# (Active) 3D Scanning

Theory and Case Studies

# 3D Scanning Applications

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

# Industrial Inspection

- Determine whether manufactured parts are within tolerances

# Medicine

- Plan surgery on computer model, visualize in real time

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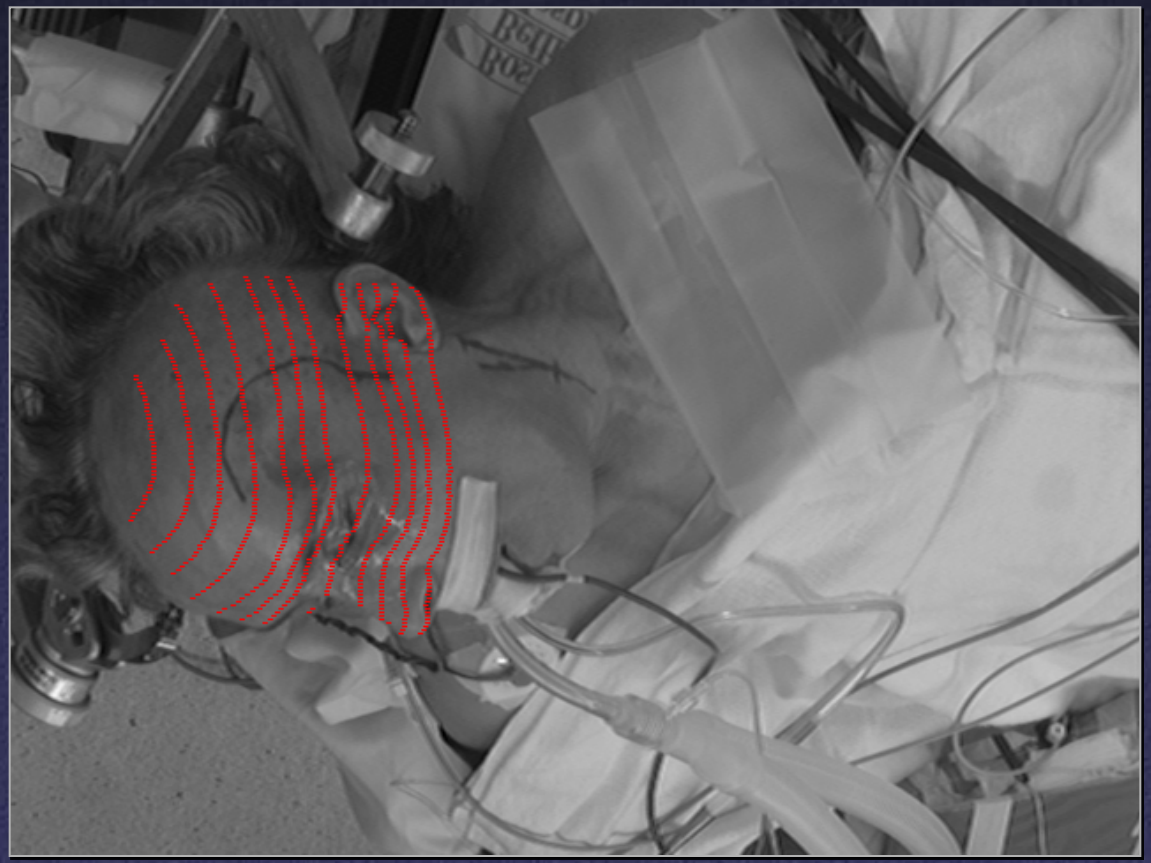

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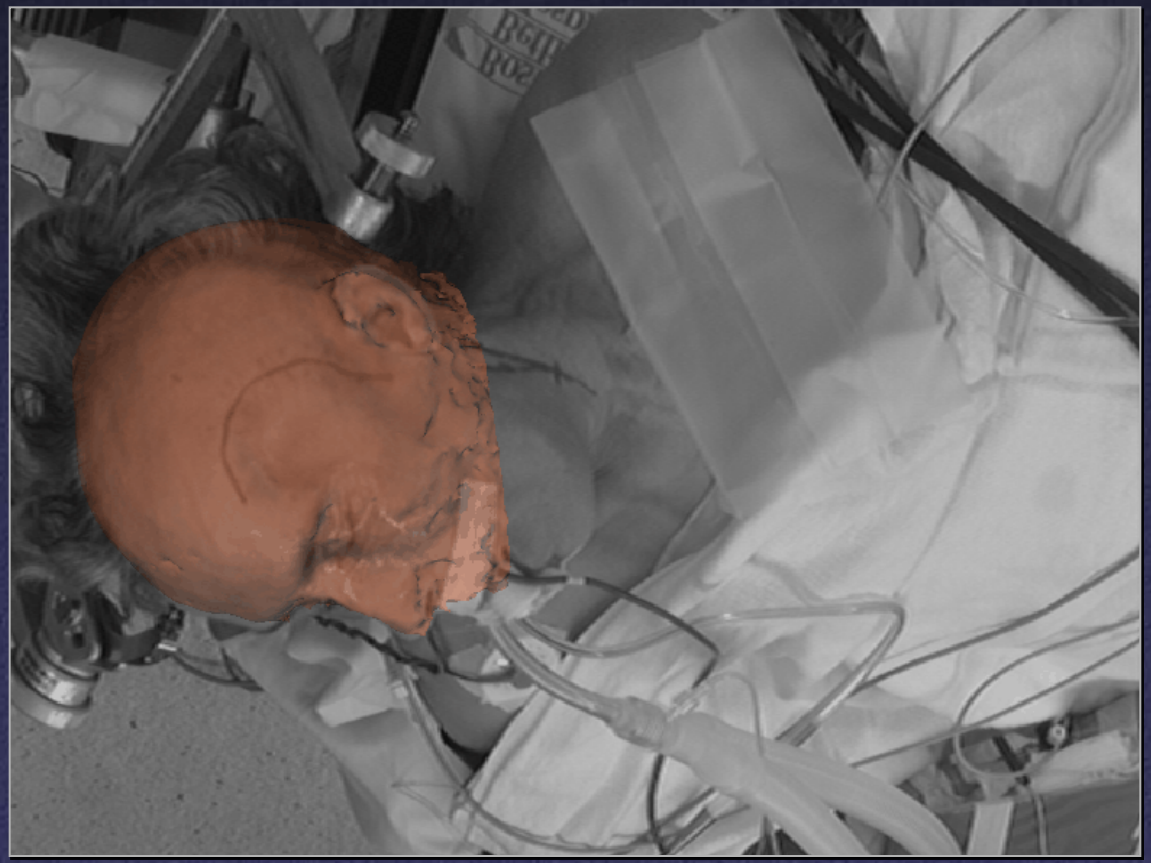

