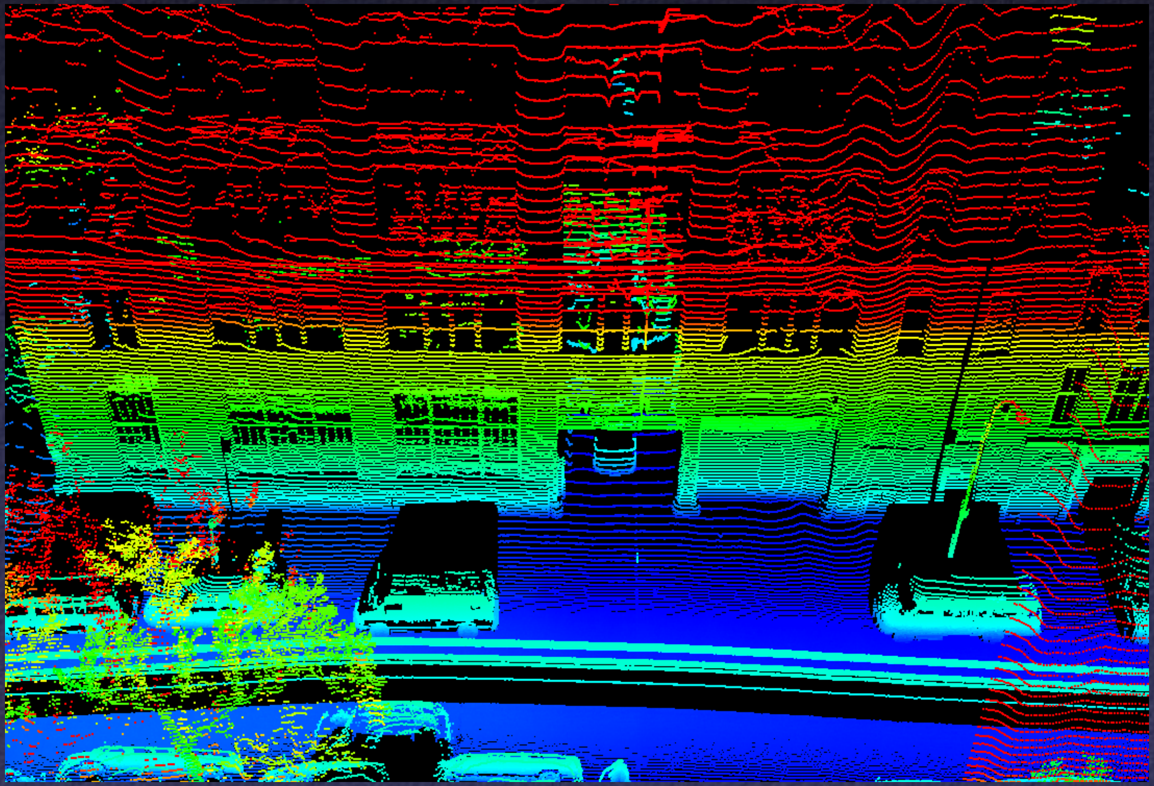
Kinect



Shotton, Fitzgibbon, Cook, Sharp, Finocchio, Moore, Kipman, Blake,
Real-Time Human Pose Recognition in Parts from a Single Depth Image, *CVPR*

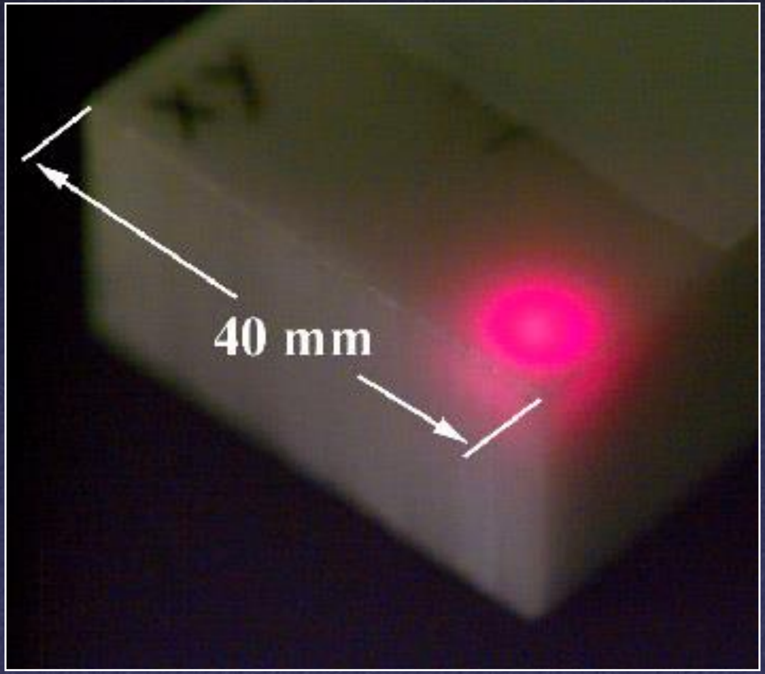
Active Scanner Issues

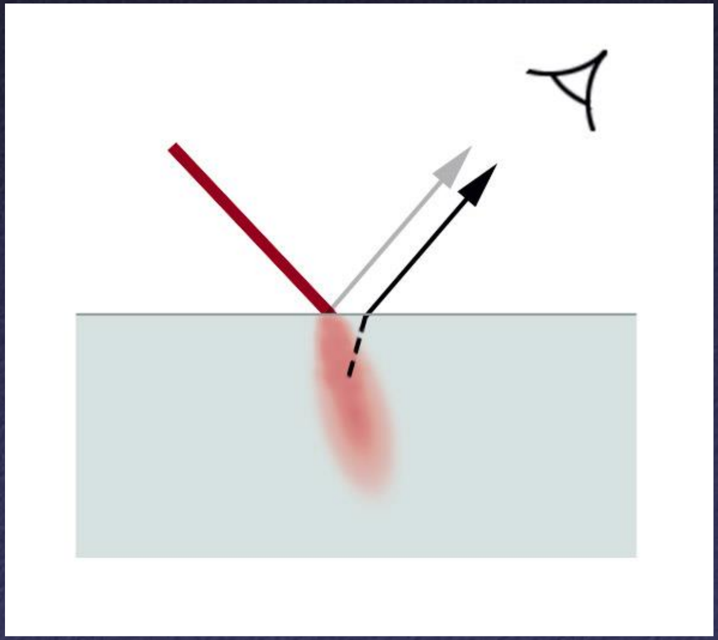
- Material properties (dark, specular)



