The Digital Michelangelo Project:
3D scanning of large statues

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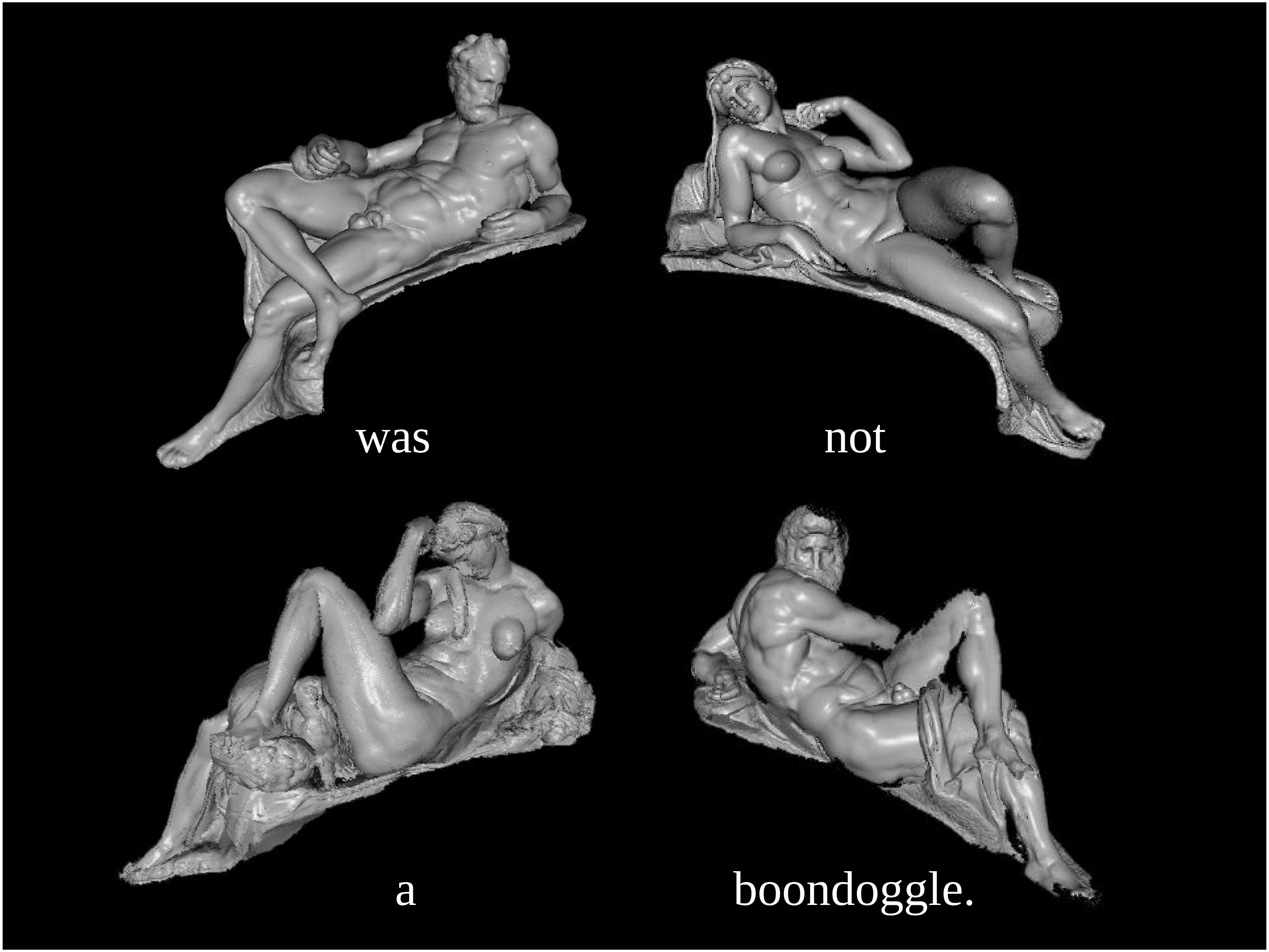
Matt Ginzton, Sean Anderson, James Davis,
Jeremy Ginsberg, Jonathan Shade, Duane Fulk

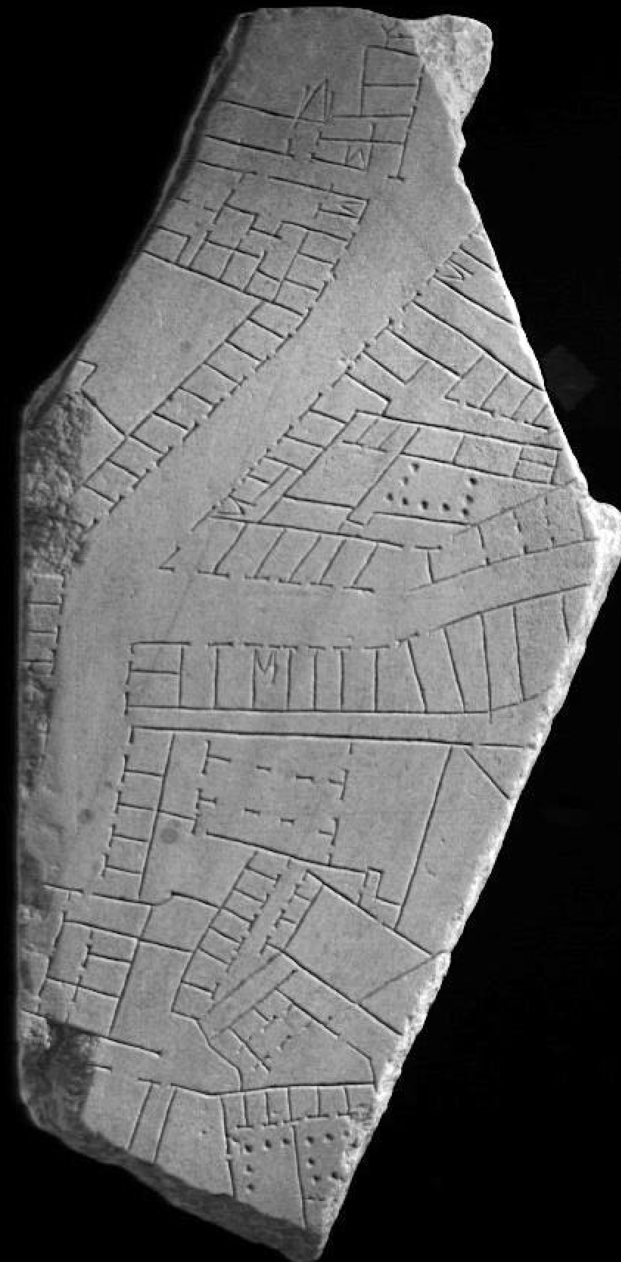
Stanford University,
University of Washington,
Cyberware Inc.

Our year in Italy…


was
not
a
boondoggle.

We

worked



hard!

Executive summary

Create a 3D computer archive of the principal statues and architecture of Michelangelo

<u>What we scanned</u>

- Slave called Atlas
- Awakening slave
- Bearded slave
- Youthful slave
- Dusk
- Dawn
- Day
- Night
- St. Matthew
- David
- 2 museum interiors
- Forma Urbis Romae

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Motivations

- push 3D scanning technology
- tool for art historians
- lasting archive

Technical goals

- scan a big statue → 5 meters
- capture chisel marks → 1/4 mm
- capture reflectance → 1/4 mm

5 meters, 1/4 mm → 20,000:1 → $20{,}000^2$ 1 billion

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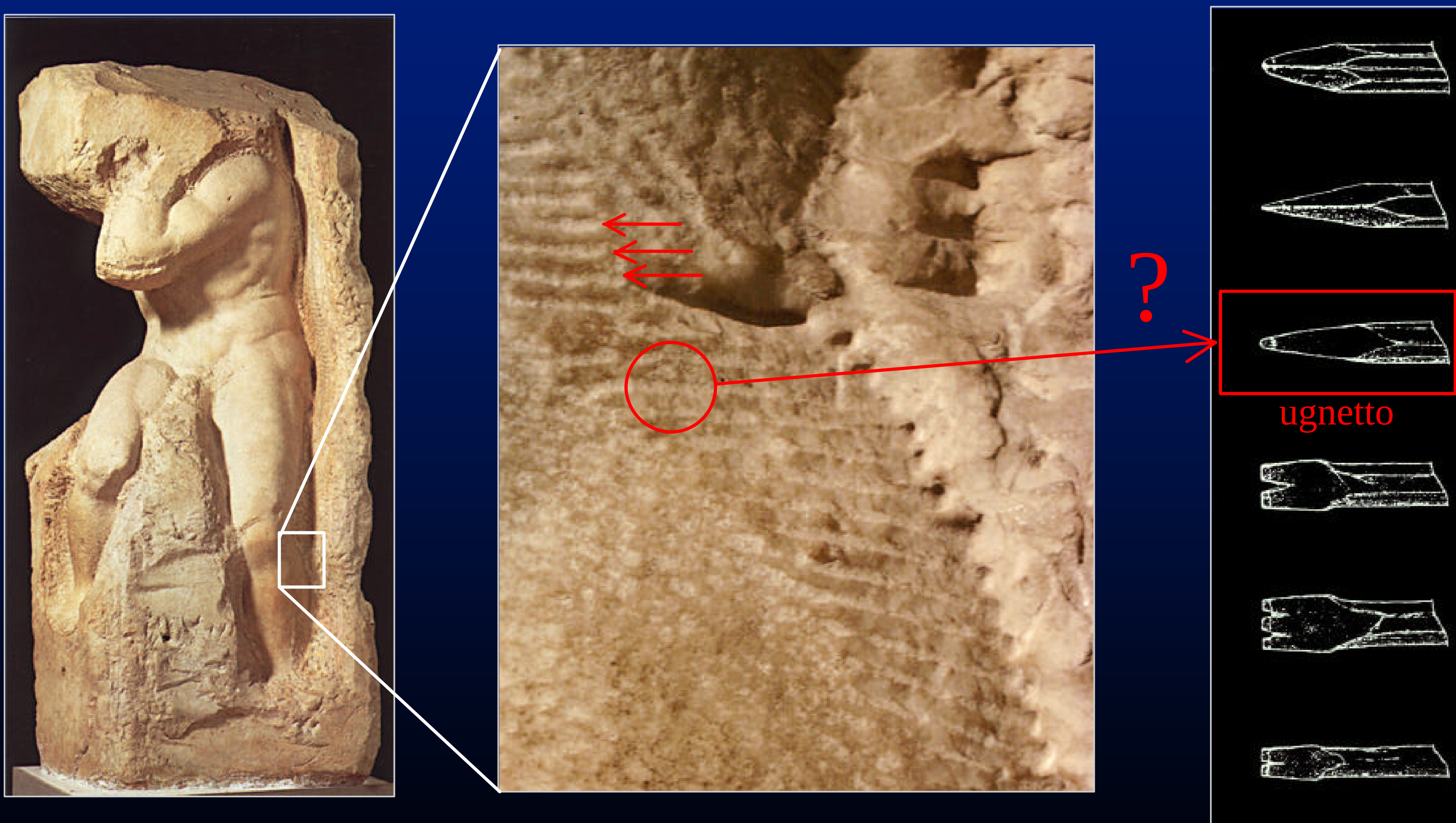
Why capture chisel marks?