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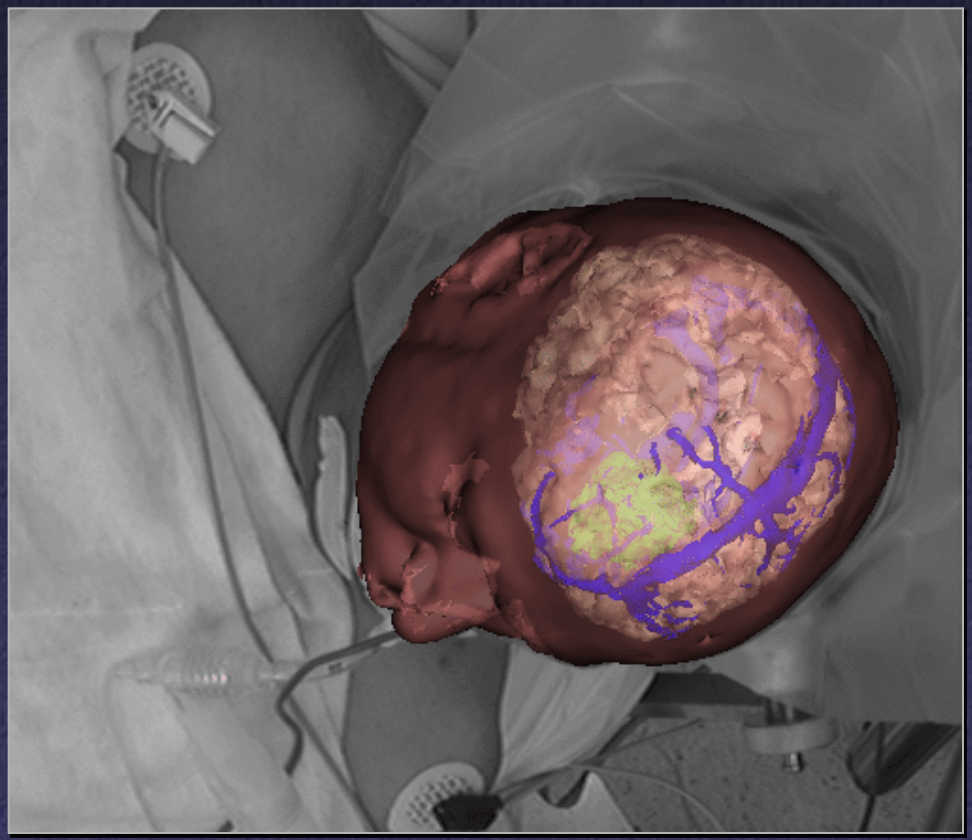
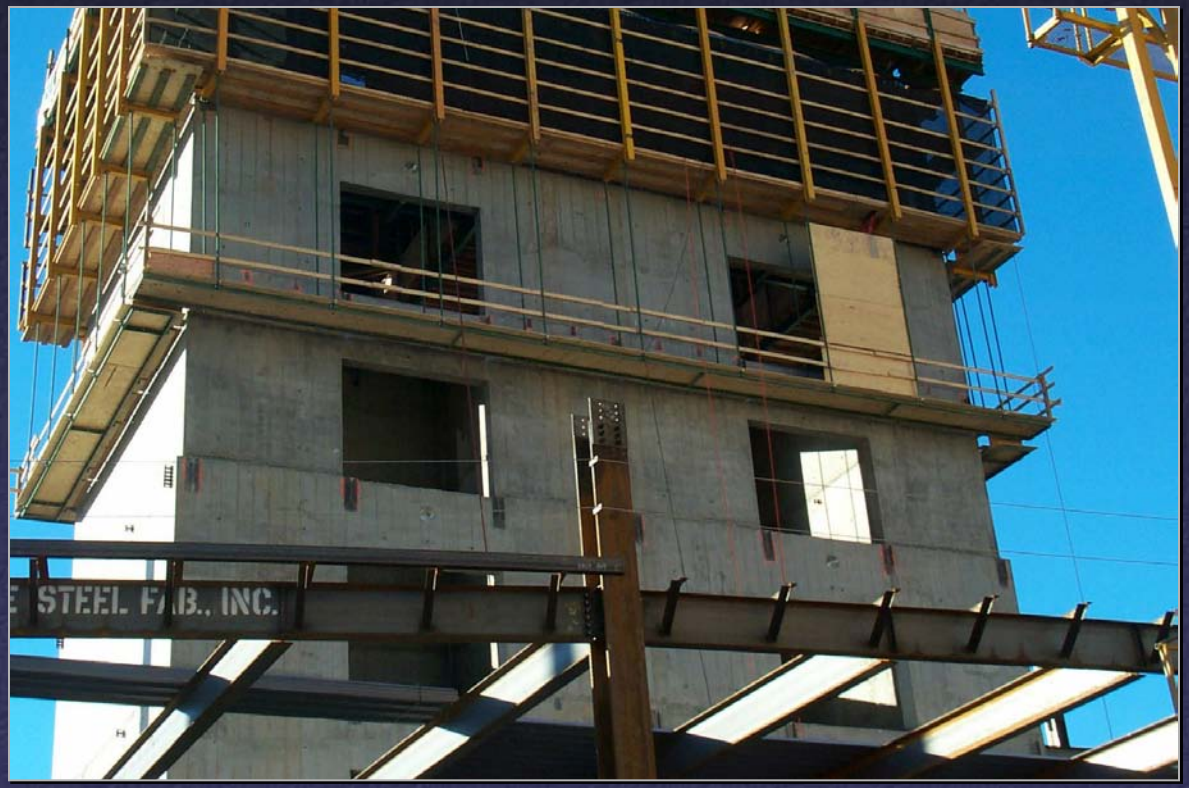


# Scanning Buildings

- Quality control during construction
- As-built models



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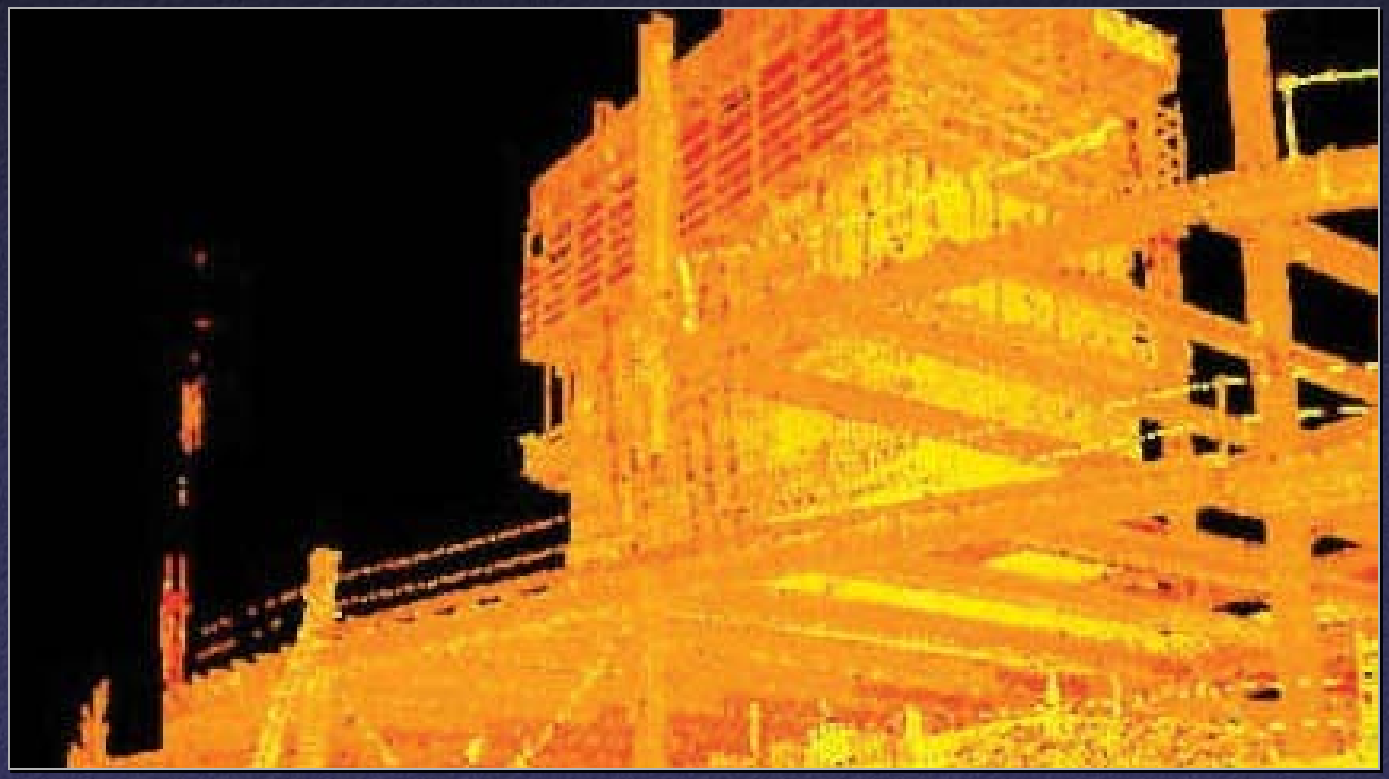
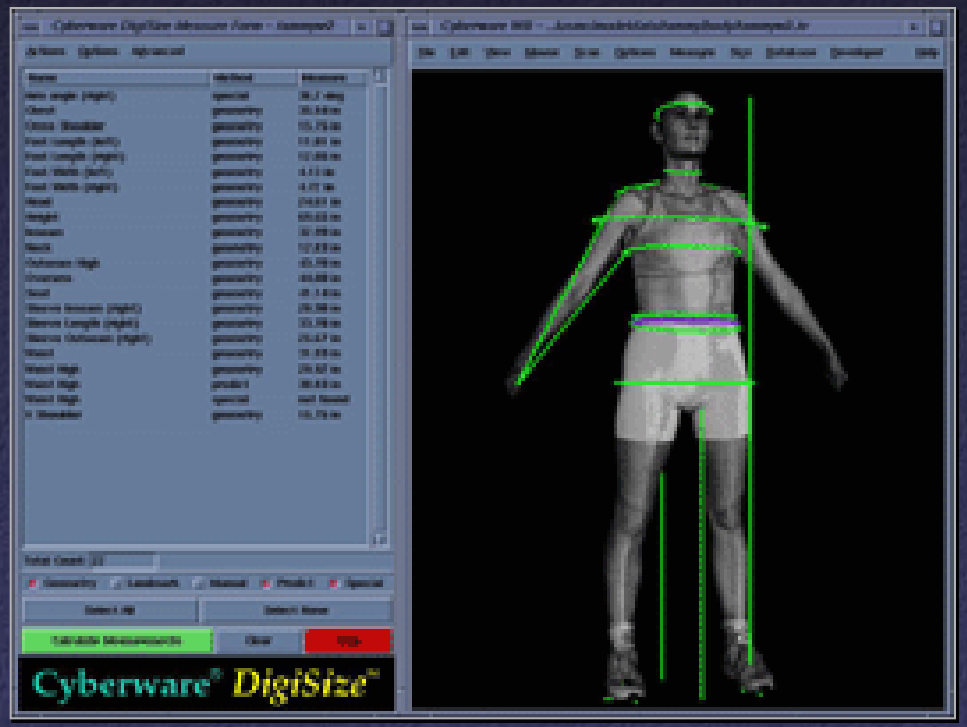
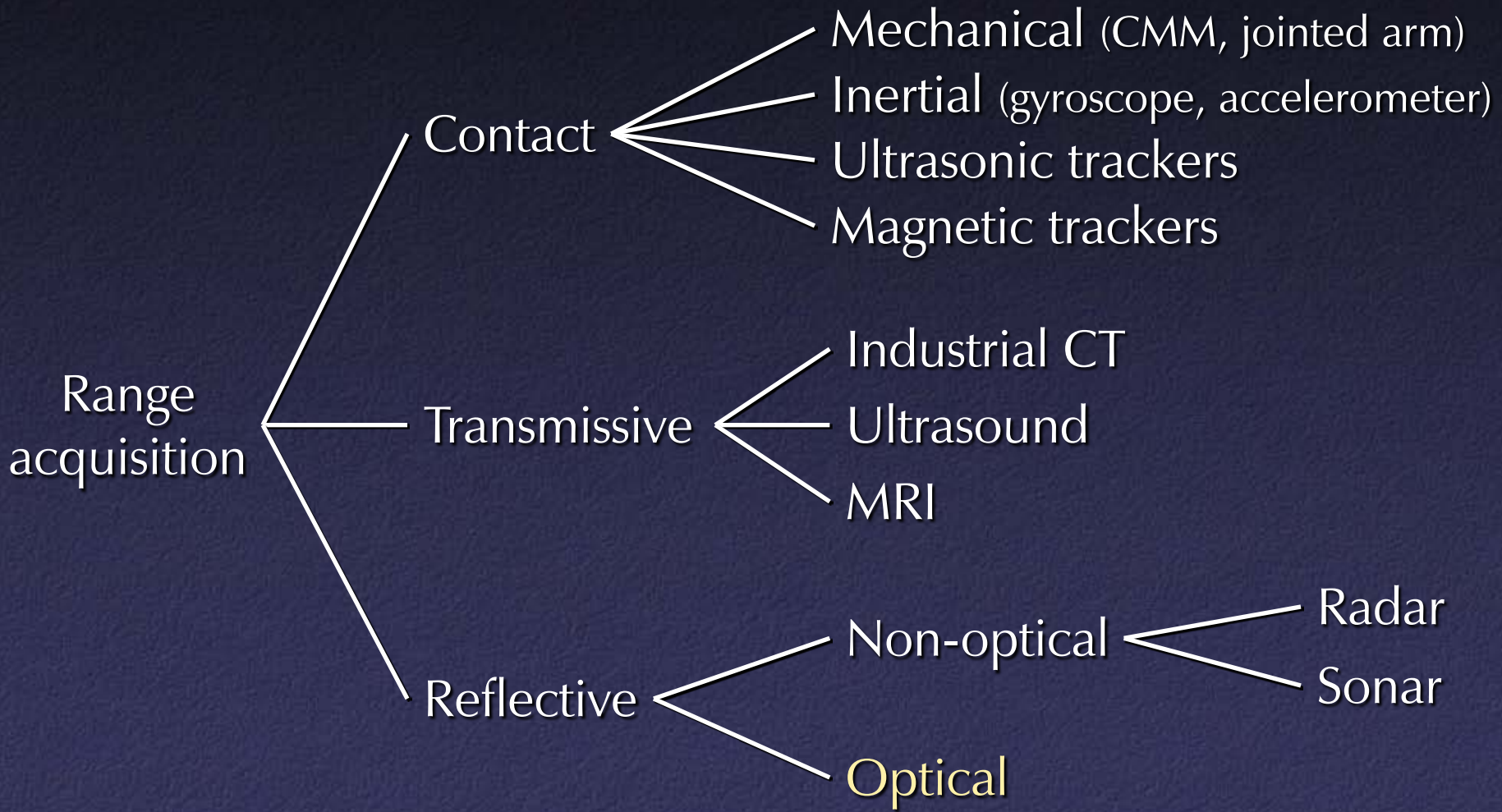