Triangulation Scanner Issues

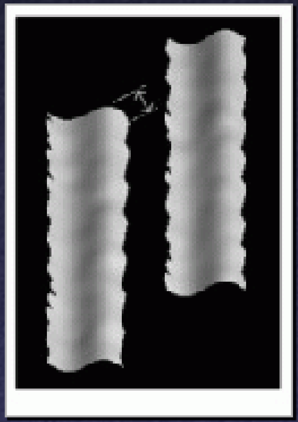
- Material properties (dark, specular)
- Subsurface scattering





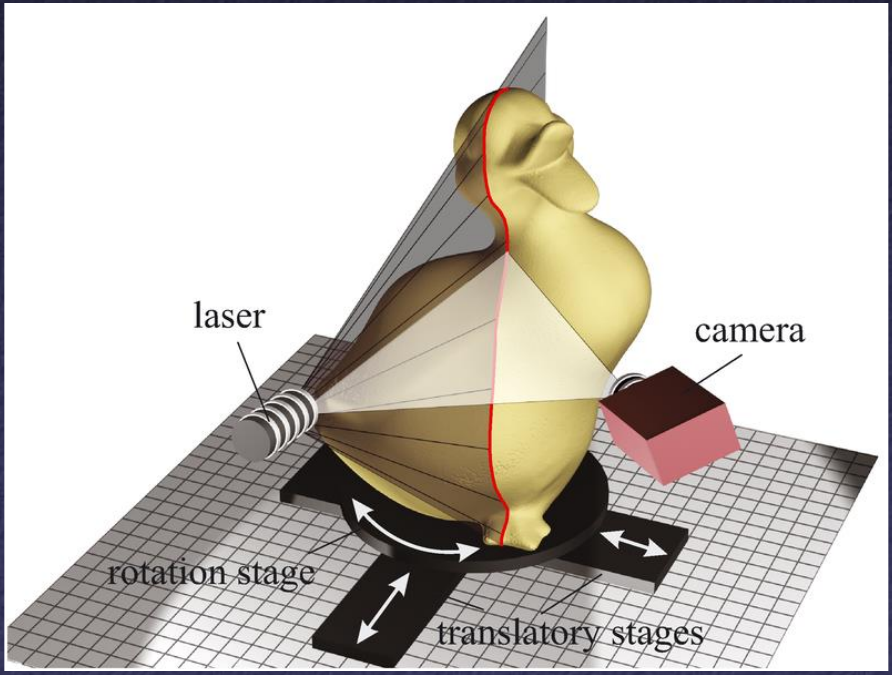
Triangulation Scanner Issues

- Material properties (dark, specular)
- Subsurface scattering
- Laser speckle
- Edge curl
- Texture embossing



Triangulation Scanner Issues

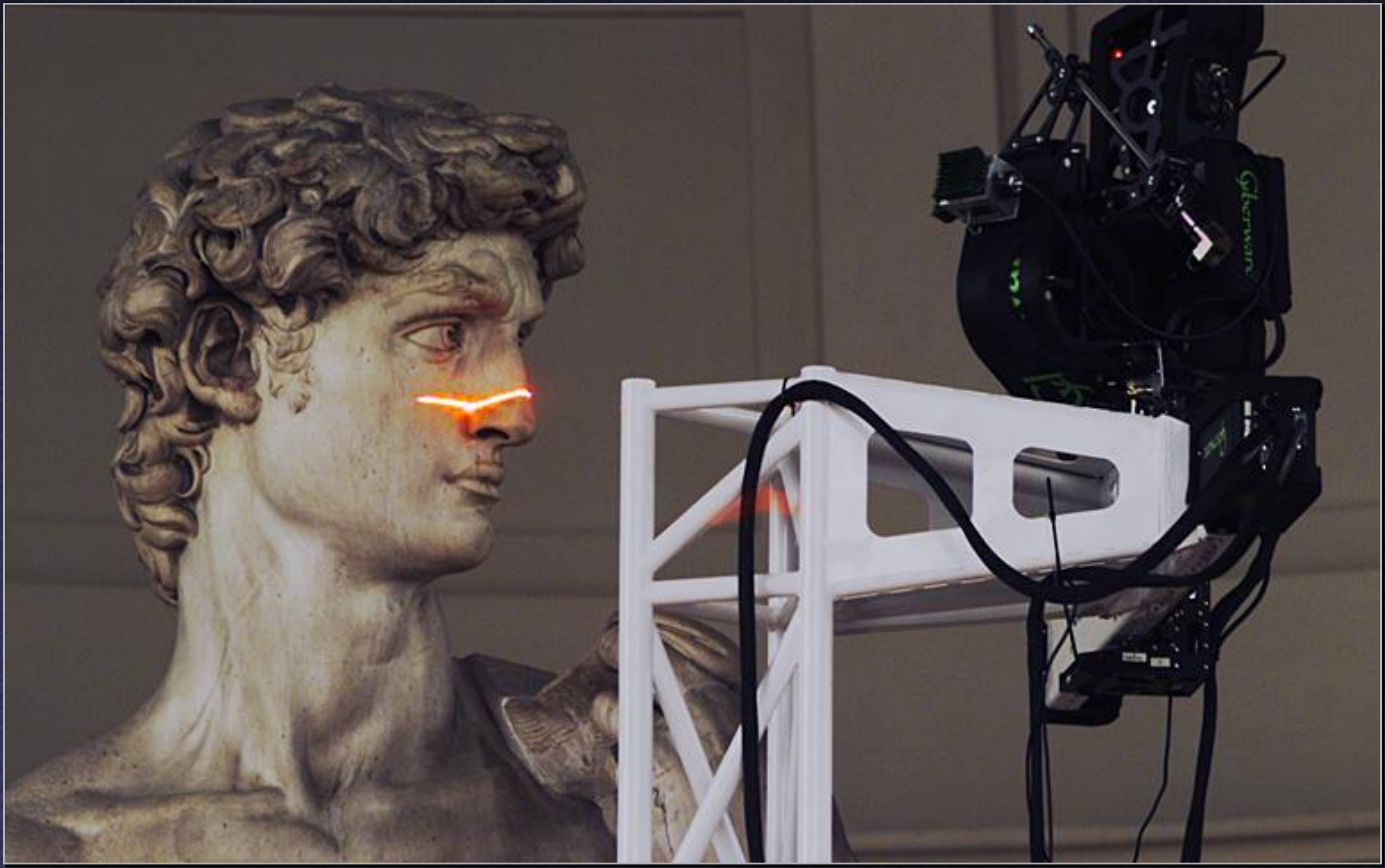
- Small working volume (baseline too large…)
- Triangulation angle: non-uniform resolution if too small, shadowing if too big (useful range: 15°-30°)
- Two-line-of-sight problem (shadowing from either camera or laser)



