(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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Scanning Buildings

- Quality control during construction
- As-built models
Scanning Buildings

- Quality control during construction
- As-built models
Clothing

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

Range acquisition

- Contact
  - Mechanical (CMM, jointed arm)
  - Inertial (gyroscope, accelerometer)
  - Ultrasonic trackers
  - Magnetic trackers

- Transmissive
  - Industrial CT
  - Ultrasound
  - MRI

- Reflective
  - Non-optical
    - Radar
    - Sonar

- Optical
Touch Probes

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

Faro Arm – Faro Technologies, Inc.
Range Acquisition Taxonomy

Optical methods

Passive

Active

Shape from X:
- stereo
- motion
- shading
- texture
- focus
- defocus

Active variants of passive methods
- Stereo w. projected texture
- Active depth from defocus
- Photometric stereo

Time of flight

Triangulation
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 $\frac{1}{2} \lambda_m n$
AM Modulation Time of Flight

- Accuracy / working volume tradeoff
  (e.g., noise ~ $1/500$ 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
Triangulation: Moving the Camera and Illumination
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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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, 0.1 mm 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
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- Lisa Pacelle
- Dr. Kari Pulli
- John Gerth
- Prof. Marc Levoy
- Domi Pitturo

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- Matti Auvinen
- Dottssa Franca Falletti
- Alessandra Marino

In Rome
- Prof. Eugenio La Rocca
- Dottssa Anna Somella
- Dottssa Susanna Le Pera
- Dottssa Laura Ferrea

In Pisa
- Roberto Scopigno

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Equipment donors
- Cyberware
- Faro Technologies
- Silicon Graphics
- 3D Scanners
- Sony
- Intel
- Cyra Technologies
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 a Large Object

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

- Uncalibrated motions
  - vertical translation
  - rolling the gantry
  - remounting the scan head
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