# Clothing

- Scan a person, custom-fit clothing
- U.S. Army; booths in malls



# Range Acquisition Taxonomy

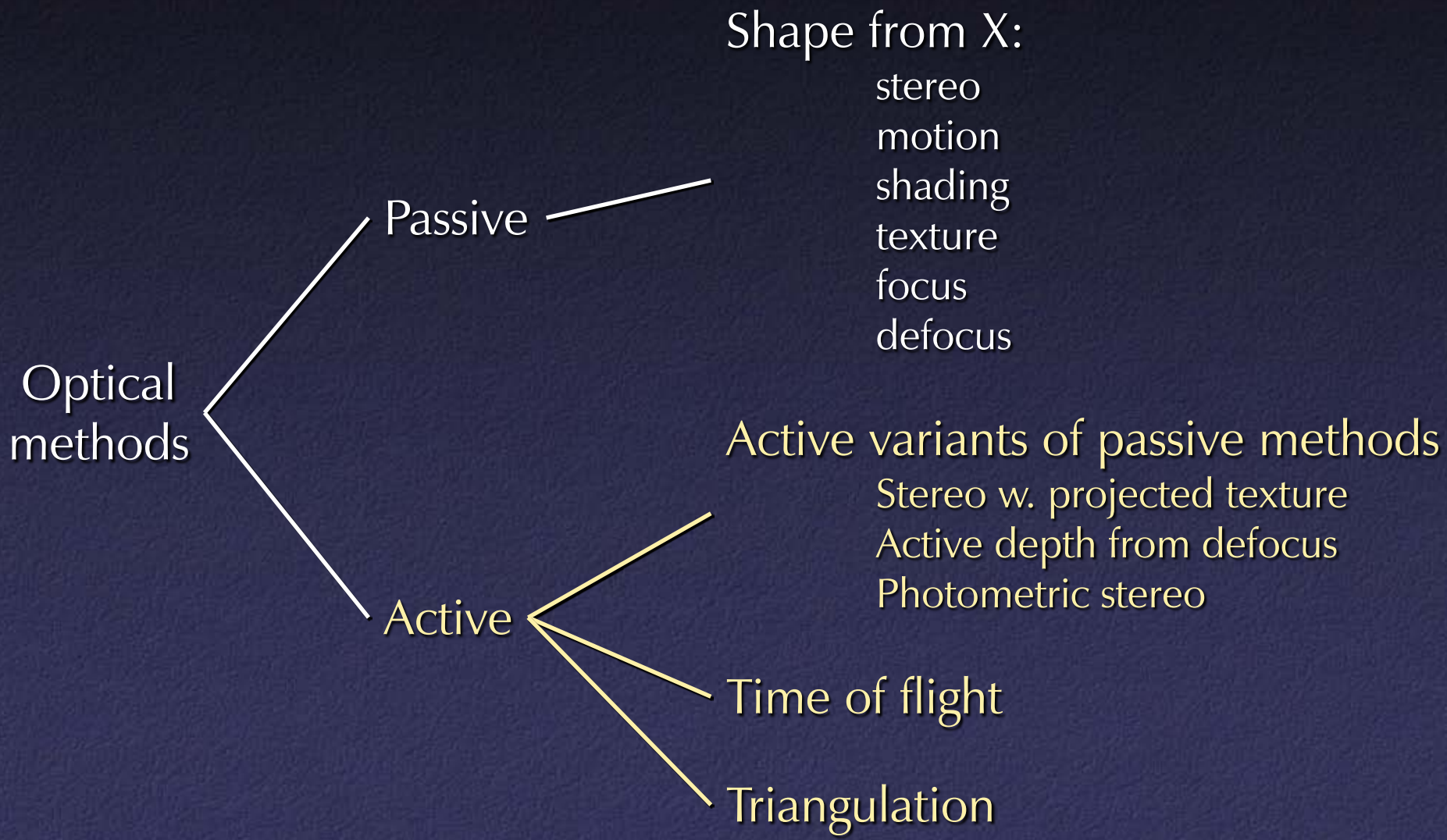


# Touch Probes

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

Faro Arm – Faro Technologies, Inc.

# Range Acquisition Taxonomy



# Active Optical Methods

- Advantages:
  - Usually can get dense data
  - Usually much more robust and accurate than passive techniques
- Disadvantages:
  - Introduces light into scene (distracting, etc.)
  - Not motivated by human vision

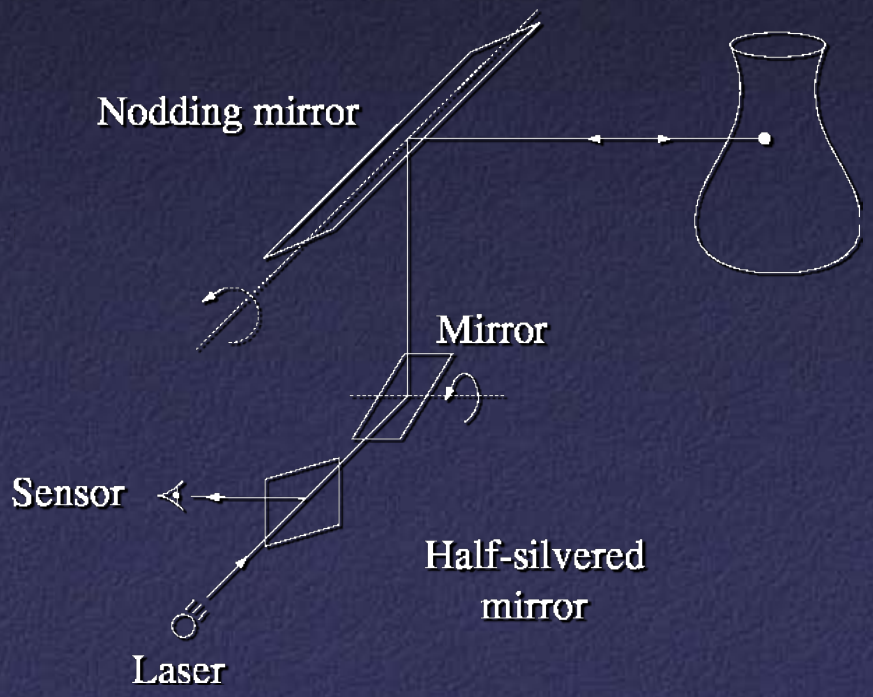
# Active Variants of Passive Techniques

- Regular stereo with projected texture
  - Provides features for correspondence
- Active depth from defocus
  - Known pattern helps to estimate defocus
- Photometric stereo
  - Shape from shading with multiple known lights