Atlas (Accademia)

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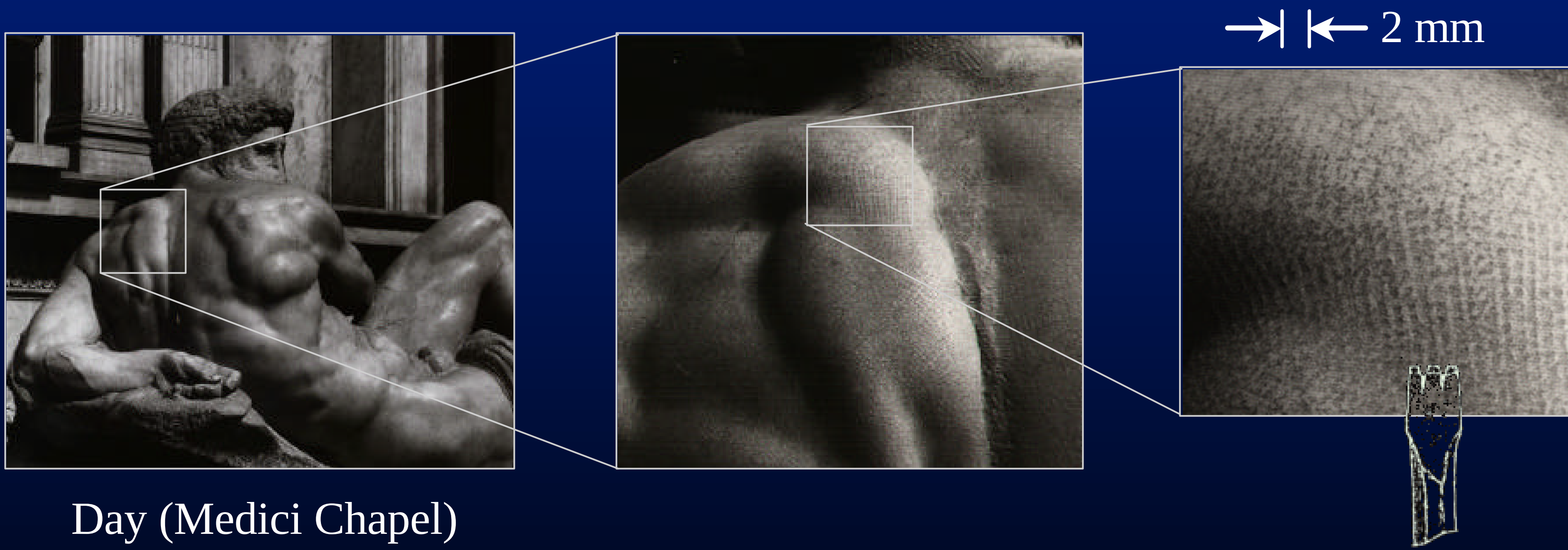

Day (Medici Chapel)

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Outline of talk

- scanner design
- scanning procedure
- post-processing pipeline
- scanning the David
- side project: the Forma Urbis Romae
- future work

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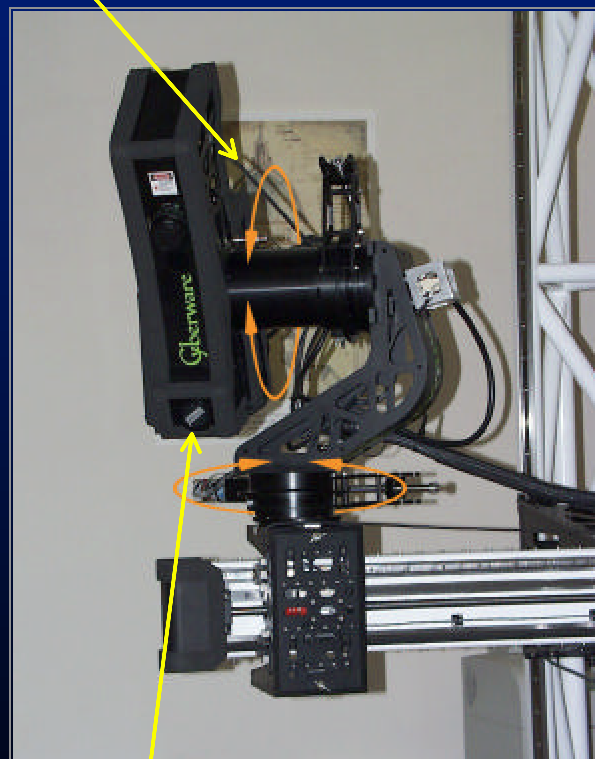
Scanner design

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

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Scanning St. Matthew

working in
the museum

scanning
geometry

scanning
color

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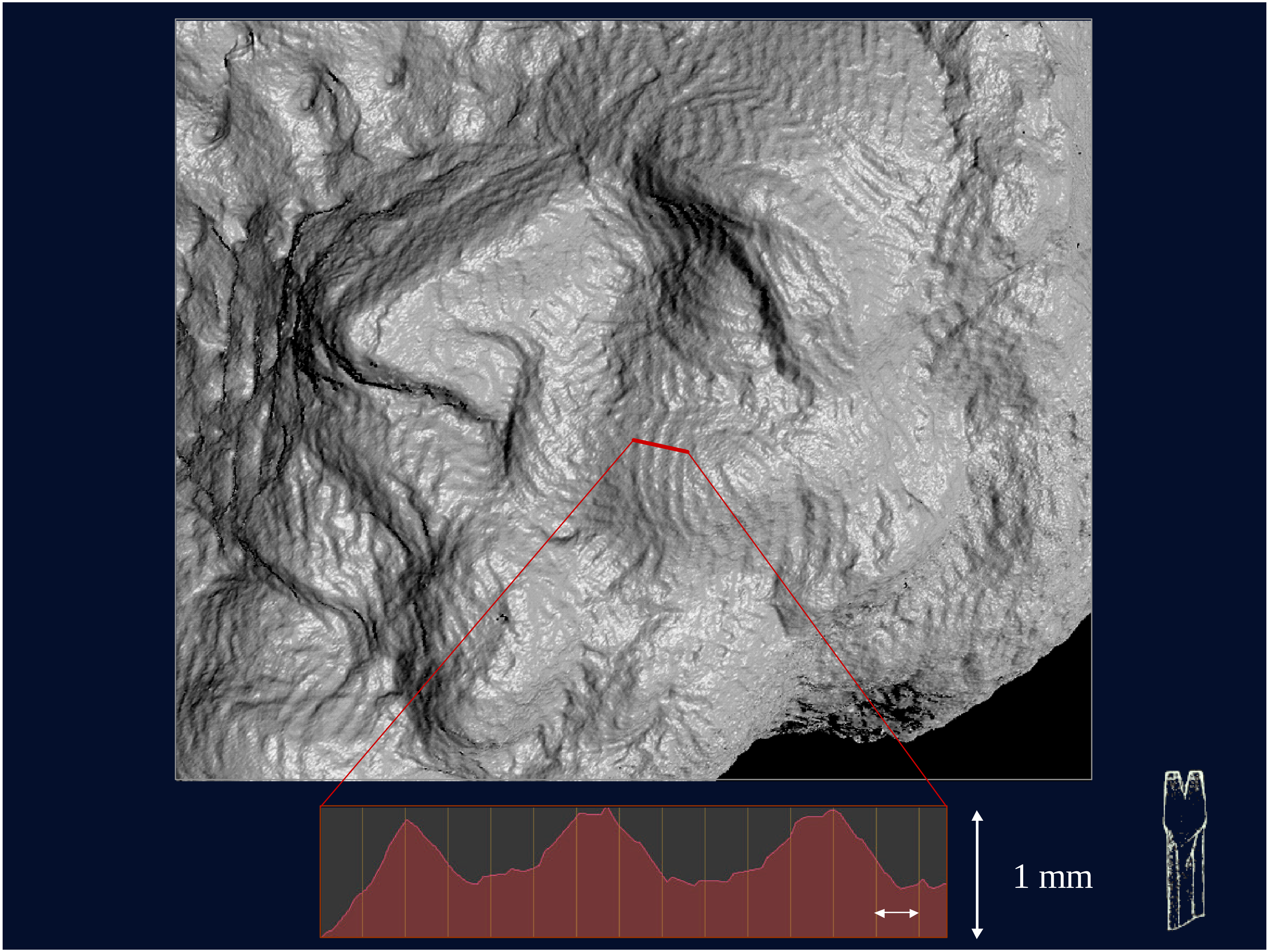
1 mm