Outline

- 3D scanning methods
- 3D scan processing ⟵
- Example applications

3D Scan Processing Pipeline



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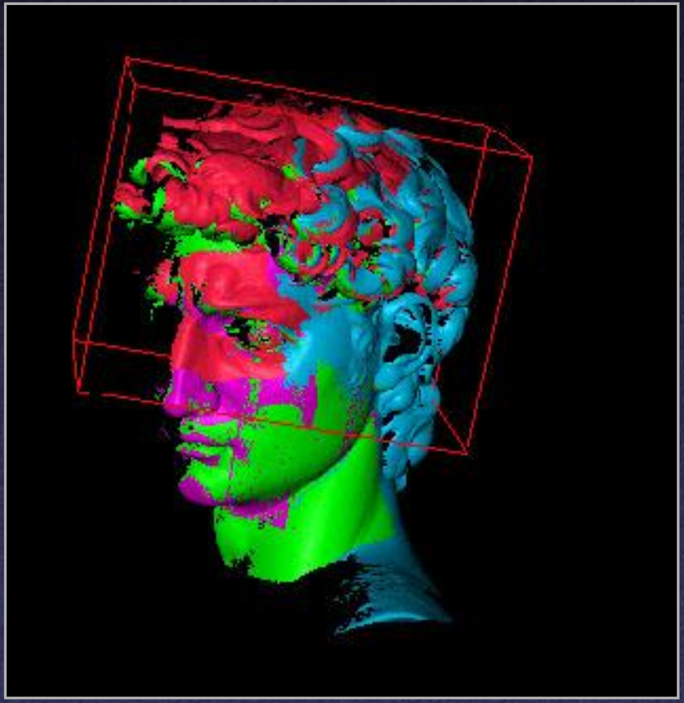

- Steps
  1. manual initial alignment
  2. ICP to one existing scan
  3. automatic ICP of all overlapping pairs
  4. global relaxation to spread out error
  5. merging using volumetric method

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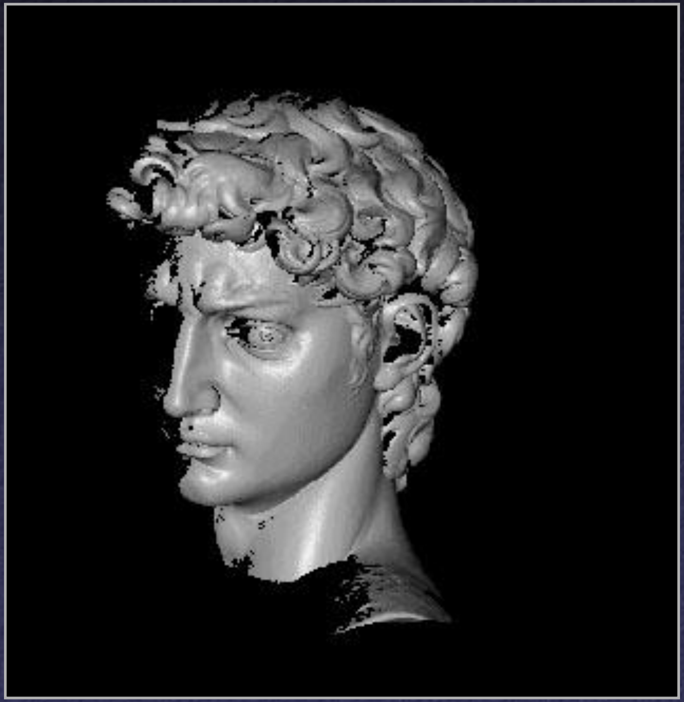

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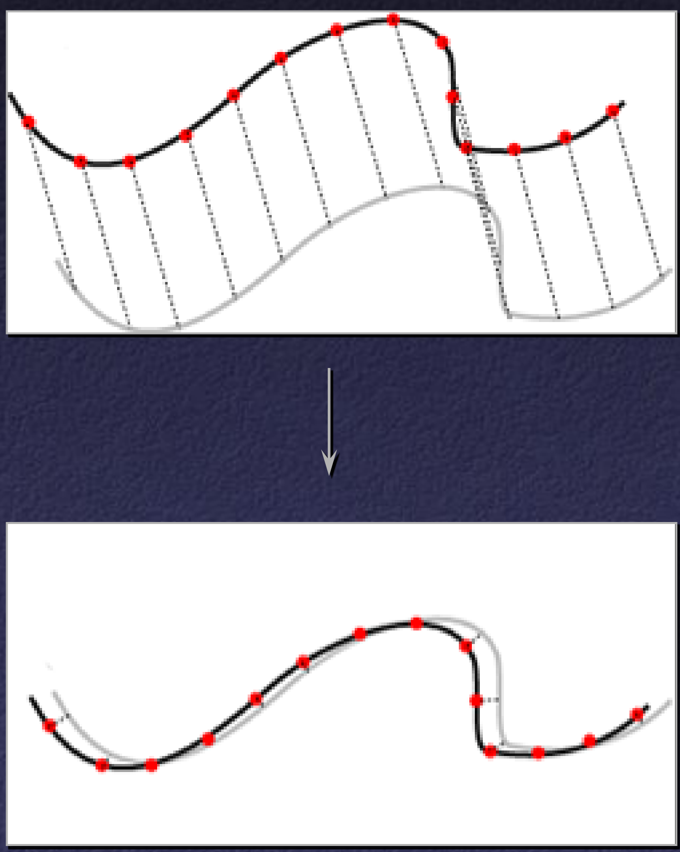