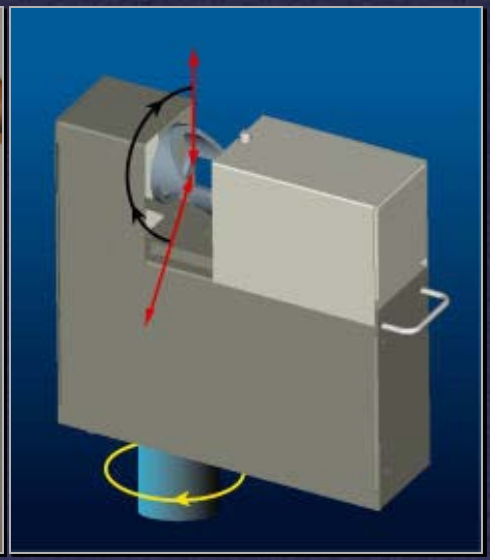
# Pulsed Time of Flight

- 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.

# AM Modulation Time of Flight

- Modulate a laser at frequency $\nu_m$, it returns with a phase shift $\Delta\varphi$

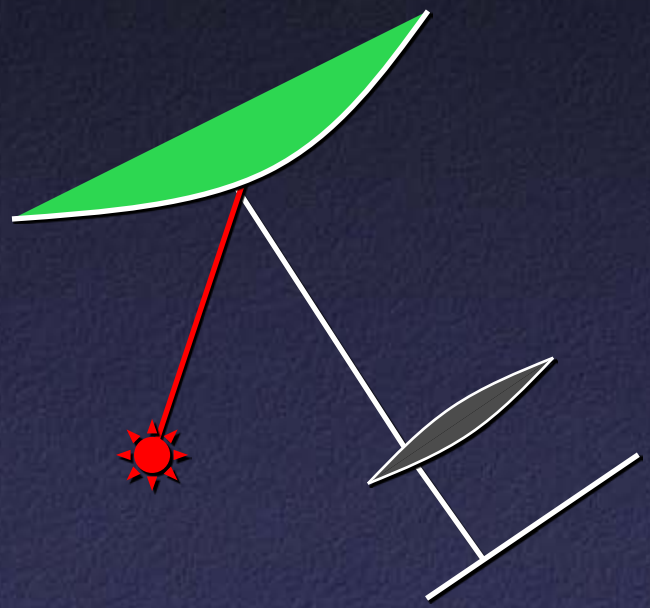
$$d = \frac{1}{2}\left(\frac{c}{\nu_m}\right)\left(\frac{\Delta\varphi \pm 2\pi n}{2\pi}\right)$$

- Note the ambiguity in the measured phase!
  $\Rightarrow$ Range ambiguity of $^1/_2\lambda_m n$

# AM Modulation Time of Flight

- Accuracy / working volume tradeoff (e.g., noise $\sim {}^{1}/_{500}$ working volume)
- In practice, often used for room-sized environments (cheaper, more accurate than pulsed time of flight)

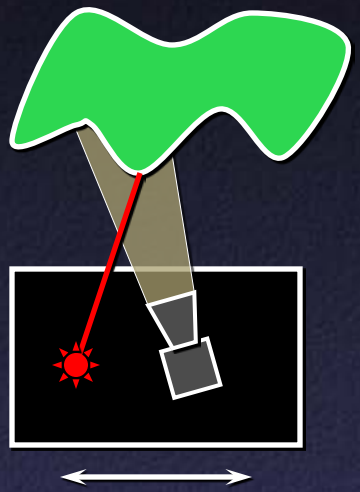
# Triangulation

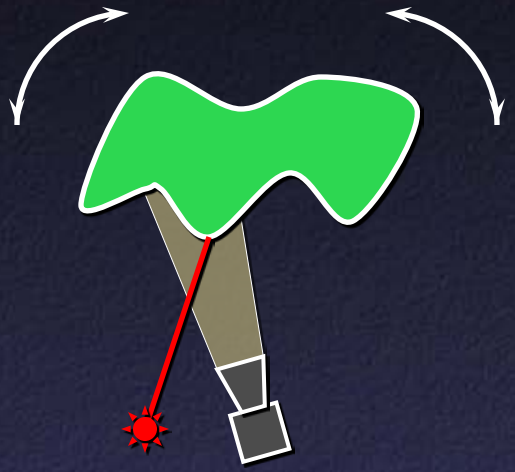


# Triangulation: Moving the Camera and Illumination

- Moving independently leads to problems with focus, resolution
- Most scanners mount camera and light source rigidly, move them as a unit

# Triangulation: Moving the Camera and Illumination



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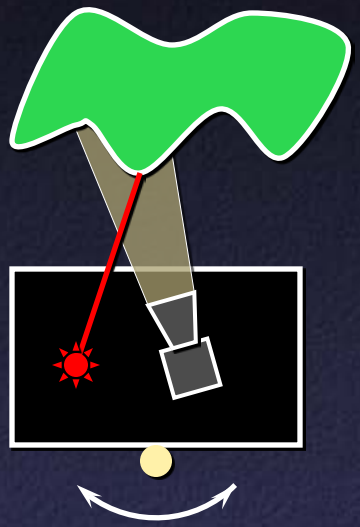
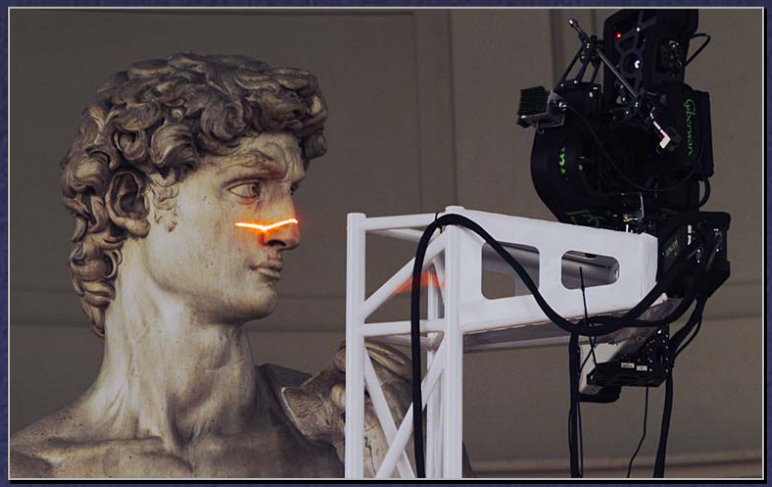
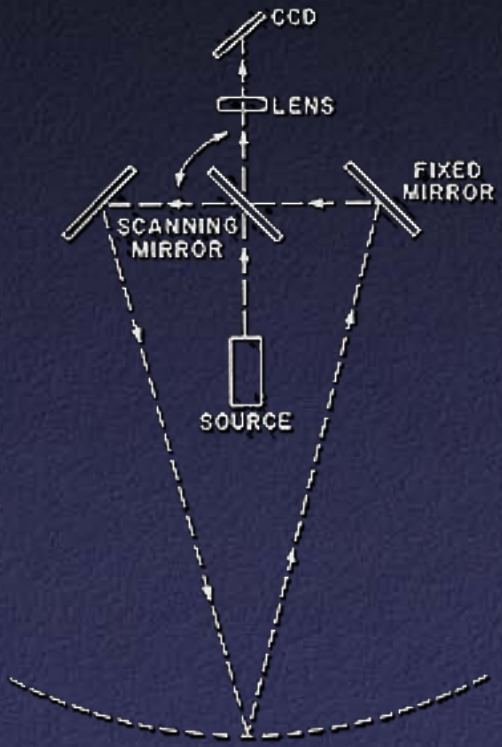
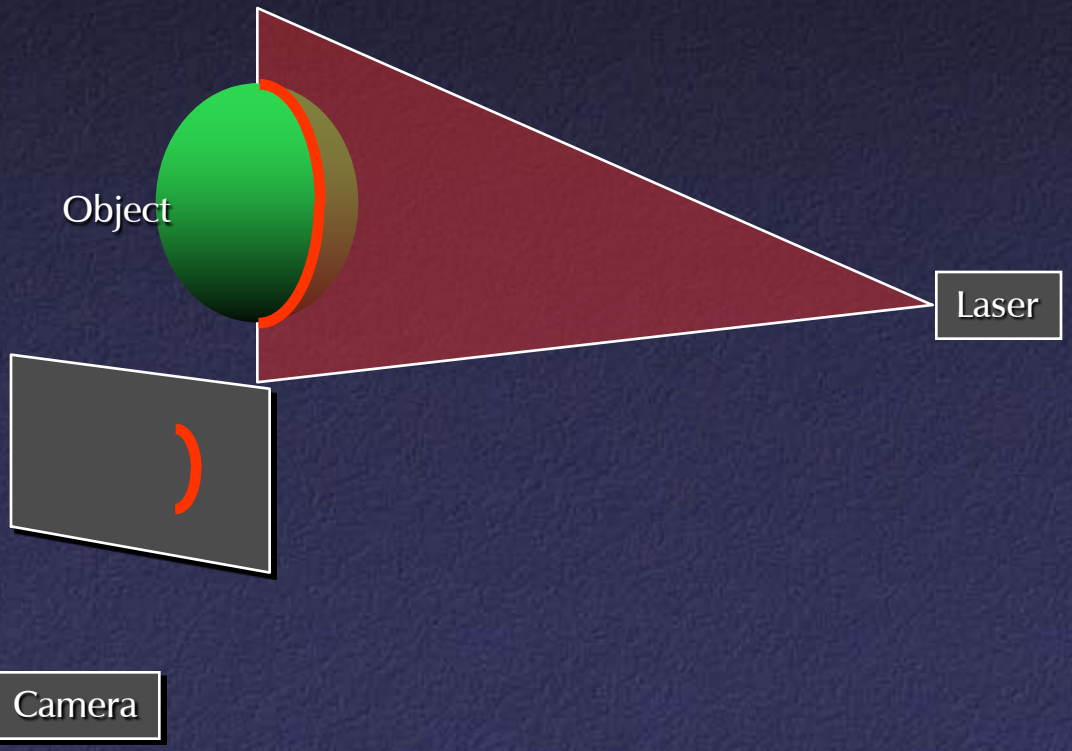