Prior work

- large-scale 3D scanning
  - NRC [Beraldin et al. 1997]
  - IBM [Rushmeier et al. 1998]
- our pipeline
  - registration [Pulli 1999]
  - merging [Curless & Levoy 1996]
  - reflectance [Sato et al. 1997]

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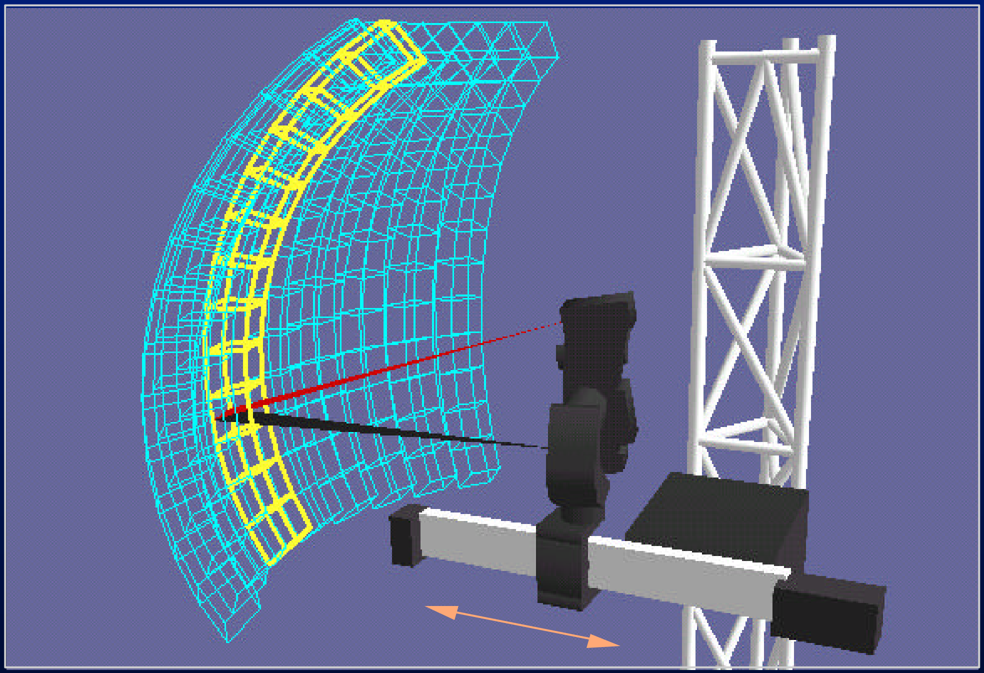
Scanning a large object



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

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Our scan of St. Matthew

- 104 scans
- 800 million polygons
- 4,000 color images
- 15 gigabytes
- 1 week of scanning

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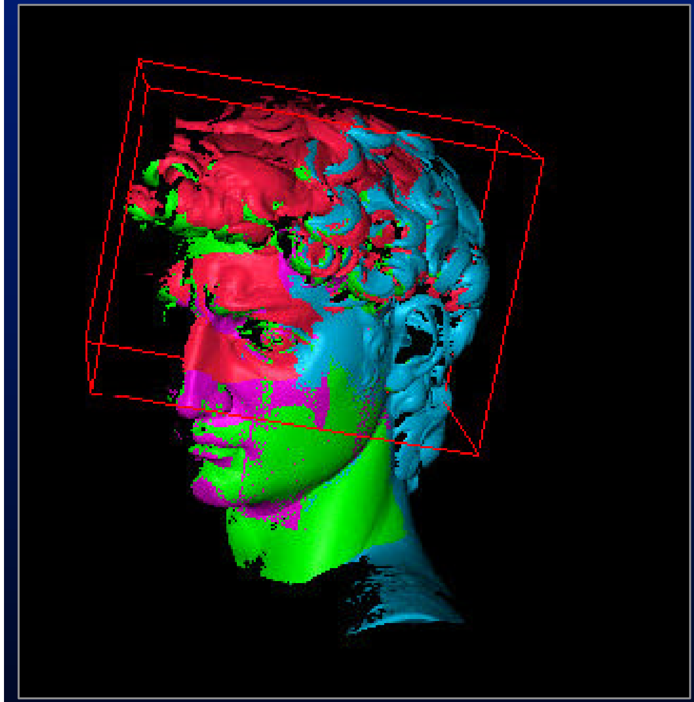
Range processing pipeline



- 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
- lessons learned
  – should have tracked the gantry location
  – ICP is unstable on smooth surfaces

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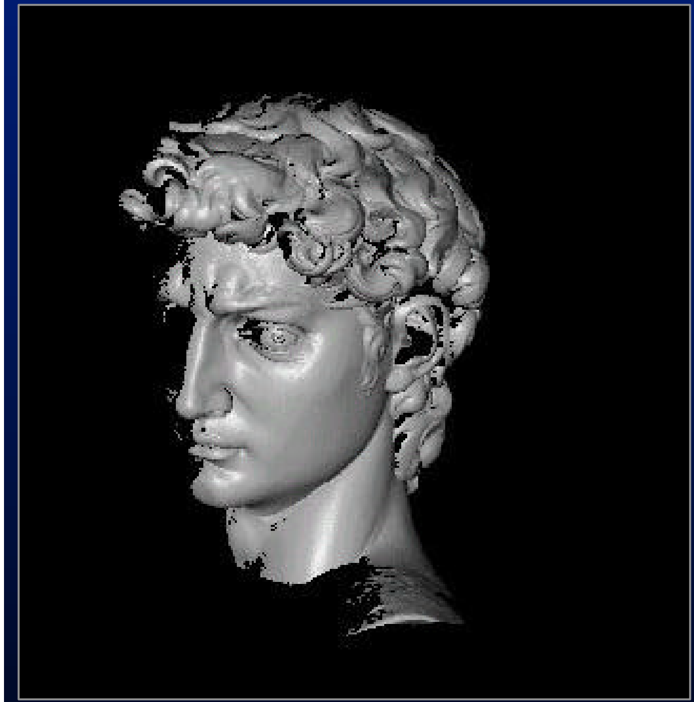
Range processing pipeline



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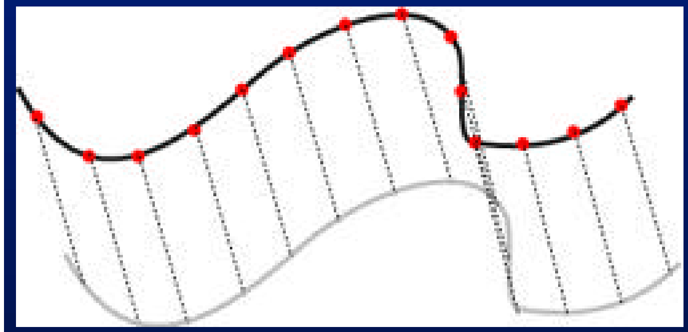

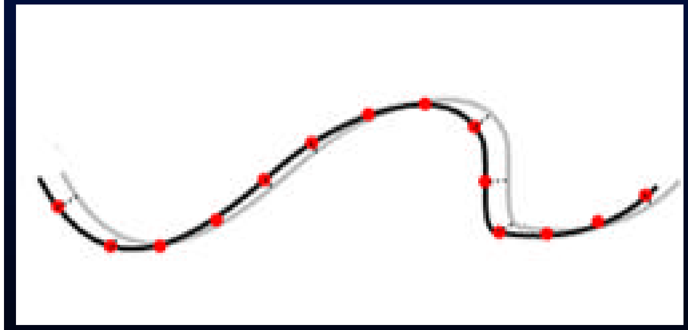

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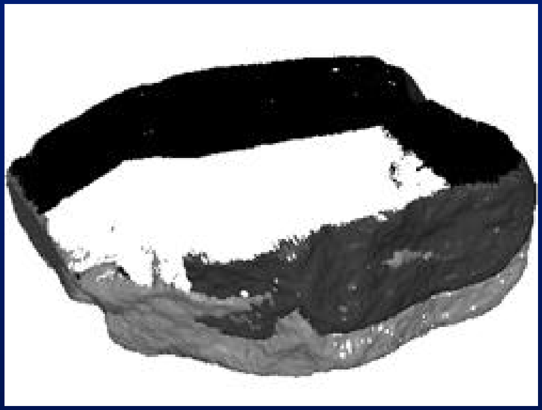