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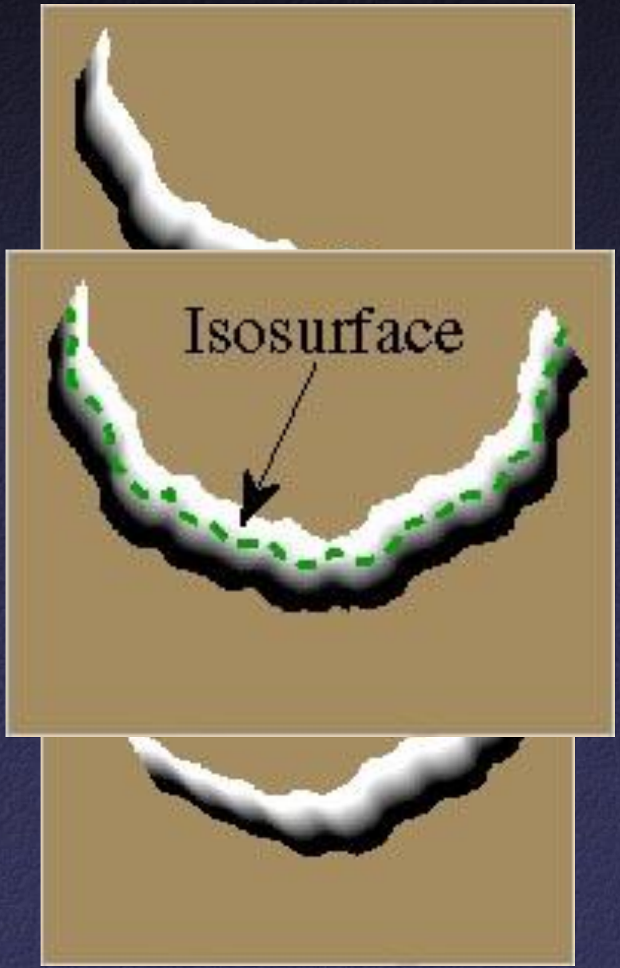

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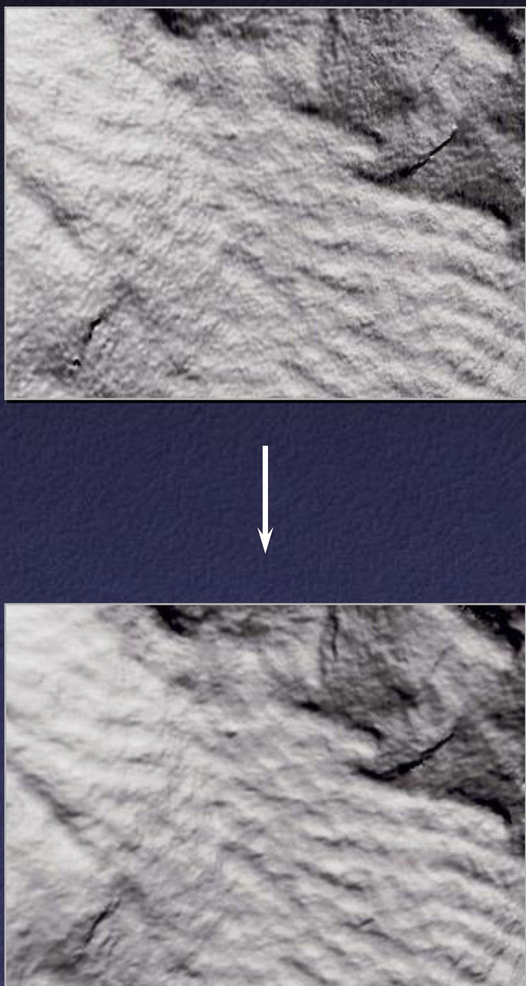

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Outline

- 3D scanning methods
- 3D scan processing
- Example applications ⟵

Example Application: Scanning Sculptures

- The Pietà Project

  IBM Research

- The Digital Michelangelo Project

  Stanford University

- The Great Buddha Project

  University of Tokyo

Why Scan Sculptures?

- Sculptures interesting objects to look at
- Introduce scanning to new disciplines
  - Art: studying working techniques
  - Art history
  - Cultural heritage preservation
  - Archeology
- High-visibility projects

Why Scan Sculptures?

- Challenging
  - High detail, large areas
  - Large data sets
  - Field conditions
  - Pushing hardware, software technology
- But not too challenging
  - Simple topology
  - Possible to scan most of surface

Issues Addressed

- Resolution
- Coverage
  - Theoretical: limits of scanning technologies
  - Practical: physical access, time
- Type of data
  - High-res 3D data vs. coarse 3D + normal maps
  - Influenced by eventual application
- Intellectual Property

IBM's Pietà Project

- Michelangelo's "Florentine Pietà"
- Late work (1550s)
- Partially destroyed by Michelangelo, recreated by his student
- Currently in the Museo dell'Opera del Duomo in Florence

Who?

- Dr. Jack Wasserman, professor emeritus of art history at Temple University
- Visual and Geometric Computing group @ IBM Research:

Fausto Bernardini
Holly Rushmeier
Ioana Martin
Joshua Mittleman
Gabriel Taubin
Andre Gueziec
Claudio Silva

Scanner

- Visual Interface "Virtuoso"
- Active multibaseline stereo
- Projector (stripe pattern),
  6 B&W cameras, 1 color camera
- Augmented with 5 extra "point" light sources for photometric stereo (active shape from shading)

Data

- Range data has 2 mm spacing, 0.1mm noise
- Each range image: 10,000 points, 20×20 cm
- Color data: 5 images with controlled lighting, 1280×960, 0.5 mm resolution
- Total of 770 scans, 7.2 million points

Scanning

- Final scan June 1998, completed July 1999
- Total scanning time: 90 hours over 14 days (includes equipment setup time)

Postprocessing

- Use 11×11 grid of projected laser dots to help with pairwise alignment
- Align all scans to each other, then apply nonrigid "conformance smoothing"
- Reconstruct surface using BPA
- Compute normal and albedo maps, align to geometry