# Triangulation: Extending to 3D

- Possibility #1: add another mirror (flying spot)
- Possibility #2: project a stripe, not a dot

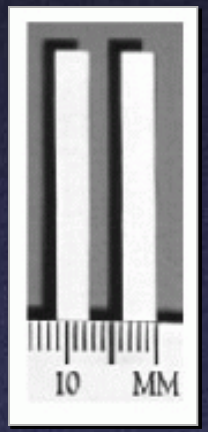


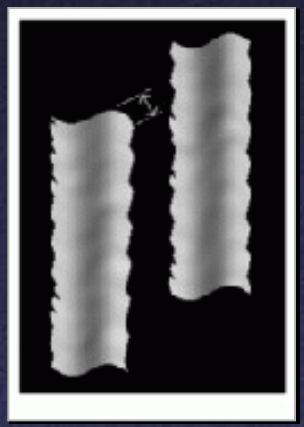
# Triangulation Scanner Issues

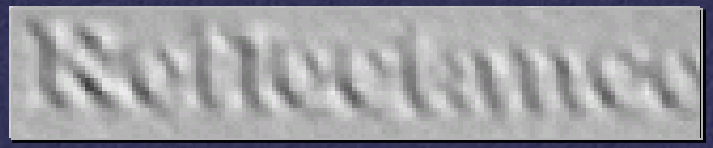
- Accuracy proportional to working volume (typical is ~1000:1)
- Scales down to small working volume (e.g. 5 cm. working volume, 50 μm. accuracy)
- Does not scale up (baseline too large…)
- Two-line-of-sight problem (shadowing from either camera or laser)
- Triangulation angle: non-uniform resolution if too small, shadowing if too big (useful range: 15°-30°)

# Triangulation Scanner Issues

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

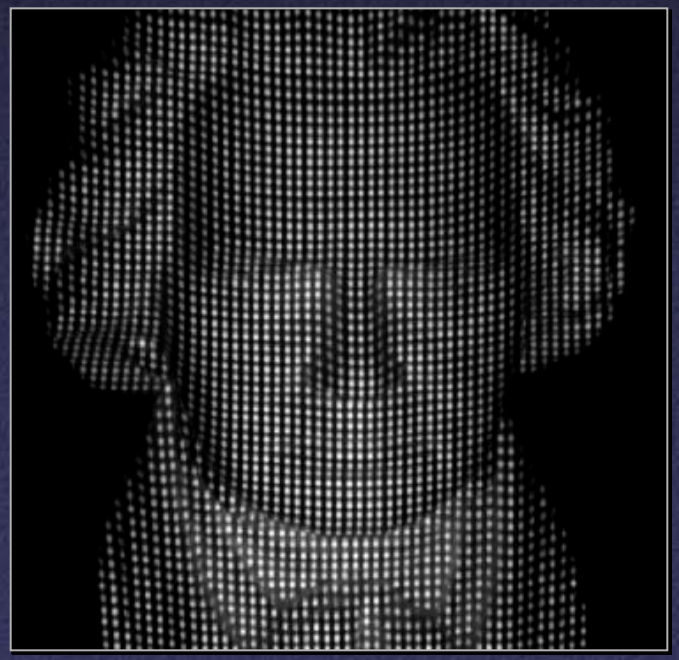


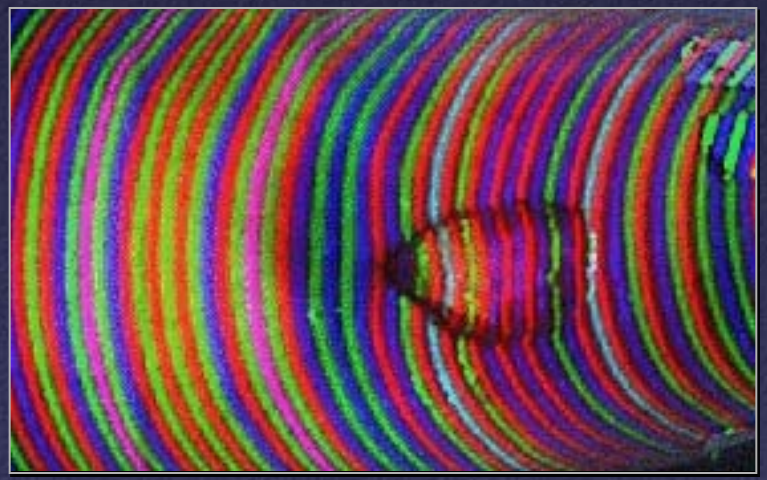
# Multi-Stripe Triangulation

- To go faster, project multiple stripes
- But which stripe is which?
- Answer #1: assume surface continuity



# Multi-Stripe Triangulation

- To go faster, project multiple stripes
- But which stripe is which?
- Answer #2: colored stripes (or dots)