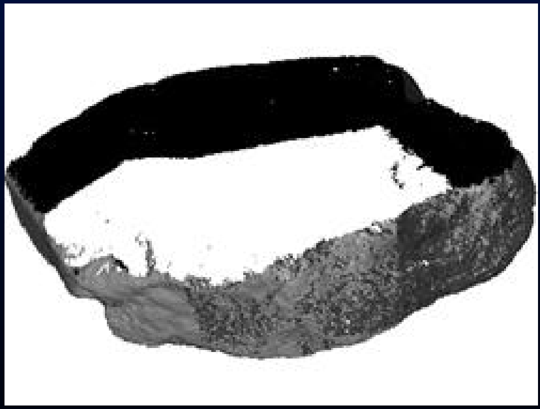

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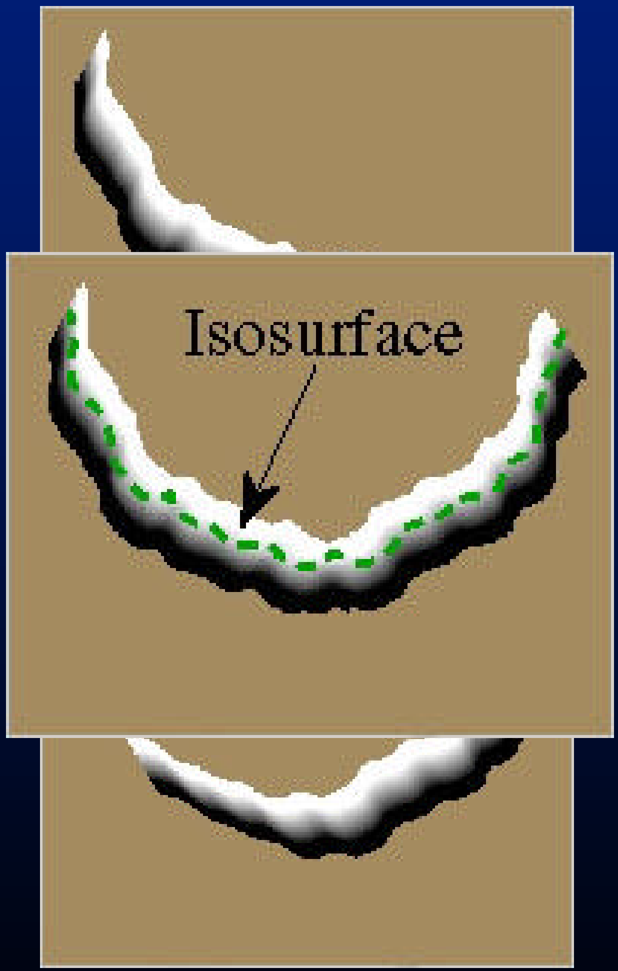

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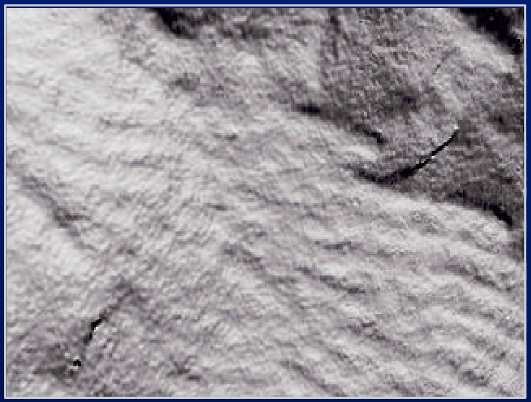

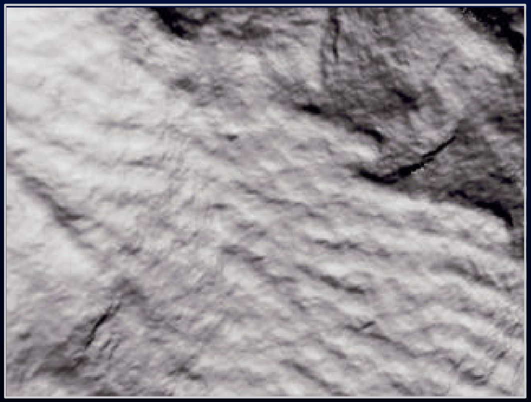

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Color processing pipeline

- steps
  1. compensate for ambient illumination
  2. discard shadowed or specular pixels
  3. map onto vertices – one color per vertex
