3D Scanning
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3D Scanning Applications

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

Computer Graphics Pipeline

- Human time = expensive
- Sensors = cheap
  - Computer graphics increasingly relies on measurements of the real world

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

Clothing

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

The Digital Michelangelo Project
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 project

Why Capture Chisel Marks as Geometry?

- Day (Medici Chapel)
  - 2 mm

Side project: The Forma Urbis Romae

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

Forma Urbis Romae Fragment
Range Acquisition Taxonomy

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

- Transmissive
  - Industrial CT
  - Ultrasound
  - MRI

- Reflective
  - Non-optical
  - Optical

- Range acquisition

Optical methods

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

- Time of flight

- Triangulation

Passive

Active

Active variants of passive methods

- Stereo w. projected texture
- Active depth from defocus
- Photometric stereo

Why More Than 2 Views?

- Baseline
  - Too short – low accuracy
  - Too long – matching becomes hard

Touch Probes

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

Faro Arm – Faro Technologies, Inc.

Stereo

- Find feature in one image, search along epipolar line in other image for correspondence
**Why More Than 2 Views?**
- Ambiguity with 2 views

**Shape from Motion**
- "Limiting case" of multibaseline stereo
- Track a feature in a video sequence
- For $n$ frames and $f$ features, have $2nf$ knowns, $6n+3f$ unknowns

**Shape from Shading**
- Given: image of surface with known, constant reflectance under known point light
- Estimate normals, integrate to find surface
- Problem: ambiguity
  - Advantages:
    - Single image
    - No correspondences
    - Analogue in human vision
  - Disadvantages:
    - Mathematically unstable
    - Can’t have texture
    - "Photometric stereo" (active method) more practical than passive version

**Shape from Texture**
- Mathematically similar to shape from shading, but uses stretch and shrink of a (regular) texture
Shape from Focus and Defocus

- Shape from focus: at which focus setting is a given image region sharpest?
- Shape from defocus: how out-of-focus is each image region?
- Passive versions rarely used
- Active depth from defocus can be made practical

Pulsed Time of Flight

- Basic idea: send out pulse of light (usually laser), time how long it takes to return
  \[ d = \frac{1}{2} c \Delta t \]

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

- 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

- Project laser stripe onto object

Depth from ray-plane 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

Scanning a Large Object

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

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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**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

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**Head of Michelangelo’s David**

- Photograph
- 1.0 mm computer model