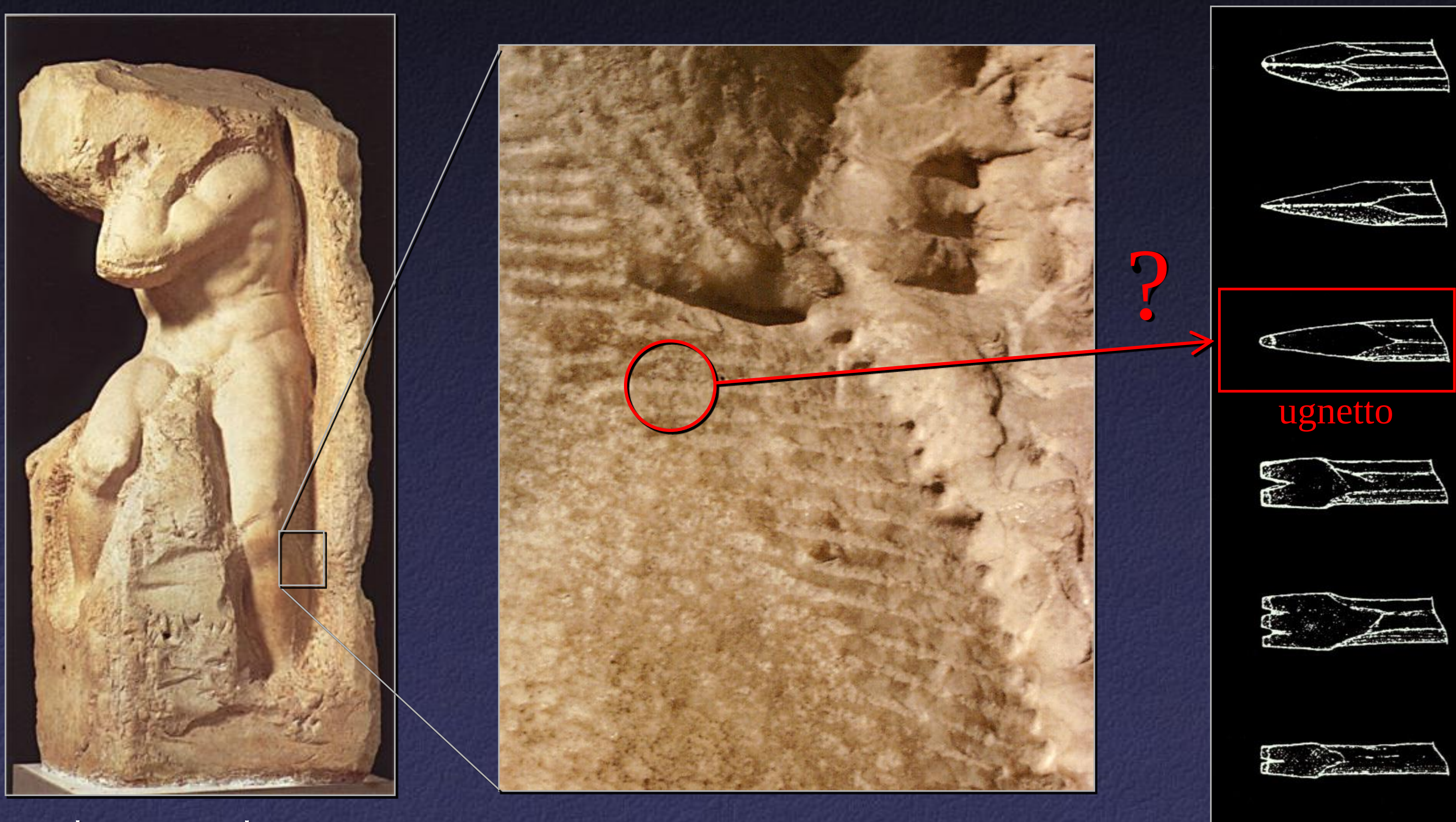
Results

The Digital Michelangelo Project

Goals

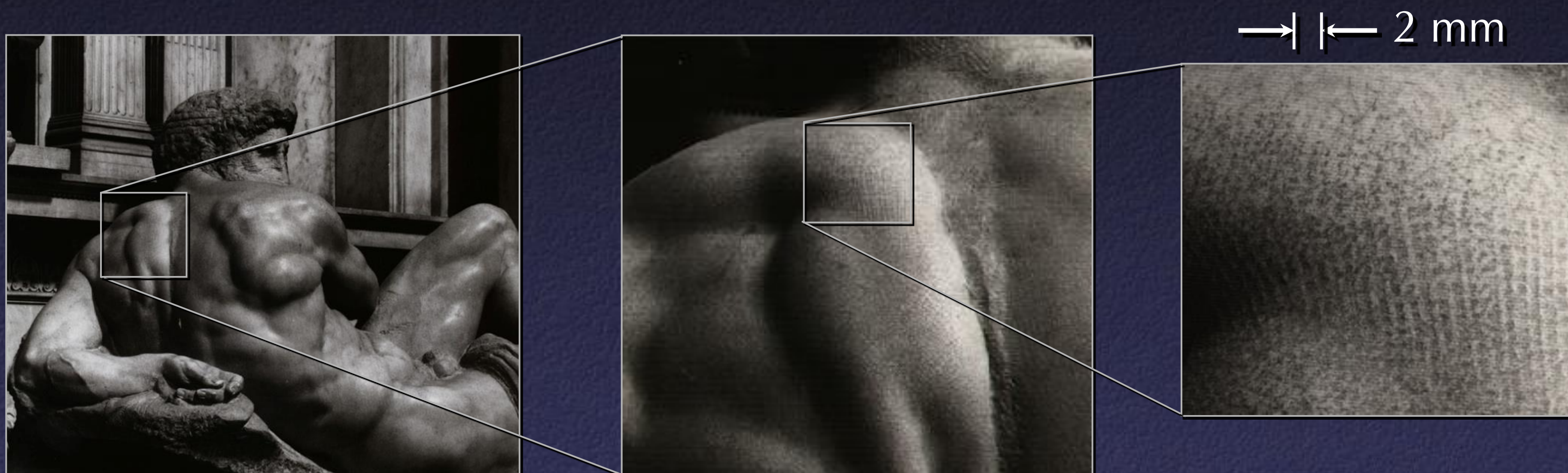
- Scan 10 sculptures by Michelangelo
- High-resolution ("quarter-millimeter") geometry
- Side projects: architectural scanning (Accademia and Medici chapel), scanning fragments of Forma Urbis Romae

Why Capture Chisel Marks?