  4. correct for irradiance → diffuse reflectance
- limitations
  – ignored interreflections
  – ignored subsurface scattering
  – treated diffuse as Lambertian

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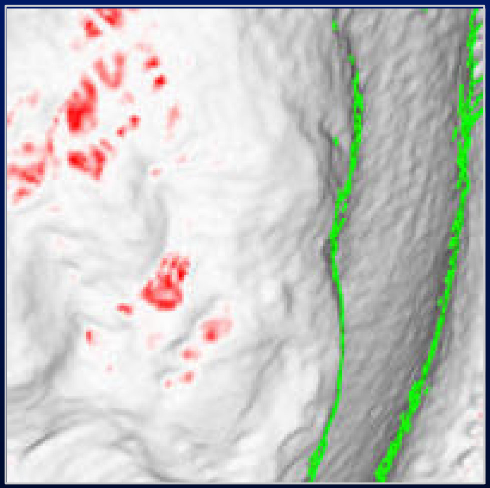
Color processing pipeline



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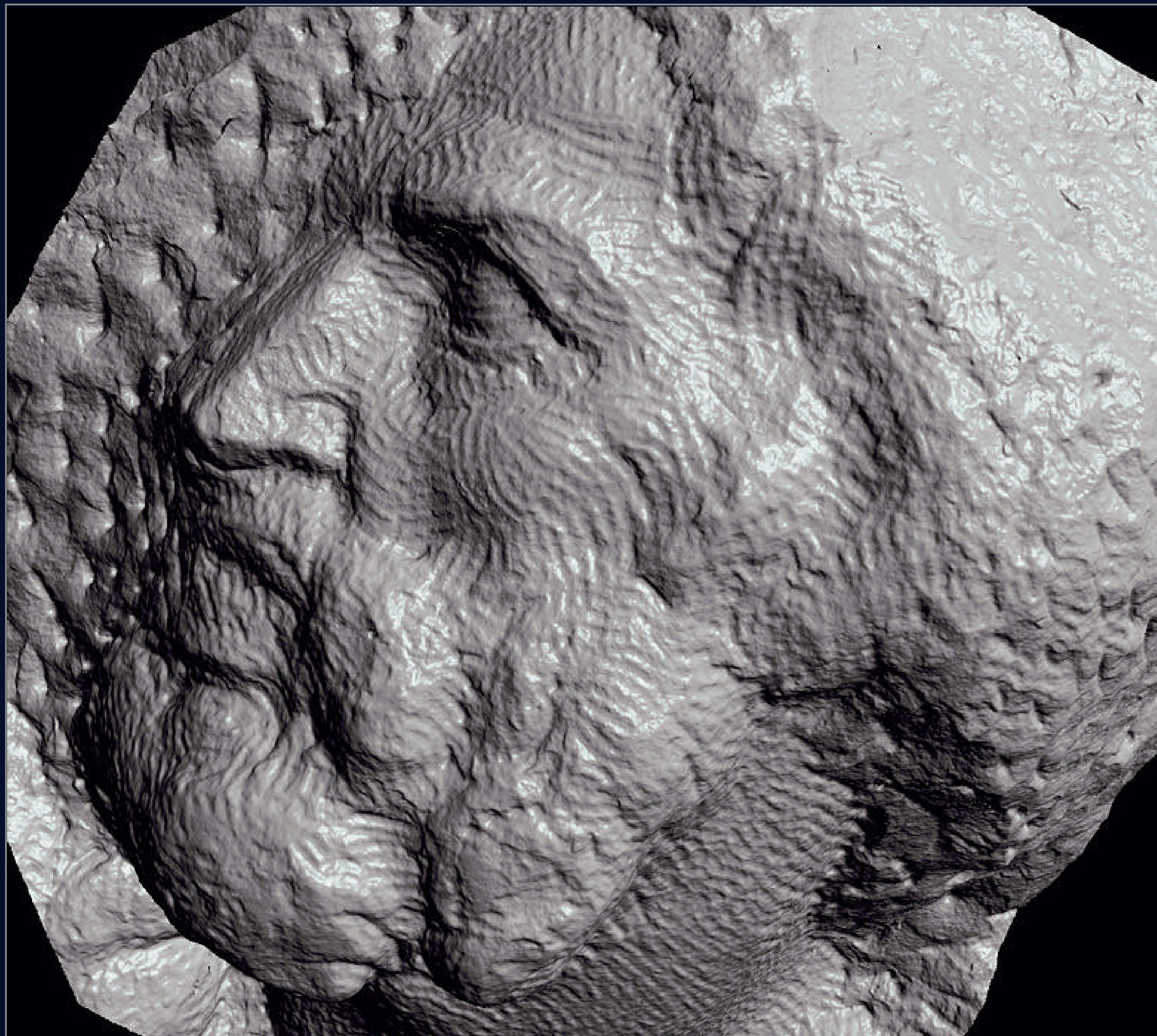
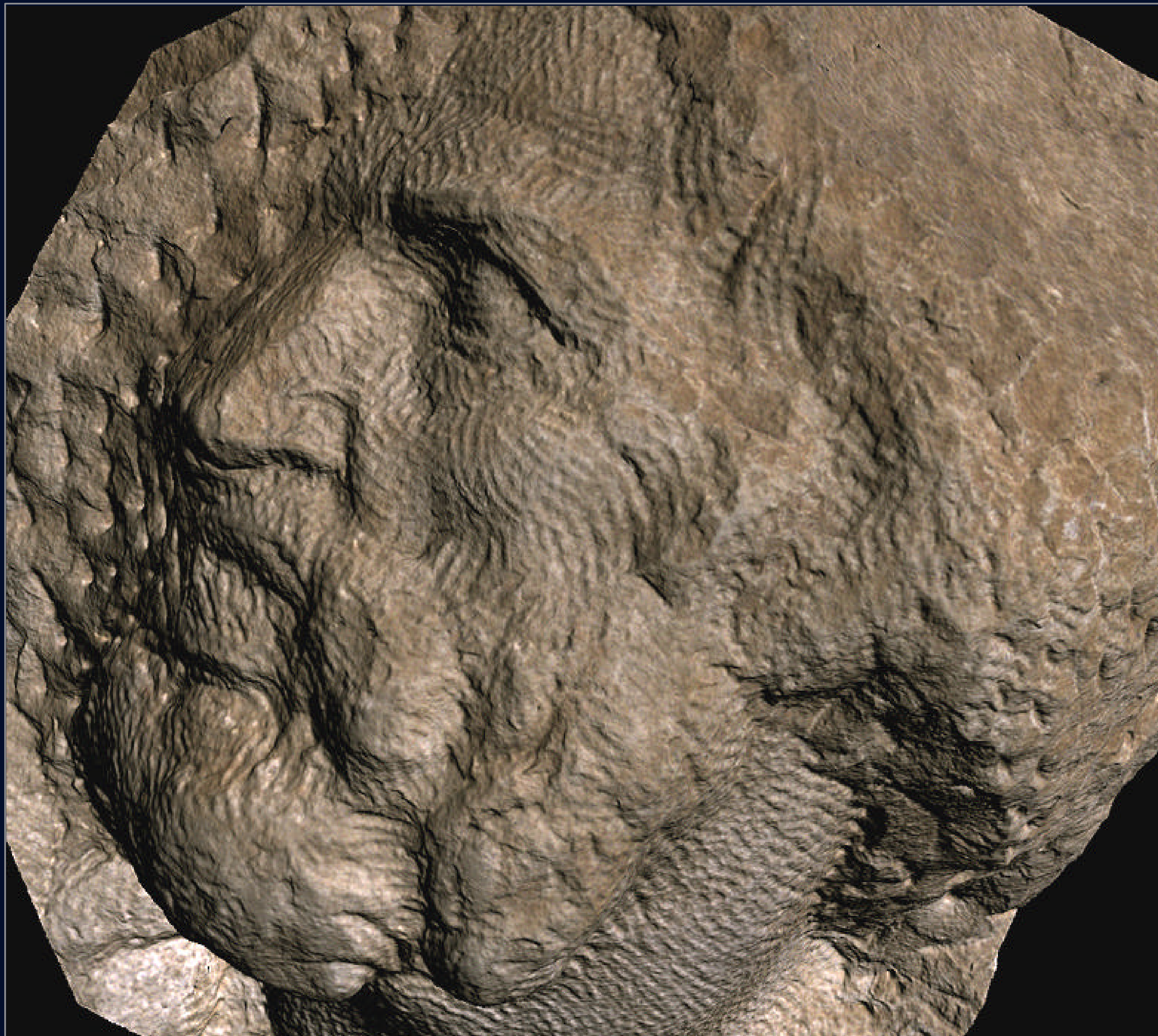
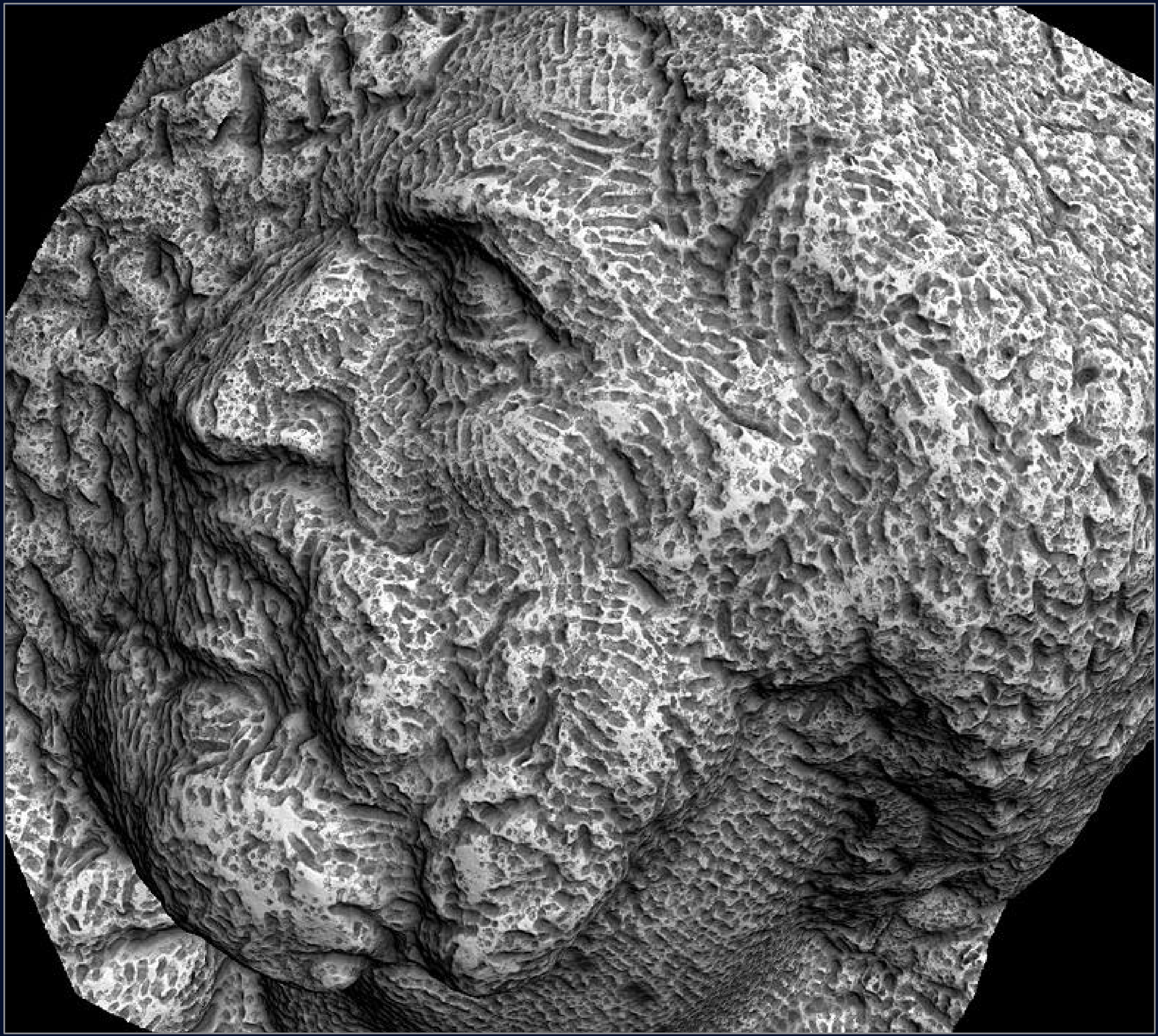


