The Digital Michelangelo Project: 3D scanning of large statues

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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

What we scanned

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

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

Technical goals

• scan a big statue \( \rightarrow 5 \text{ meters} \)
• capture chisel marks \( \rightarrow 1/4 \text{ mm} \)
• capture reflectance \( \rightarrow 1/4 \text{ mm} \)

\( 20,000^2 \) \( 1 \text{ billion} \) \( 20,000:1 \)
Why capture chisel marks?

Atlas (Accademia)
Day (Medici Chapel)

\[ \rightarrow | \leftarrow 2 \text{ mm} \]
Outline of talk

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

• 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

4 motorized axes

laser, range camera, white light, and color camera
Scanning St. Matthew

working in the museum

scanning geometry

scanning color
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]
Scanning a large object

- calibrated motions
  - pitch (yellow)
  - pan (blue)
  - horizontal translation (orange)

- uncalibrated motions
  - vertical translation
  - rolling the gantry
  - remounting the scan head
Our scan of St. Matthew

- 104 scans
- 800 million polygons
- 4,000 color images
- 15 gigabytes
- 1 week of scanning
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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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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artificial surface reflectance
estimated diffuse reflectance
artificial surface reflectance
estimated diffuse reflectance
accessibility shading
Hard problem #1:
view planning

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

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

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
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
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
Scanning the David

- height of gantry: 7.5 meters
- weight of gantry: 800 kilograms
Statistics about the scan

- 480 individually aimed scans
- 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
The importance of viewpoint

classic 3/4 view
left profile
The importance of lighting

lit from above

lit from below
David’s left eye
Side project:
The Forma Urbis Romae
side face
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 !!
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
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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