Atlas (Accademia)

Why Capture Chisel Marks as Geometry?



Day (Medici Chapel)

Who?

Faculty and staff

Prof. Brian Curless | John Gerth
Jelena Jovanovic | Prof. Marc Levoy
Lisa Pacelle | Domi Pitturo
Dr. Kari Pulli

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James Davis | Dave Koller
Lucas Pereira | Szymon Rusinkiewicz
Jonathan Shade | Marco Tarini
Daniel Wood

Undergraduates

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Jeremy Ginsberg | Matt Ginzton
Unnur Gretarsdottir | Rahul Gupta
Wallace Huang | Dana Katter
Ephraim Luft | Dan Perkel
Semira Rahemtulla | Alex Roetter
Joshua Schroeder | Maisie Tsui
David Weekly

In Florence

Dottssa Cristina Acidini | Dottssa Franca Falletti
Dottssa Licia Bertani | Alessandra Marino
Matti Auvinen

In Rome

Prof. Eugenio La Rocca | Dottssa Susanna Le Pera
Dottssa Anna Somella | Dottssa Laura Ferrea

In Pisa

Roberto Scopigno

Sponsors

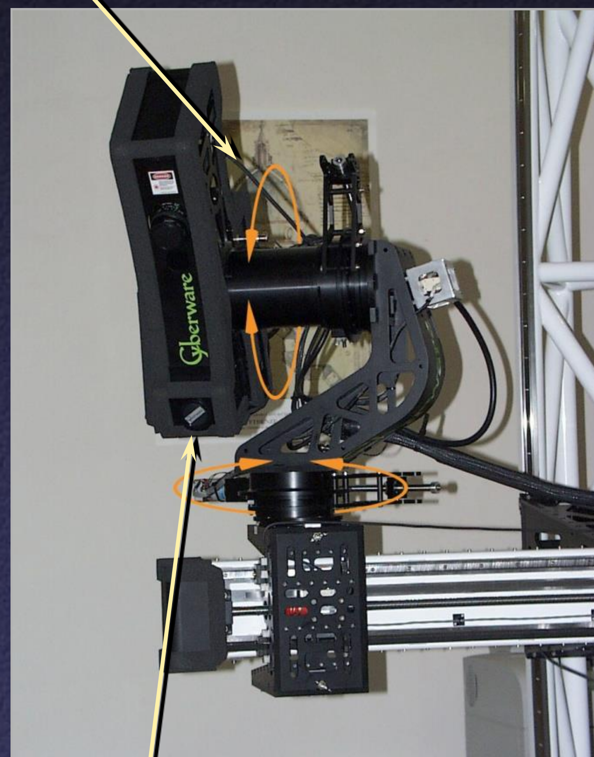
Interval Research | Paul G. Allen Foundation for the Arts
Stanford University

Equipment donors

Cyberware | Cyra Technologies
Faro Technologies | Intel
Silicon Graphics | Sony
3D Scanners