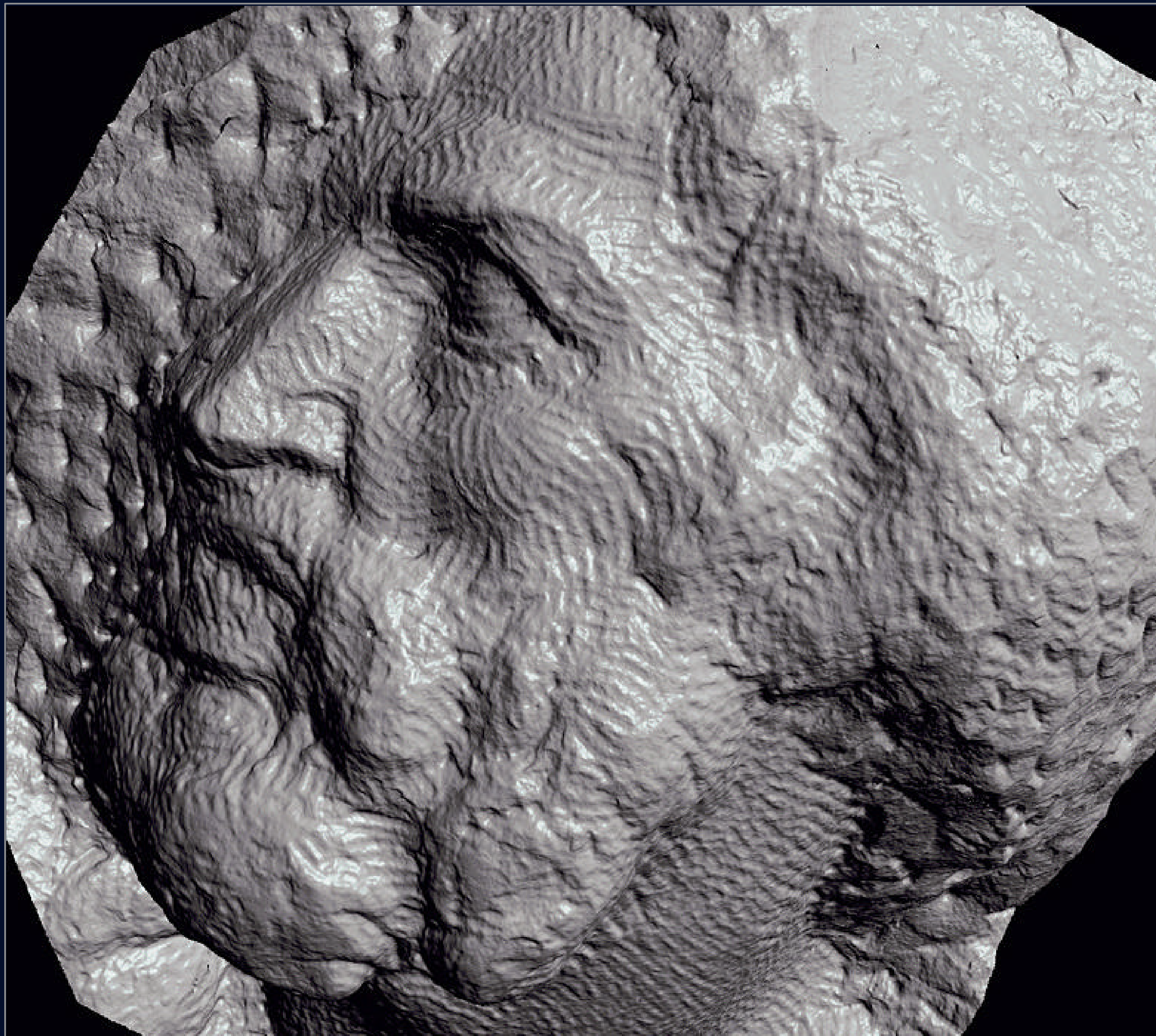
artificial surface reflectance



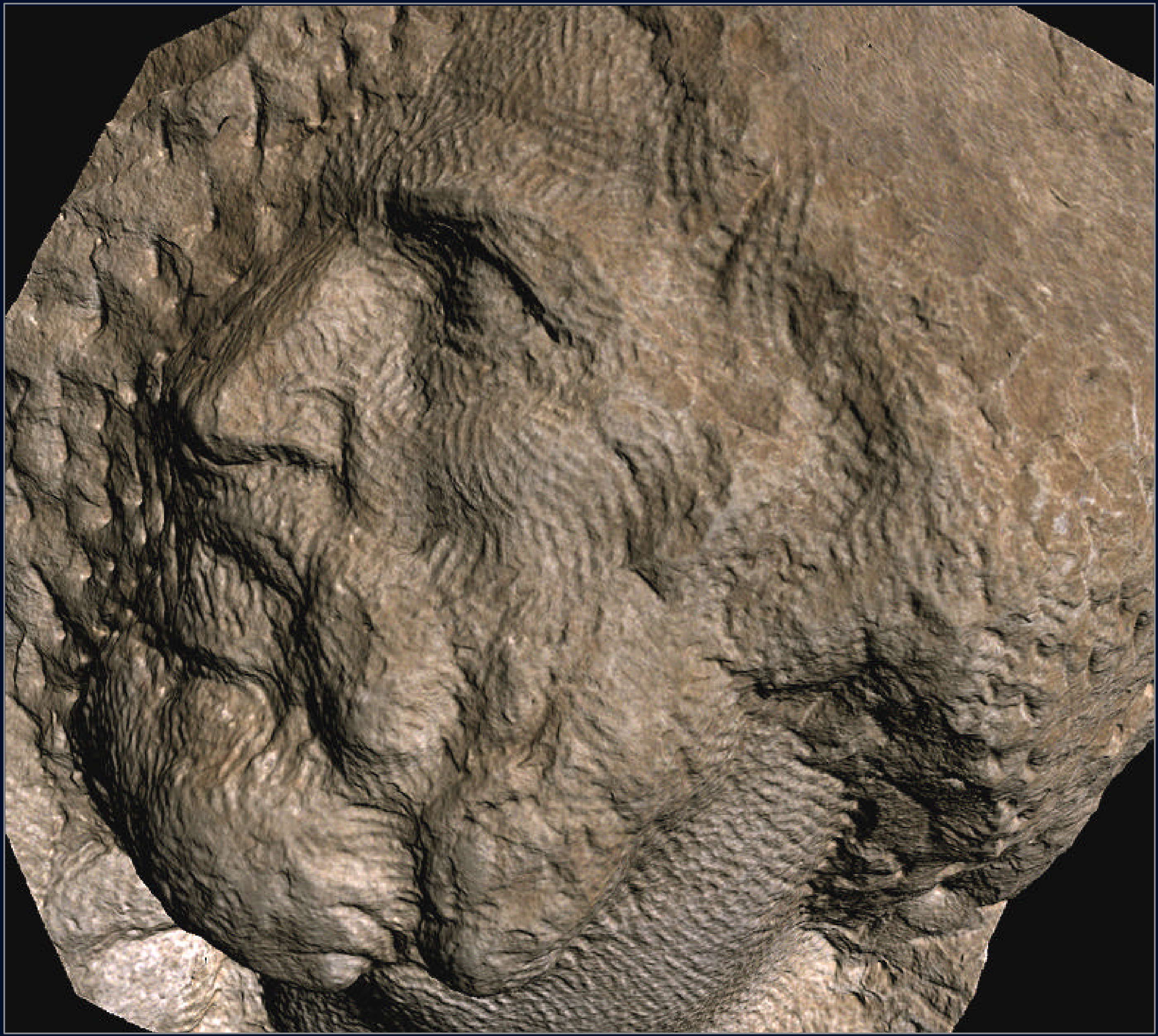
estimated diffuse reflectance



accessibility shading



artificial surface reflectance



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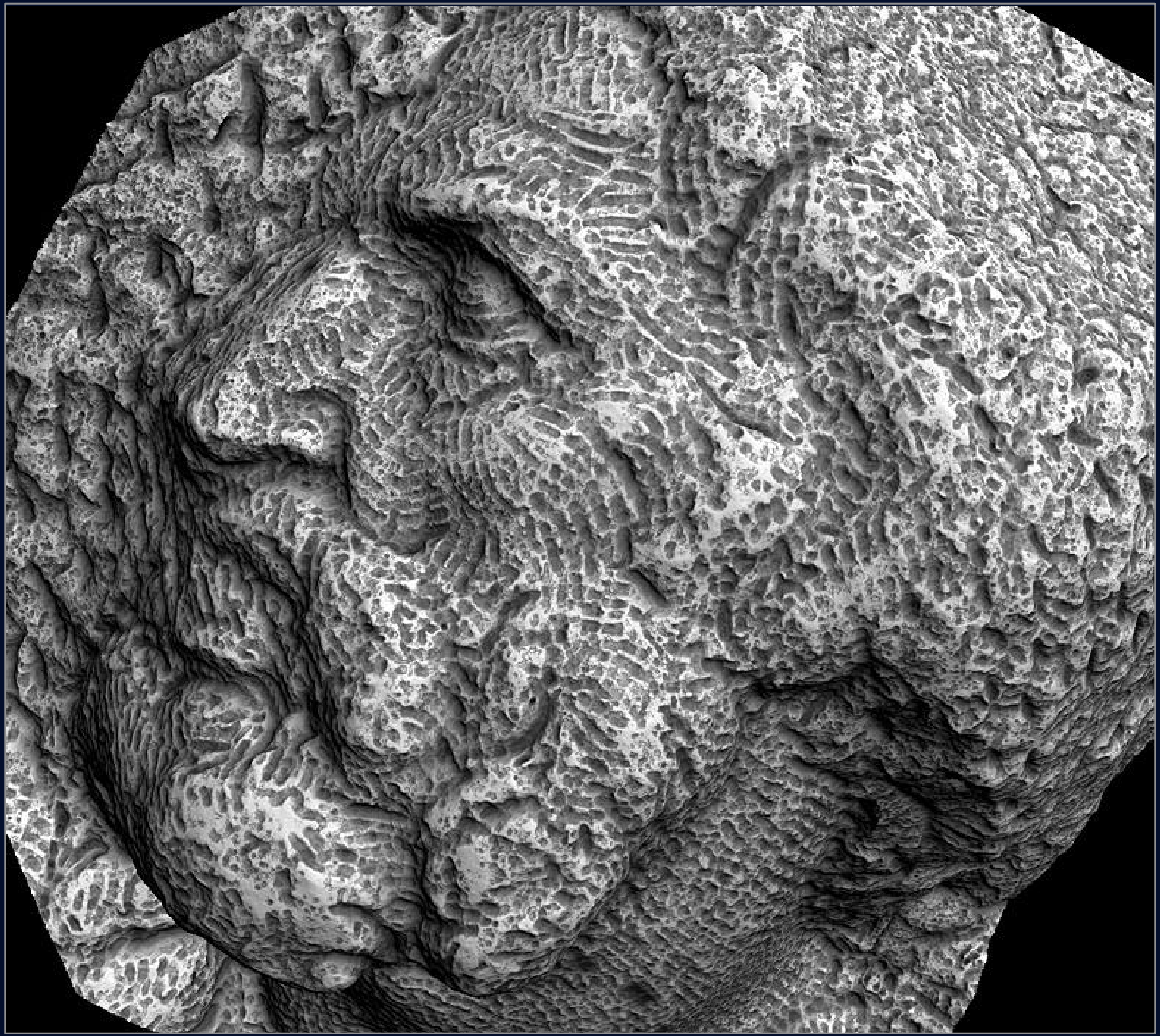

accessibility shading

Hard problem #1: view planning

- procedure
  - estimate a new view point
  - manually set scanning limits
  - run scanning script

```
for horizontal = min to max by 12 cm
    for pan = min to max by 4.3 °
        for tilt = min to max continuously
            perform fast pre-scan (5 ° /sec)
            search pre-scan for range data
        for tilt = all occupied intervals
            perform slow scan (0.5 ° /sec)
    on every other horizontal position,
        for pan = min to max by 7 °
            for tilt = min to max by 7 °
                take photographs without spotlight
        warm up spotlight
        for pan = min to max by 7 °
            for tilt = min to max by 7 °
                take photographs with spotlight
```

- lessons learned
  - need automatic view planning – especially in the endgame
  - 50% of time on first 90%, 50% on next 9%, ignore last 1%

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Hard problem #2: accurate scanning in the field

- error budget
  - 0.25mm of position, 0.013° of orientation
- design challenges
  - minimize deflection and vibration during motions
  - maximize repeatability
- lessons learned
  - motions were sufficiently accurate and repeatable
  - remounting was not sufficiently repeatable
  - calibration of such a large gantry is hard
  - used ICP to circumvent poor calibration

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Hard problem #3: handling large datasets

- range images instead of polygon meshes
  - z(u,v) [2 bytes], not xyz [3 floats]
  - yields 18:1 lossless compression
- out-of-core global registration
  - pairwise alignments only once
  - fast global relaxation of pairwise alignments
- multiresolution viewer using splatting
  - real-time frame rate when moving
  - progressive refinement when idle