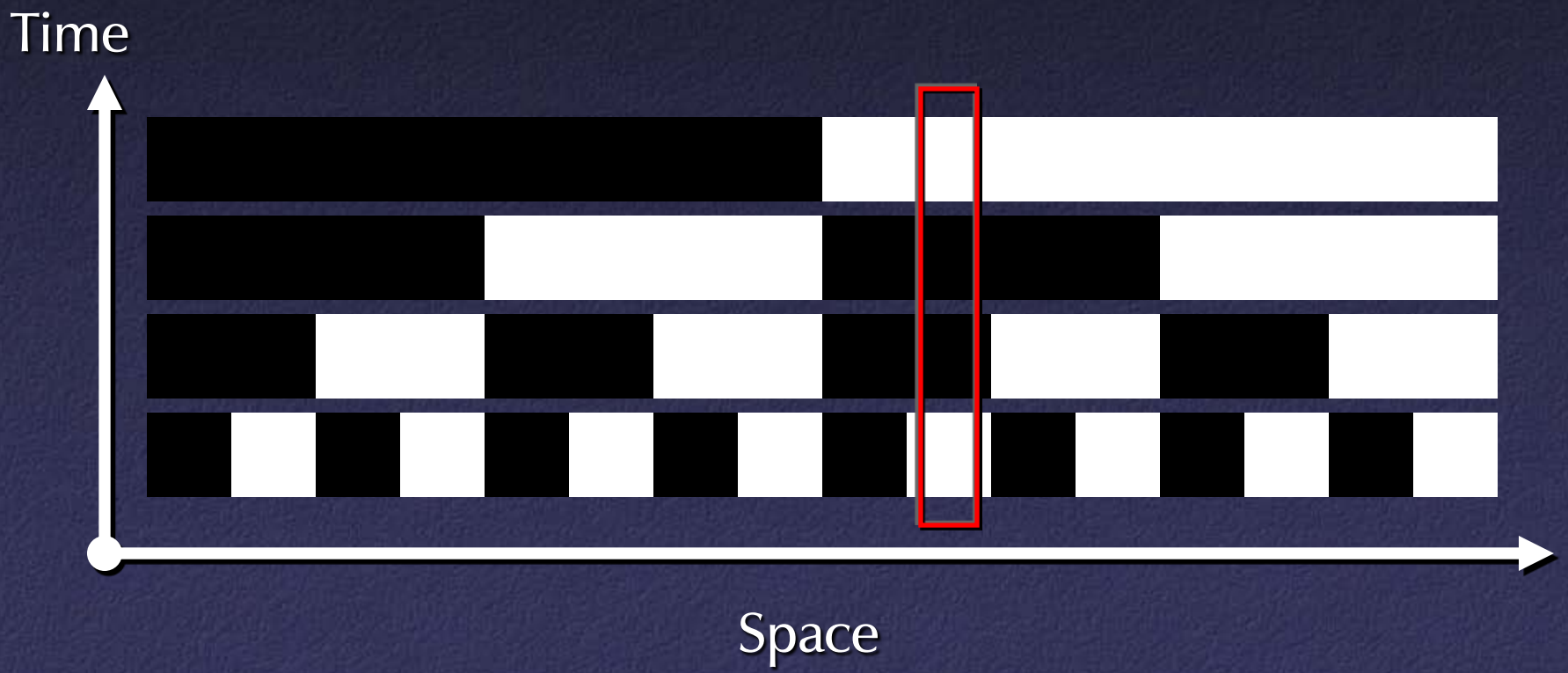


# Multi-Stripe Triangulation

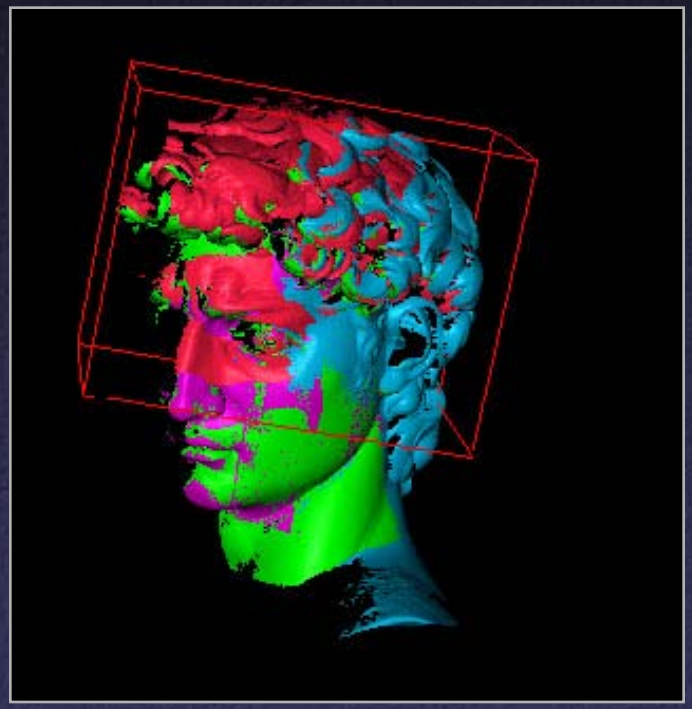
- To go faster, project multiple stripes
- But which stripe is which?
- Answer #3: time-coded stripes

# Time-Coded Light Patterns

- Assign each stripe a unique illumination code over time [Posdamer 82]



# Range Processing Pipeline



- 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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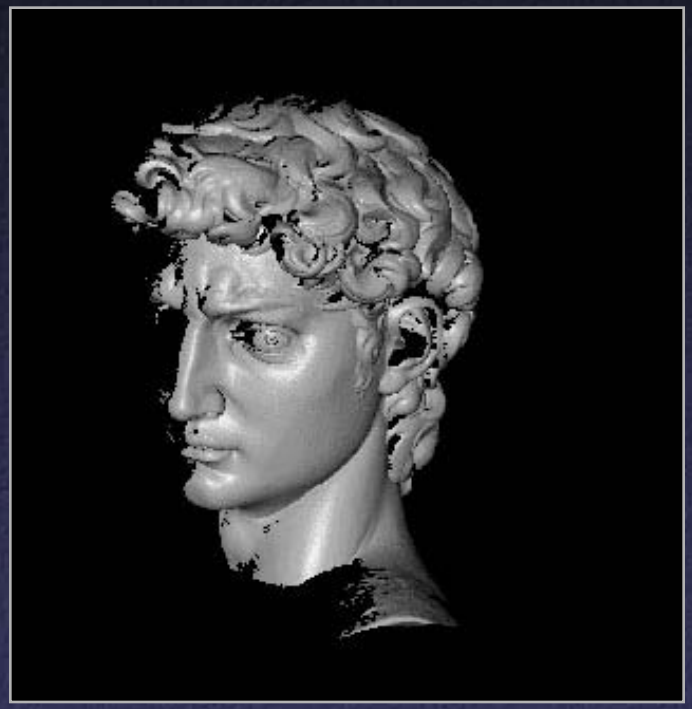

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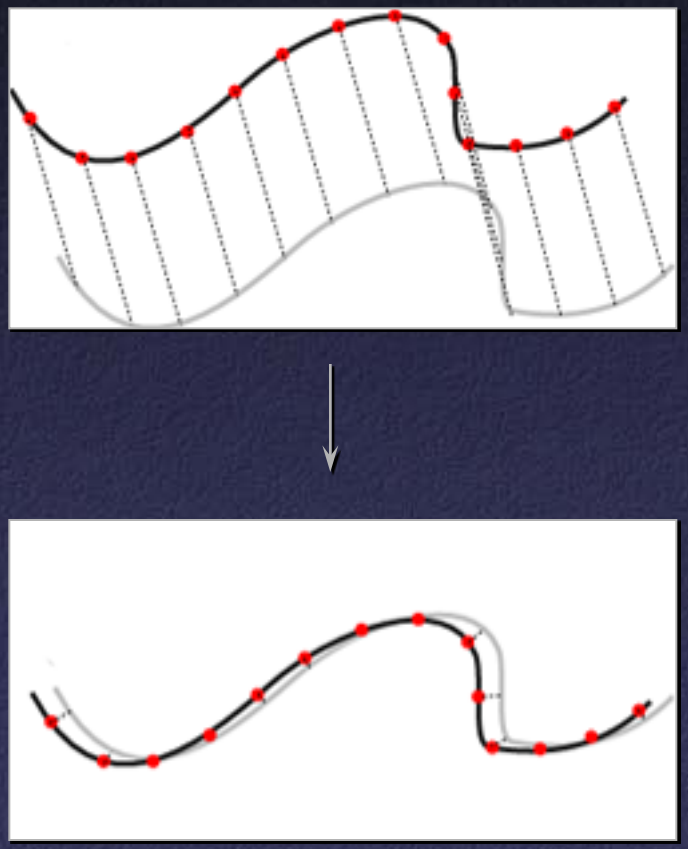

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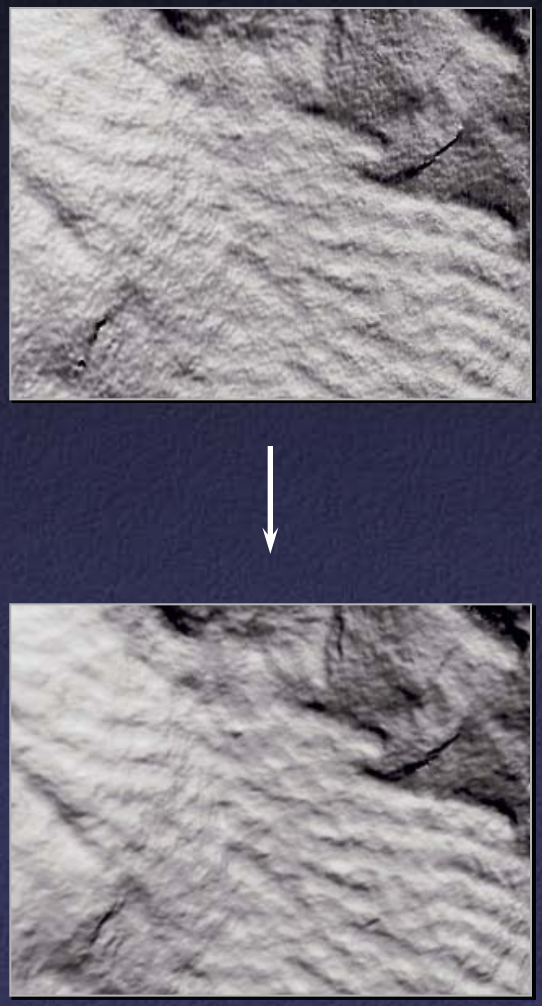

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# Applications of 3D Scanning – Scanning Sculptures

- 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

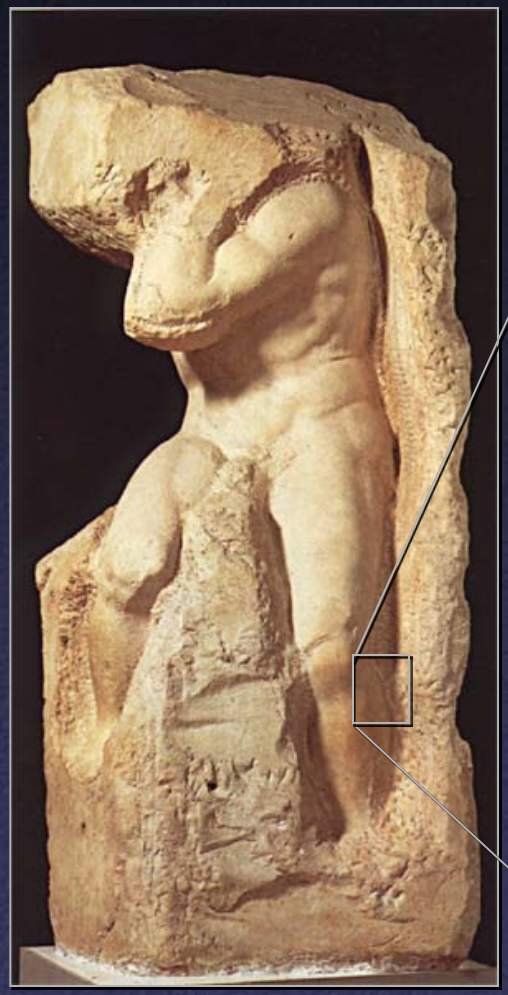
# Results

# The Digital Michelangelo Project

# Goals

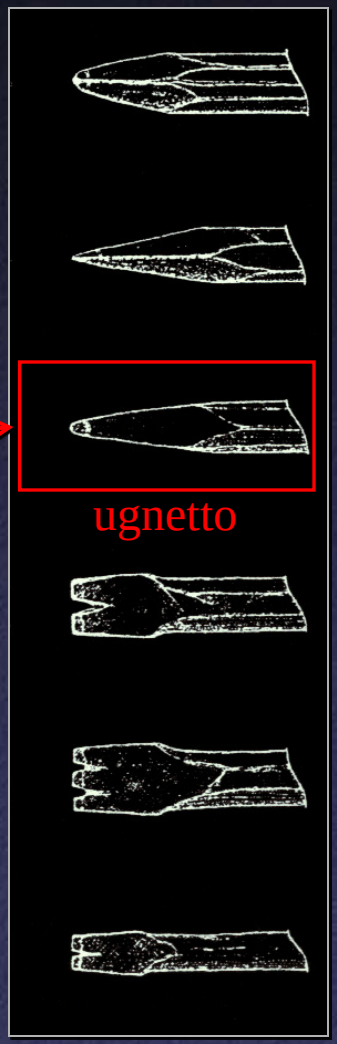
- Scan 10 sculptures by Michelangelo
- High-resolution ("quarter-millimeter") geometry
- Side projects: architectural scanning (Accademia and Medici chapel), scanning fragments of Forma Urbis Romae