Scanner Design

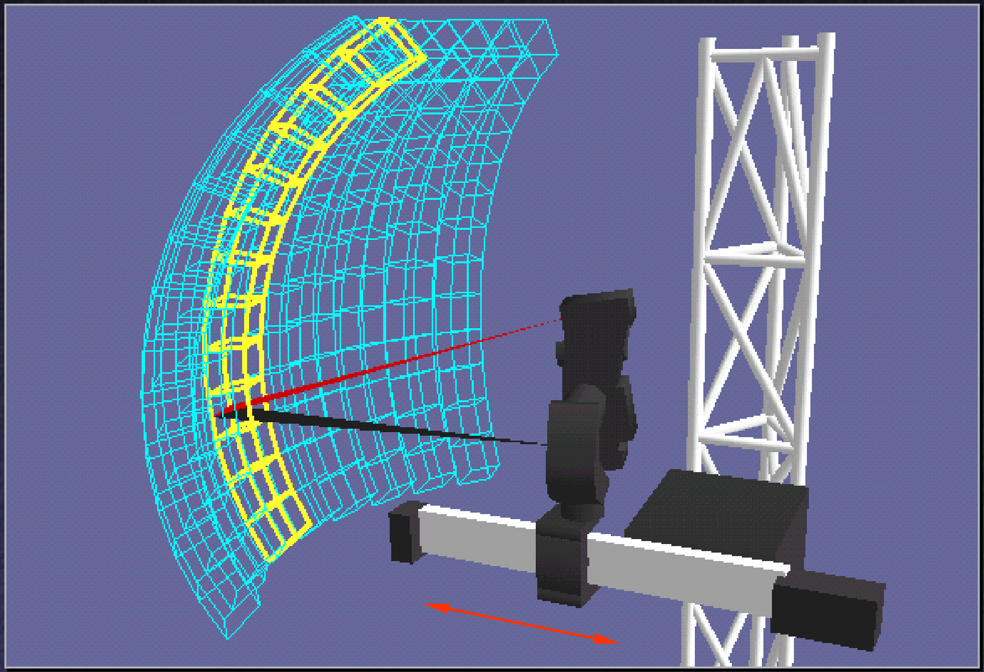
4 motorized axes



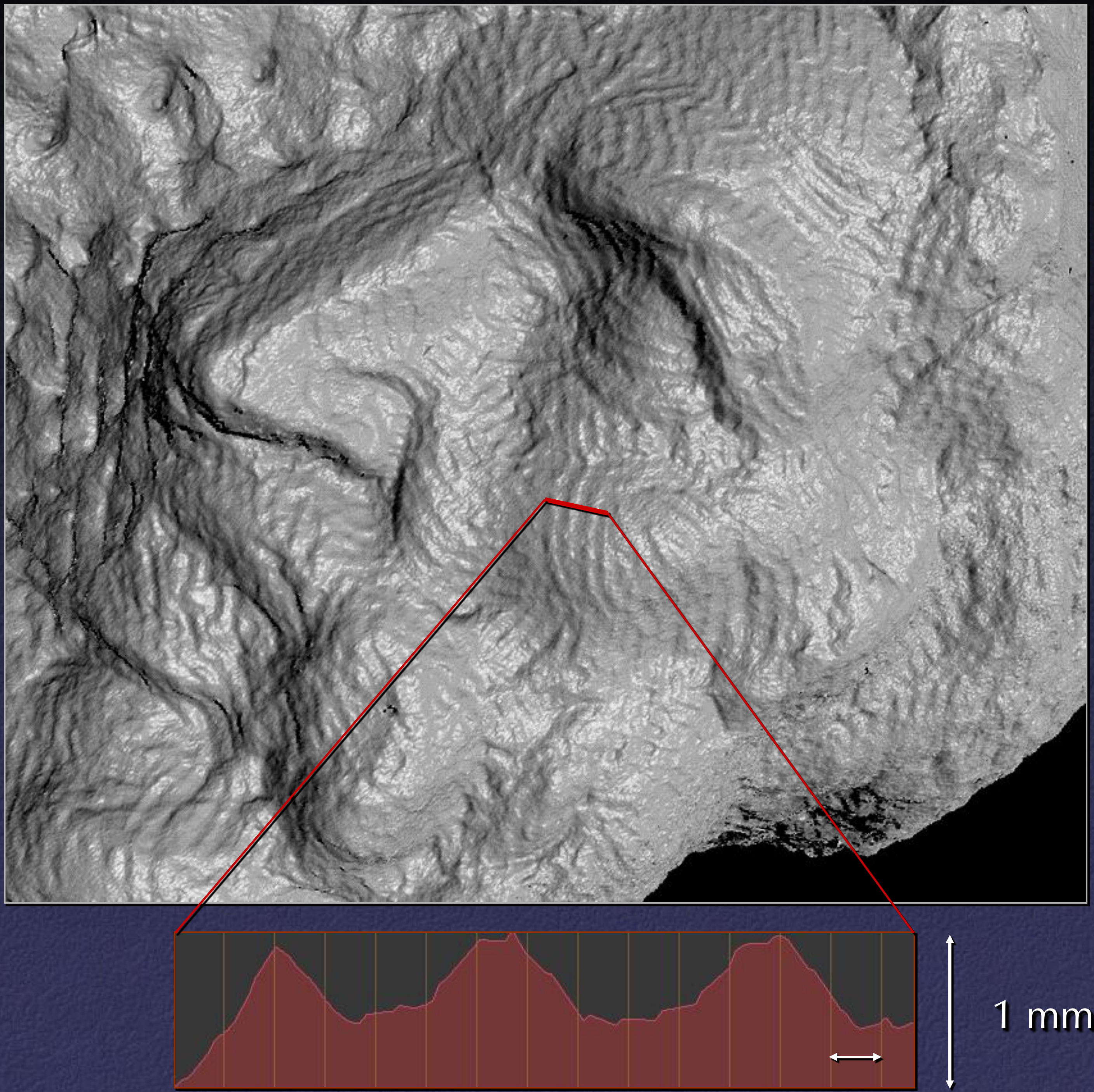
laser, range camera,
white light, and color camera

- Flexibility
  - outward-looking rotational scanning
  - 16 ways to mount scan head on arm
- Accuracy
  - center of gravity kept stationary during motions
  - precision drives, vernier homing, stiff trusses

Scanning a Large Object



- Calibrated motions
  - pitch (yellow)
  - pan (blue)
  - horizontal translation (orange)
- Uncalibrated motions
  - vertical translation
  - rolling the gantry
  - remounting the scan head


1 mm

Postprocessing

- Manual initial alignment
- Pairwise ICP, then global registration
- VRIP (parallelized across subvolumes)
- Use high-res geometry to discard bad color data, perform inverse lighting calculations

Statistics About the Scan of David

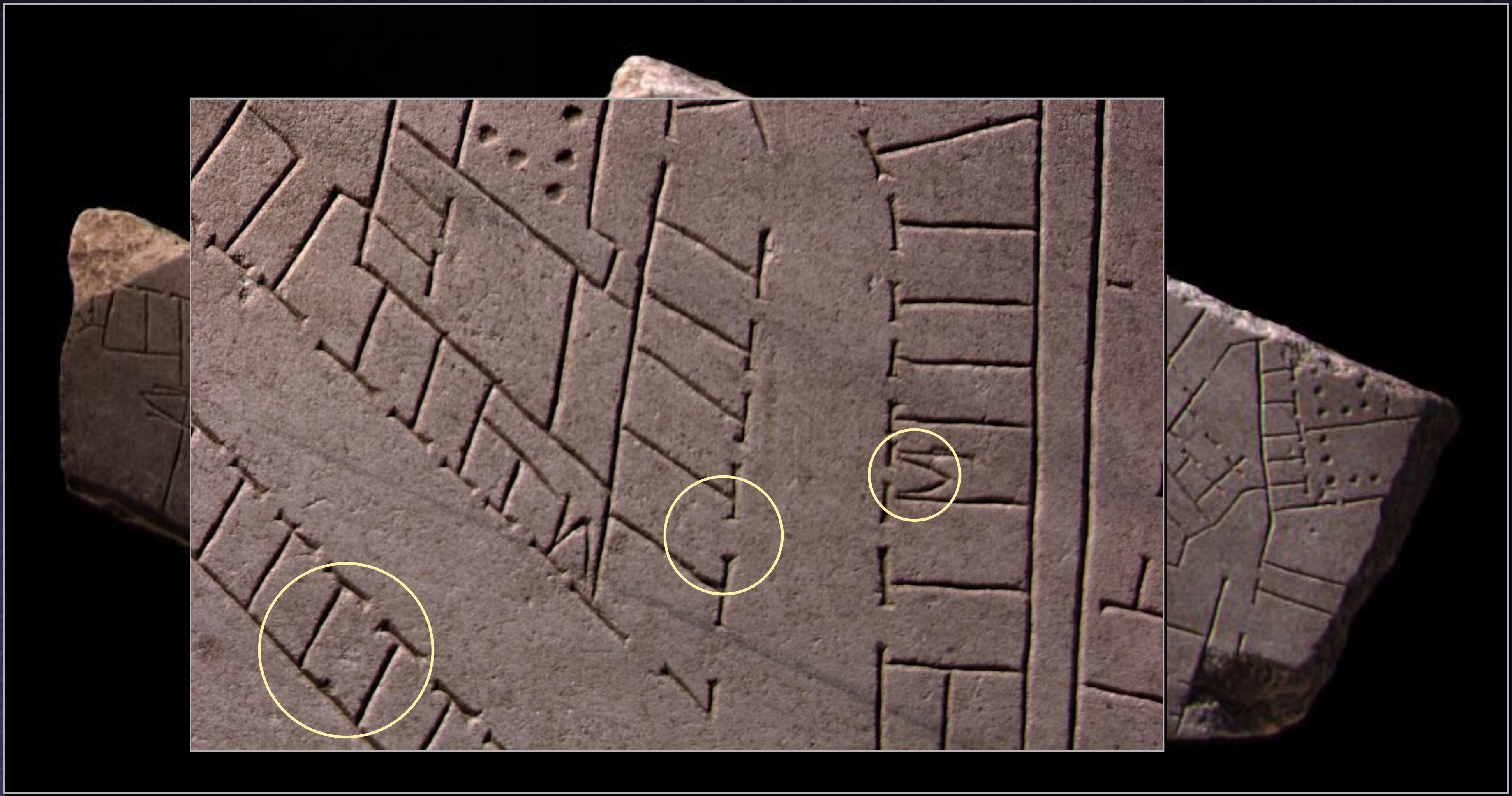
- 480 individually aimed scans
- 0.3 mm sample spacing
- 2 billion polygons
- 7,000 color images
- 32 gigabytes
- 30 nights of scanning
- 22 people