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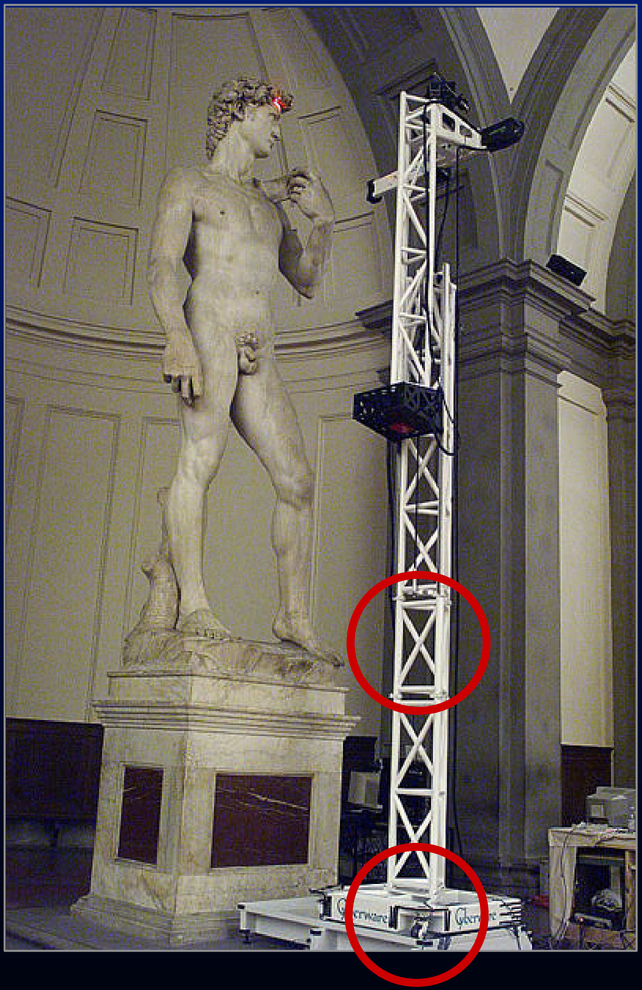
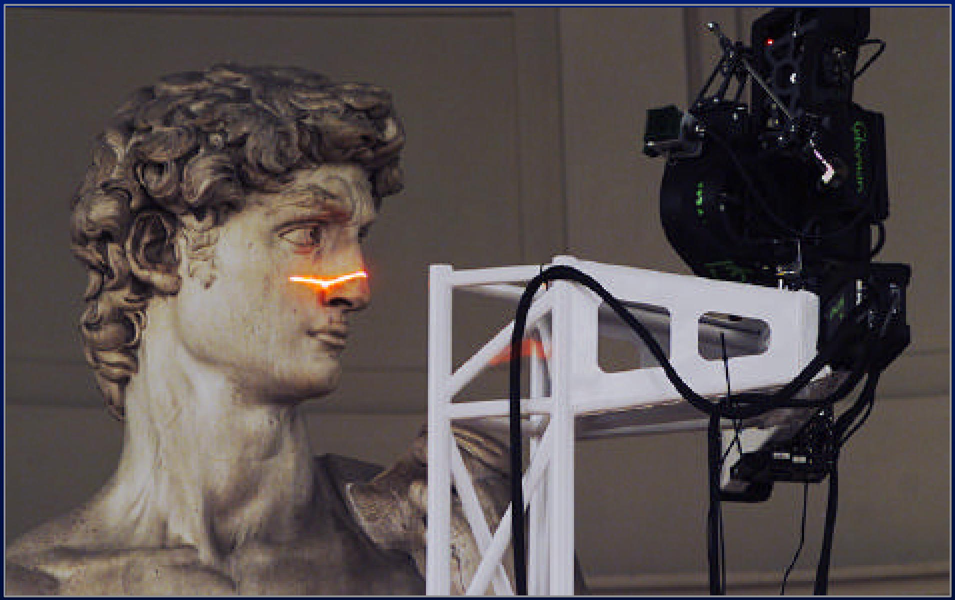
Scanning the David





height of gantry:	7.5 meters
weight of gantry:	800 kilograms

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Statistics about the scan

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

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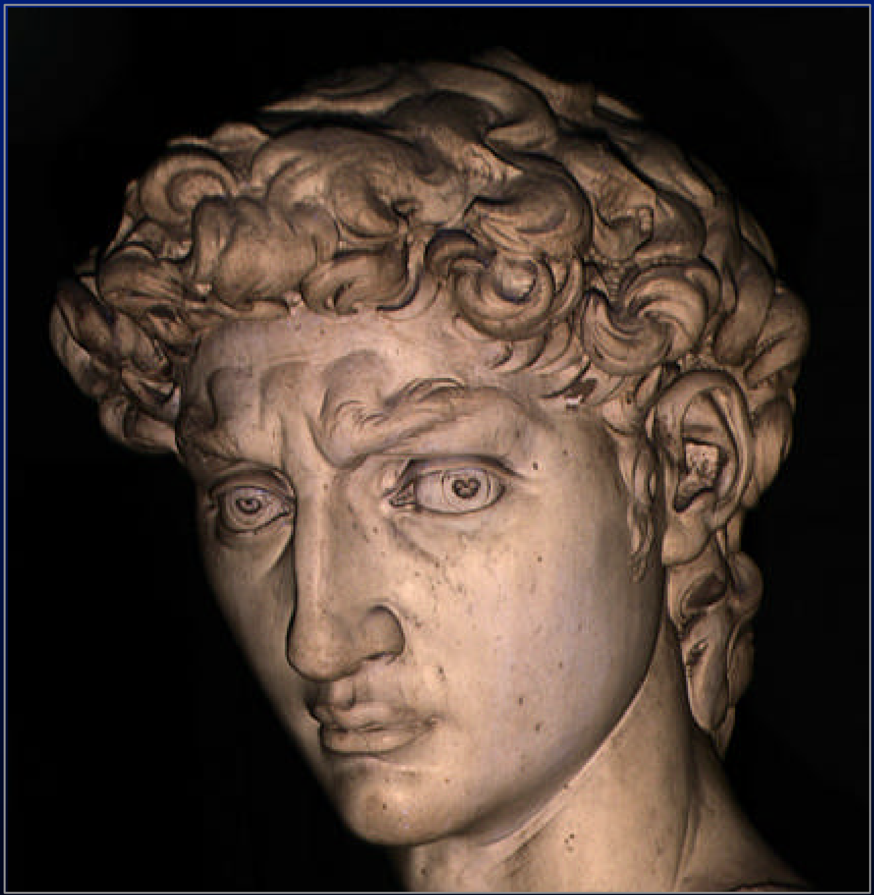
Head of Michelangelo’s David



photograph

1.0 mm computer model

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The importance of viewpoint

classic 3/4 view

left profile

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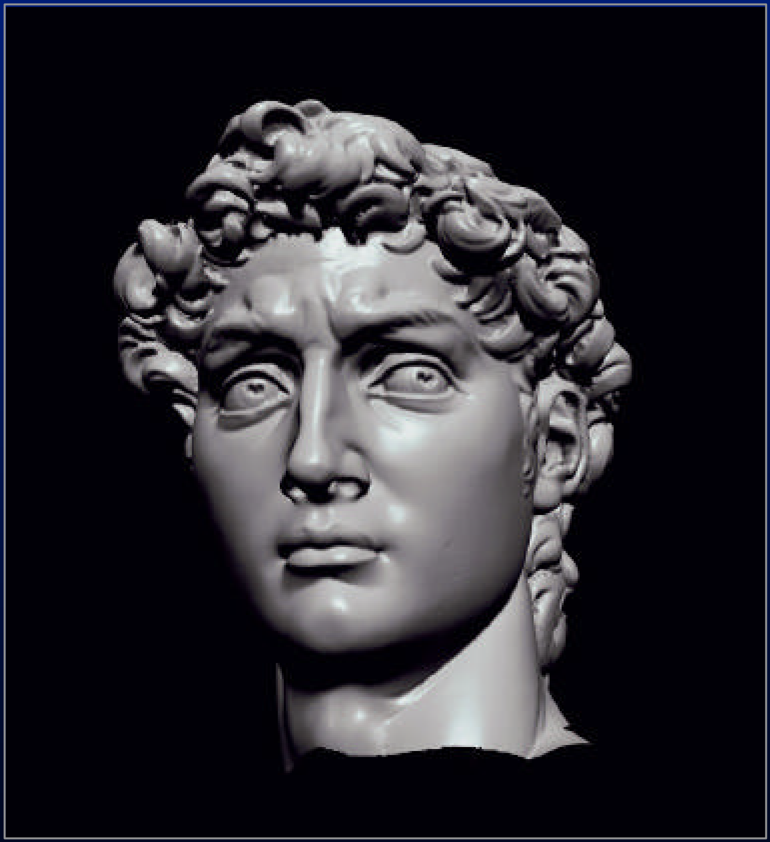
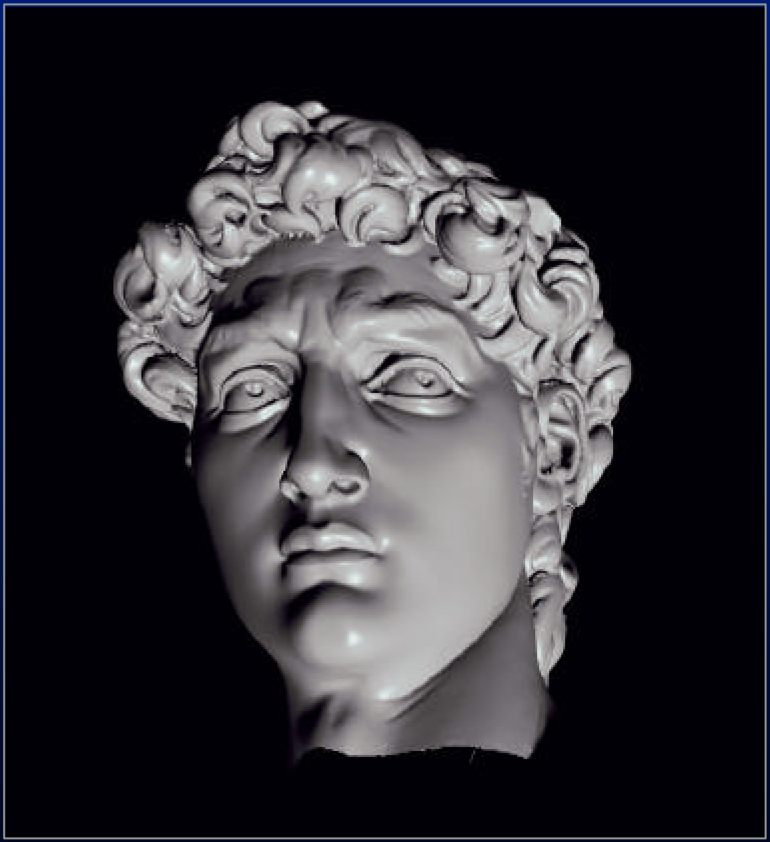
The importance of lighting