# Why Capture Chisel Marks?

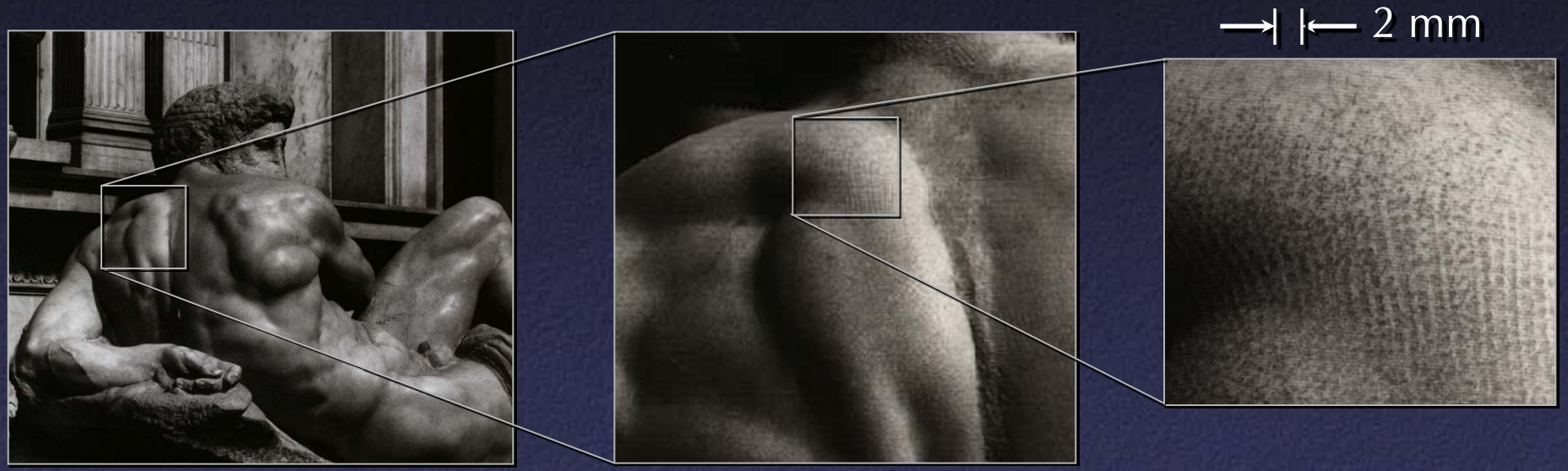


Atlas (Accademia)

?



# 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
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**Graduate students**

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Barbara Caputo
James Davis
Dave Koller
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Szymon Rusinkiewicz
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Marco Tarini
Daniel Wood

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Kathryn Chinn
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

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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**

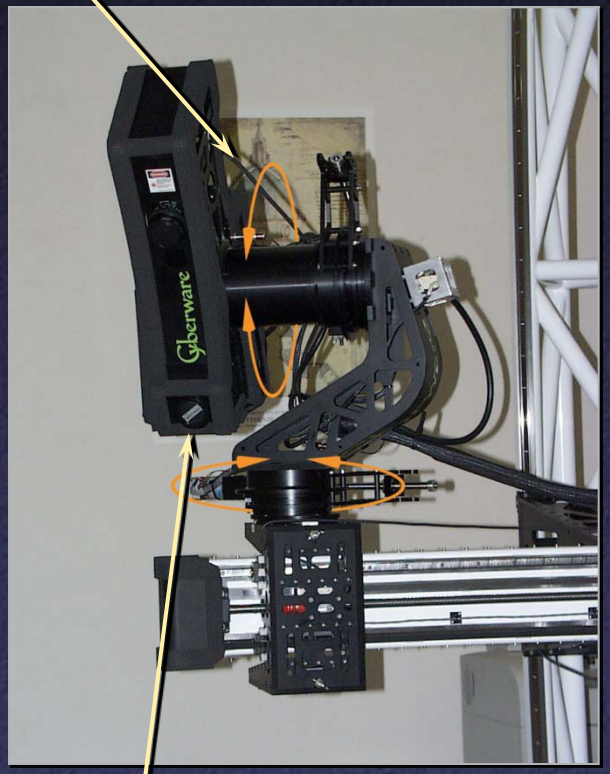
Interval Research
Paul G. Allen Foundation for the Arts
Stanford University