Head of Michelangelo's David

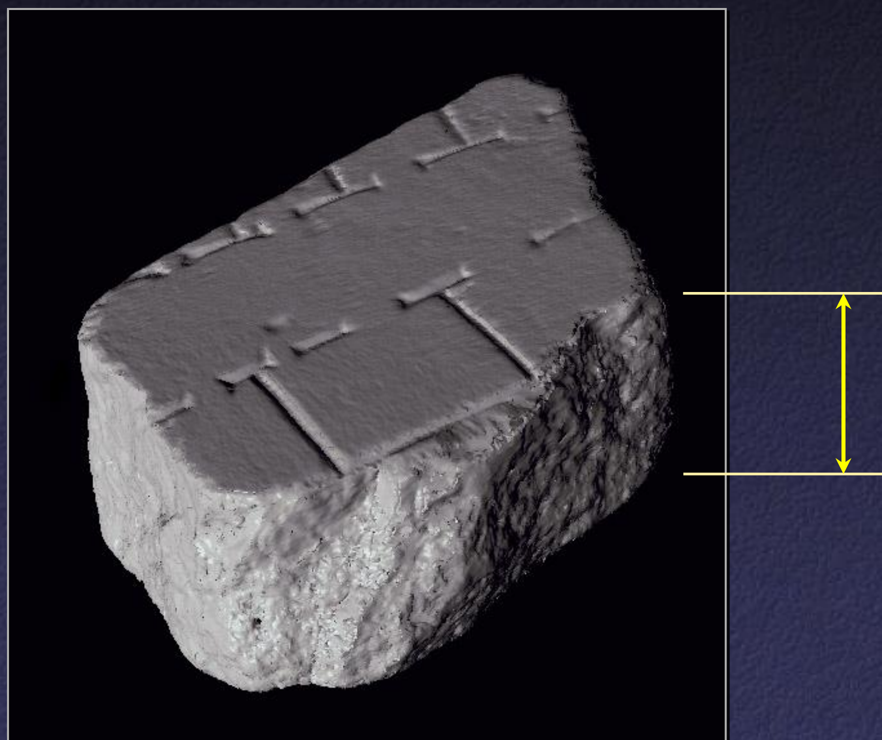
Photograph

1.0 mm computer model

Side project:
The Forma Urbis Romae



Forma Urbis Romae Fragment



forma urbis romae

Hard Problems

- Keeping scanner calibrated is hard in the lab, really hard in the museum
- Dealing with large data sets is painful
- Filling all the holes converges only asymptotically (if it converges at all…)

The Great Buddha Project

- Great Buddha of Kamakura
- Original made of wood, completed 1243
- Covered in bronze and gold leaf, 1267
- Approx. 15 m tall
- Goal: preservation of cultural heritage

Who?

- Institute of Industrial Science,
  University of Tokyo

Daisuke Miyazaki
Takeshi Ooishi
Taku Nishikawa
Ryusuke Sagawa
Ko Nishino
Takashi Tomomatsu
Yutaka Takase
Katsushi Ikeuchi

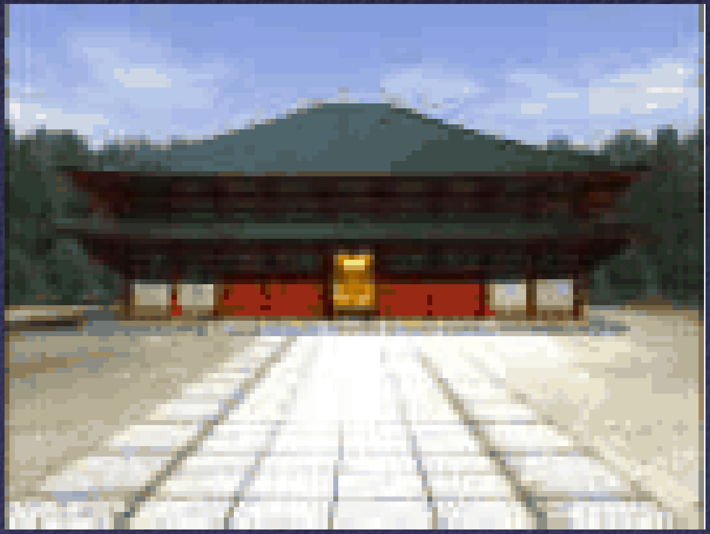
Scanner

- Cyrax range scanner
  by Cyra Technologies
- Laser pulse time-of-flight
- Accuracy: 4 mm
- Range: 100 m

Processing

- 20 range images (a few million points)
- Simultaneous all-to-all ICP
- Variant of volumetric merging (parallelized)

Results



Summary

- Advantages of active scanning
  - Usually higher accuracy
- Disadvantages of active scanning
  - Need to project light into scene
  - Limits on working volume, lighting conditions, etc.
  - Sometimes slower