lit from above



lit from below

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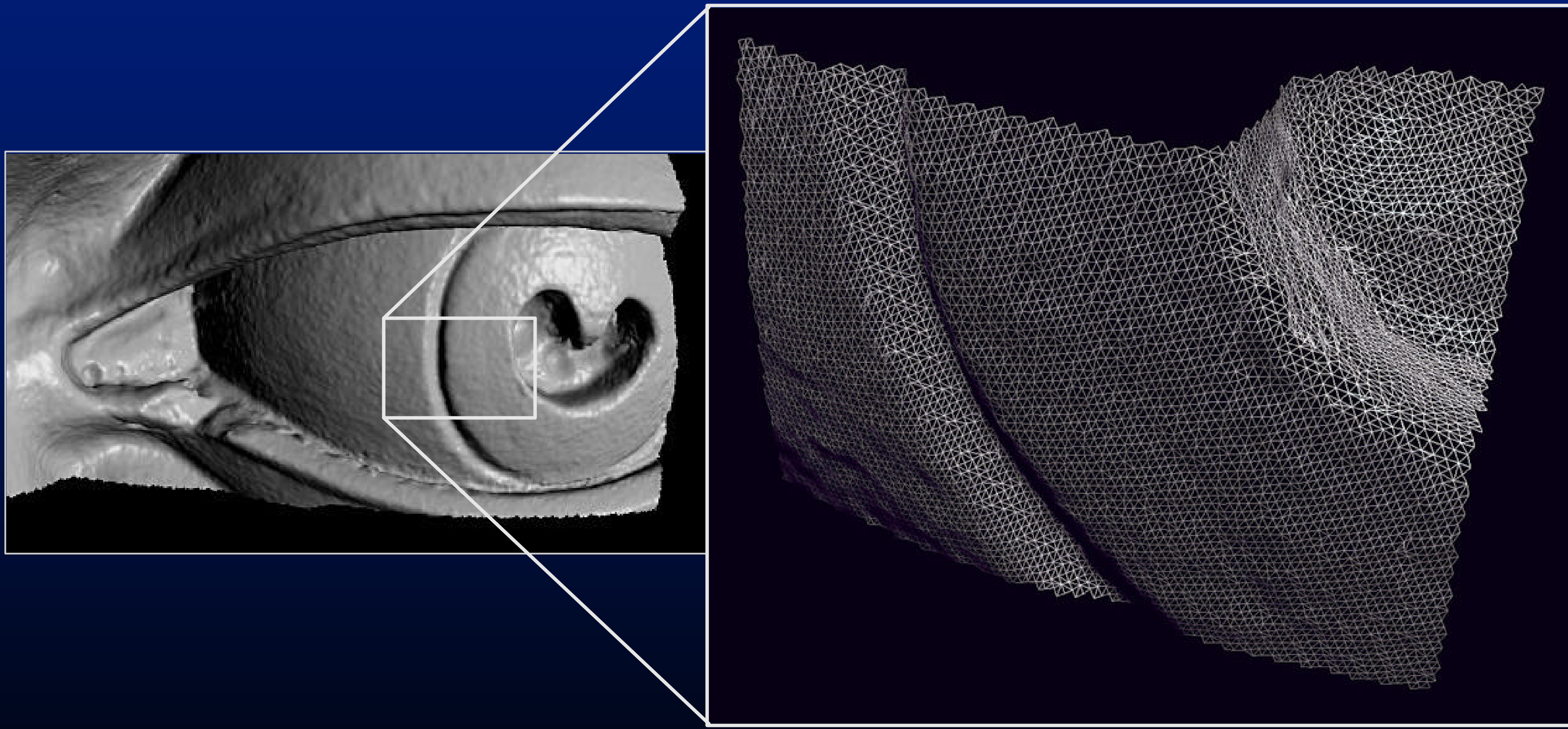
David's left eye



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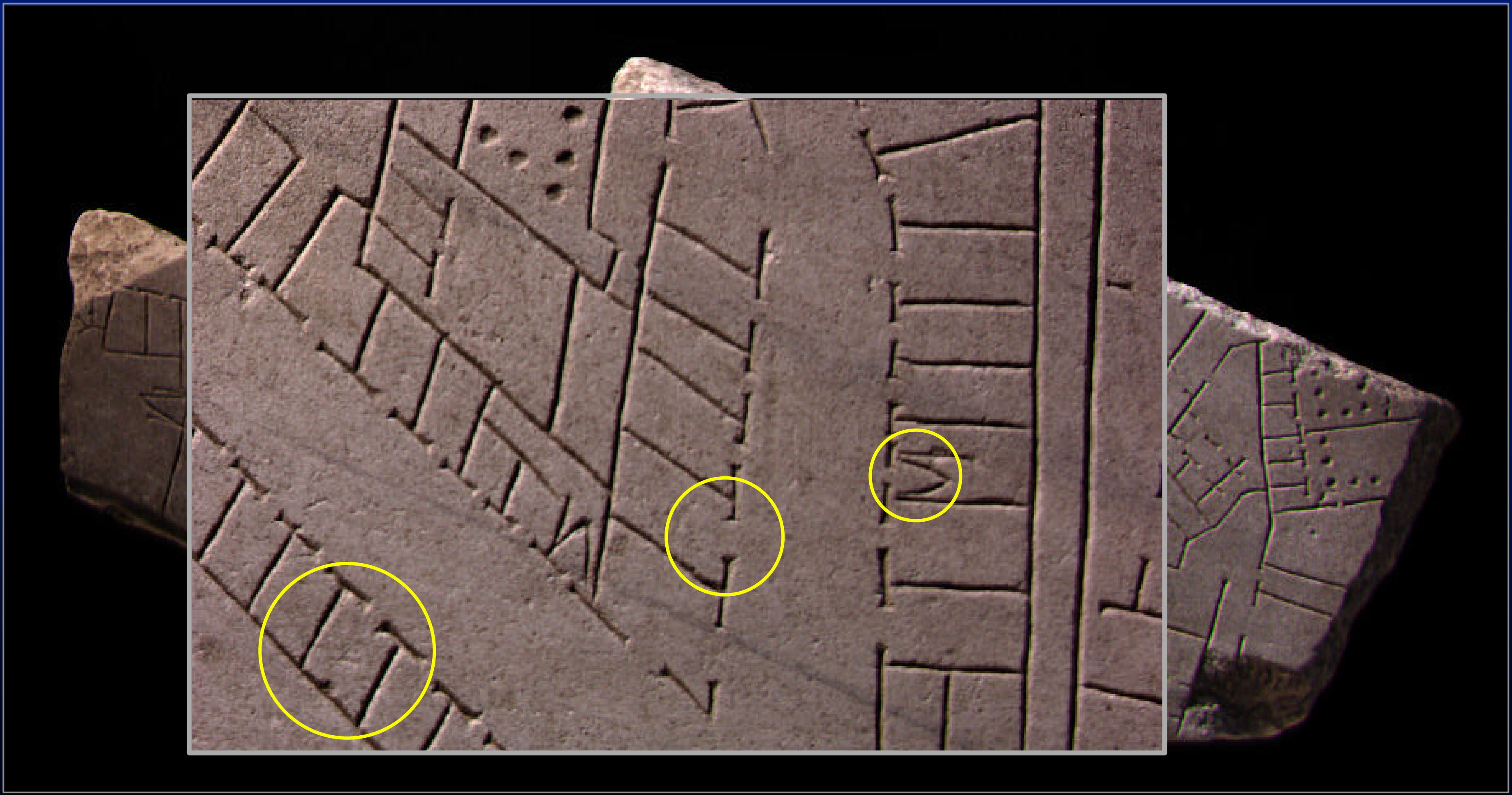
Side project:
The Forma Urbis Romae



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side face

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forma urbis romae

Logistical challenges

- getting permission to scan the statues
- recalcitrant customs officials
- inaccessible buildings
- narrow doorways
- clumsy truckers
- shaky scaffolding
- bumped scanners
- endless questions
- museum guards
- glass barricades
- adhoc repairs
- time pressure
- getting sleep

- *tourists' flashbulbs !!*

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Future work

1. hardware
   – scanner design
   – scanning in tight spots
   – tracking scanner position
   – better calibration methodologies
   – scanning uncooperative materials
   – insuring safety for the statues

2. software
   – automated view planning
   – accurate, robust global alignment
   – more sophisticated color processing
   – handling large datasets
   – filling holes

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3. uses for these models
   - permanent archive
   - virtual museums
   - physical replicas
   - restoration record
   - geometric calculations
   - projection of images onto statues

4. digital archiving
   - central versus distributed archiving
   - insuring longevity for the archive
   - authenticity, versioning, variants
   - intellectual property rights
   - permissions, distribution, payments
   - robust 3D digital watermarking
   - detecting violations, enforcement
   - real-time viewing on low-cost PCs
   - indexing, cataloguing, searching
   - viewing, measuring, extracting data

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Alex Roetter
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David Weekly

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Dott.ssa Franca Falletti
Dott.ssa Licia Bertani
Alessandra Marino
Matti Auvinen

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Dott.ssa Susanna Le Pera
Dott.ssa Anna Somella
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In Pisa

Roberto Scopigno

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Project: http://graphics.stanford.edu/projects/mich/
Software: /software/qsplat/
3D models: /data/mich/