**Equipment donors**

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

# Scanner Design

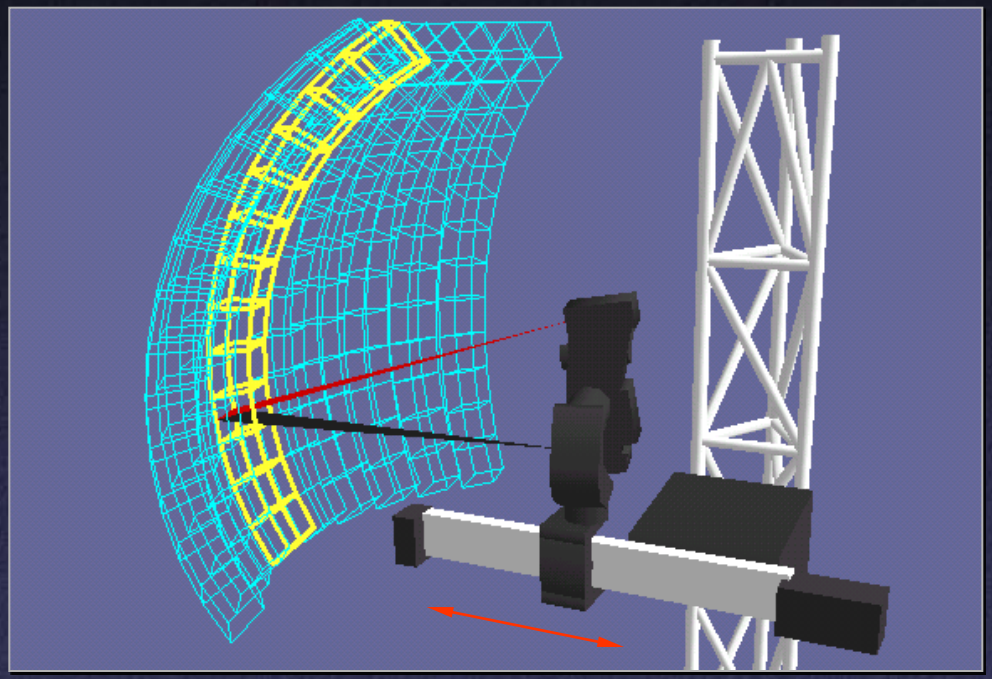
4 motorized axes

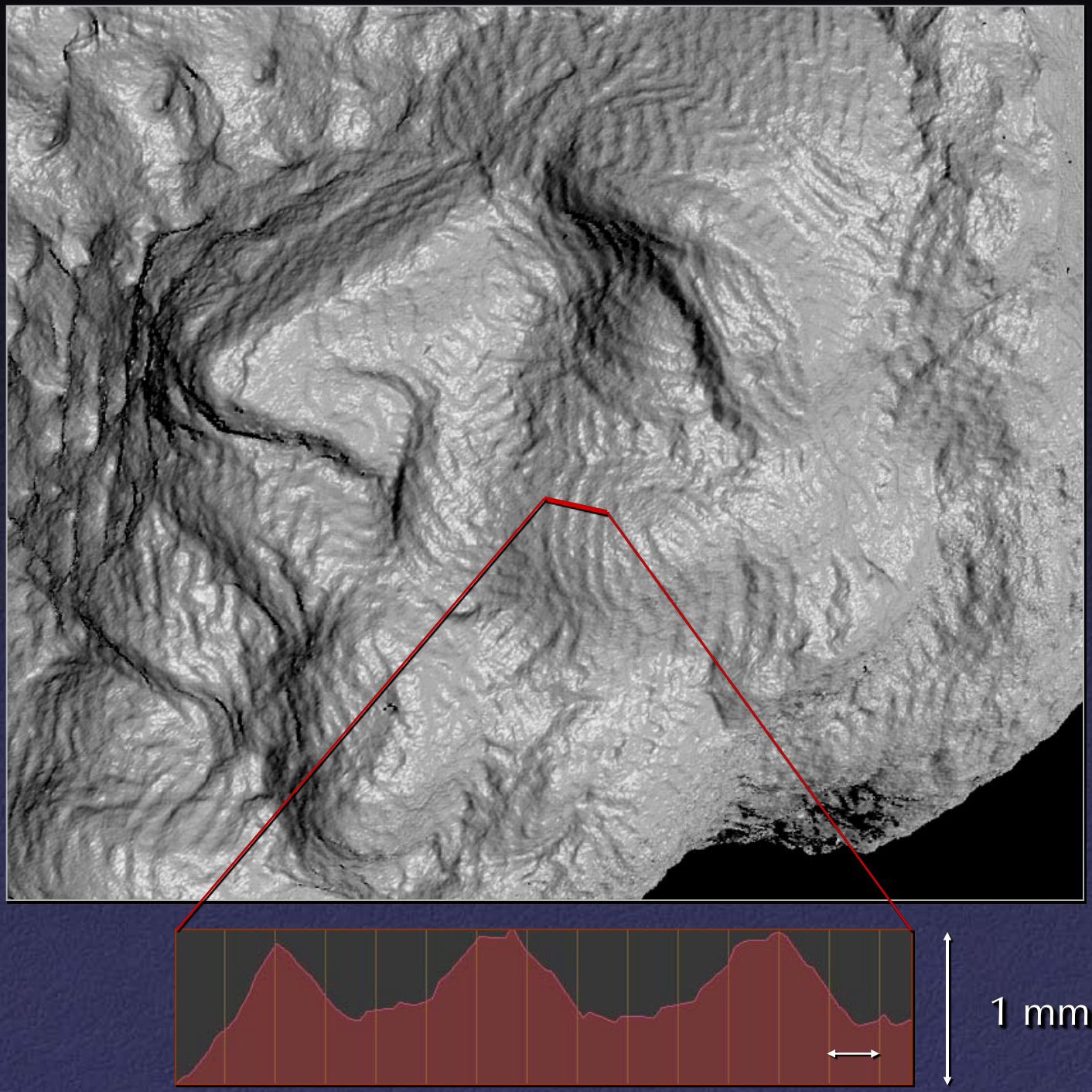

laser, range camera,
white light, and color camera

- 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

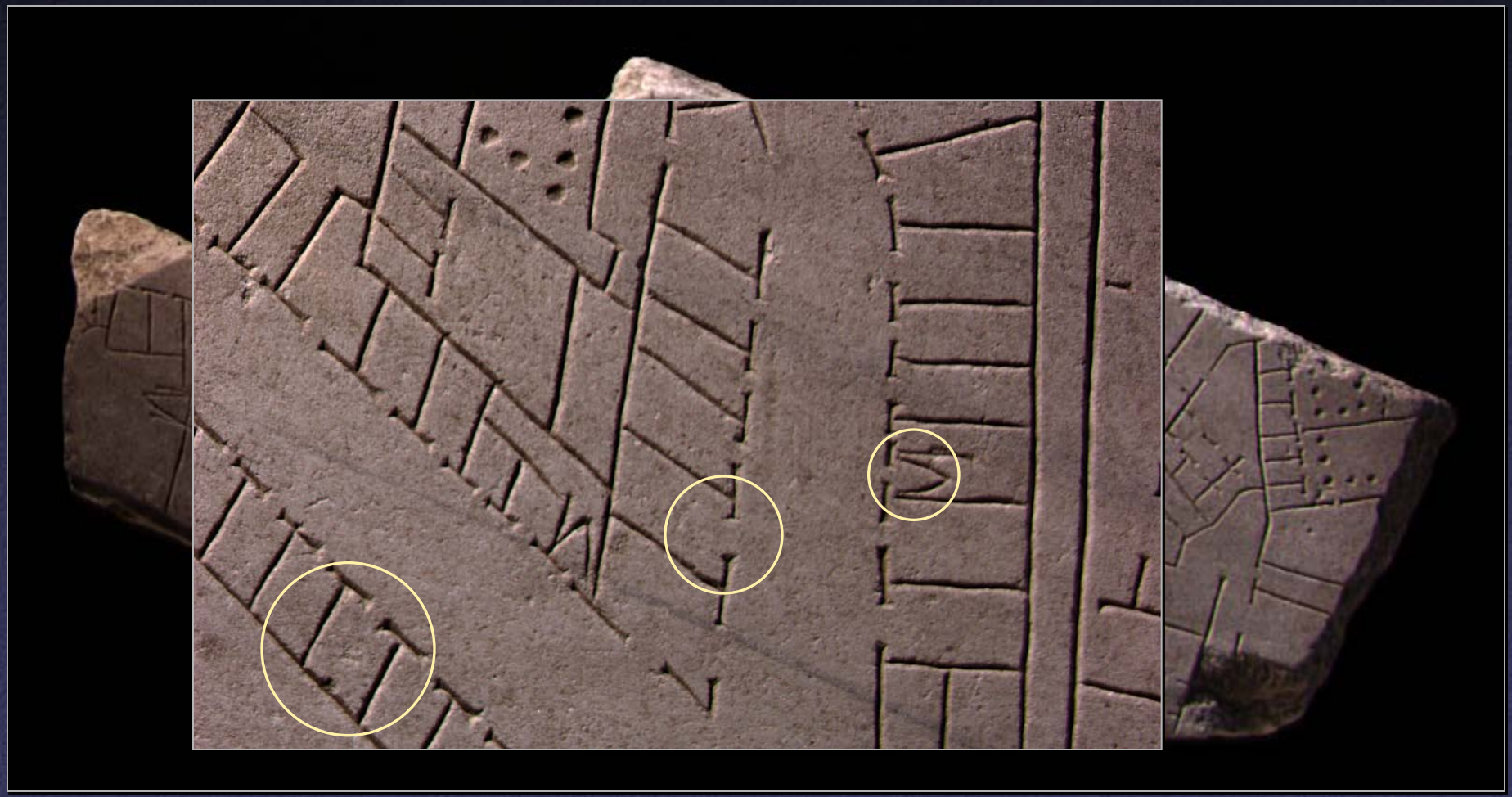
- 480 individually aimed scans
- 0.3 mm sample spacing
- 2 billion polygons
- 7,000 color images
- 32 gigabytes
- 30 nights of scanning
- 22 people

# Head of Michelangelo's David

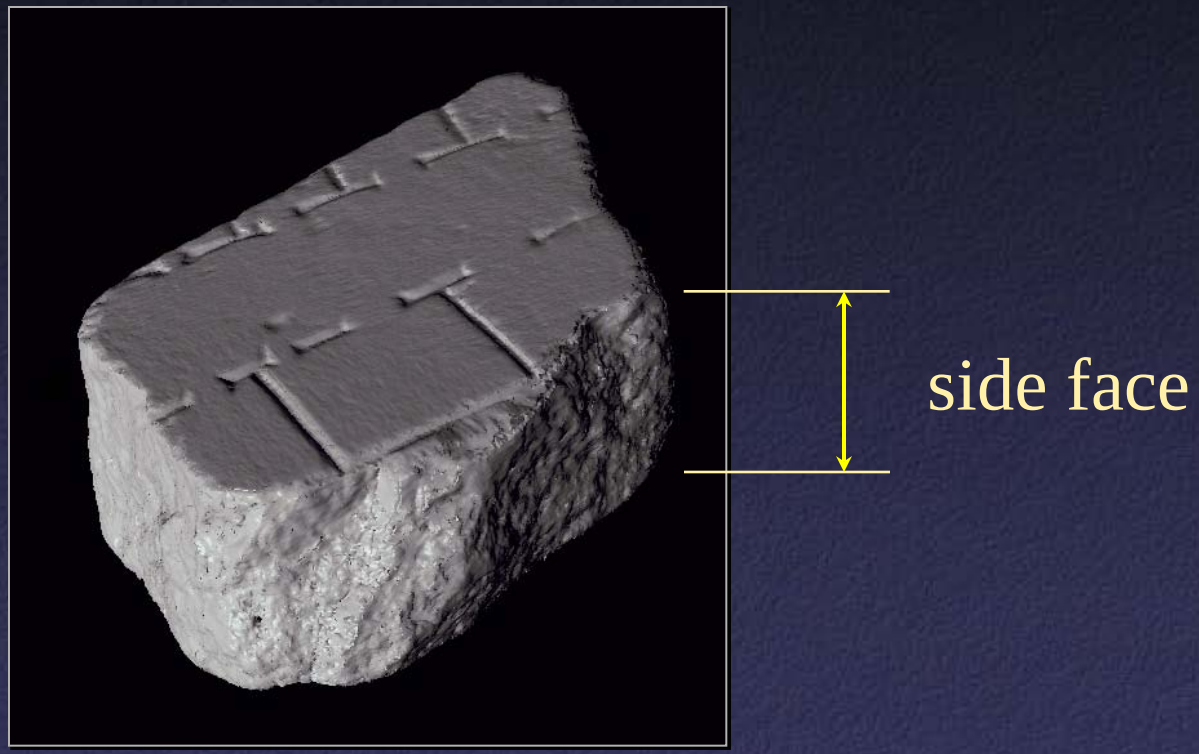
Photograph

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