Active 3D Scanning

COS 429

Princeton University
3D Scanning

The accuracy and completeness of models produced with multi-view stereo of stereo is limited.
Multiview Stereo

Snavely et al. & Furukawa et al.
Multiview Stereo

Snavely et al. & Furukawa et al.
3D Scanning
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Robotics
Digital Inspection
Entertainment

Scalable 3D Video of Dynamic Scenes
M. Waschbüsch, S. Würmlin, D. Cotting, F. Sadlo, M. Gross
Medical Imaging & Surgical Planning
Architecture & Building
Historical Preservation
3D Printing
Outline

- 3D scanning methods
- 3D scan processing
- Example applications
Outline

• 3D scanning methods
• 3D scan processing
• Example applications
3D Scanning 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.
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.
Triangulation
Triangulation
Point Triangulation

Figure 9.5: General arrangement for a method based on light spot stereo analysis.
The ray theorem (of central projection) tells us that \( \frac{X}{x} = \frac{Z}{f} = \frac{Y}{y} \), and from the trigonometry of right triangles we know that \( \tan \alpha = \frac{Z}{b-X} \). It follows that

\[
Z = \frac{X}{x} \cdot f = \tan \alpha \cdot (b-X) \quad \text{and} \quad X \cdot \left( \frac{f}{x} + \tan \alpha \right) = \tan \alpha \cdot b
\]

The solution is

\[
X = \frac{\tan \alpha \cdot b \cdot x}{f + x \cdot \tan \alpha}, \quad Y = \frac{\tan \alpha \cdot b \cdot y}{f + x \cdot \tan \alpha}, \quad Z = \frac{\tan \alpha \cdot b \cdot f}{f + x \cdot \tan \alpha}
\]
Stripe Triangulation

Diagram showing a laser, object, and camera.
Stripe Triangulation
Stripe Triangulation

Object

Light Plane

\[ AX + BY + CZ + D = 0 \]

\[ D = -d \text{ (distance)} \]

Image Point

\( (x', y') \)

Camera

Plug X, Y into plane equation to get Z

\[ X = x' \frac{Z}{f'} \]

\[ Y = y' \frac{Z}{f'} \]

\[ Z = \frac{-Df'}{Ax' + By' + Cf'} \]

Courtesy S. Narasimhan, CMU
Multi-Stripe Triangulation
Color-Coded Stripe Triangulation

Active Scanning

Zhang et al, 3DPVT 2002
Stereo Triangulation

Passive Stereo

$w(X\ Y\ Z)^T$

{$C_1$}

{$C_2$}

{$W$}
Color-Coded Stripe Triangulation

Zhang et al, 3DPVT 2002
Time-Coded Stripe Triangulation

Assign each stripe a unique illumination code over time

[Posdamer 82]
Time-Coded Stripe Triangulation
Time-Coded Stripe Triangulation
Time-Coded Stripe Triangulation

3D Reconstruction using Structured Light [Inokuchi 1984]
Structured Light Patterns

Spatial encoding strategies [Chen et al. 2007]

De Bruijn sequences [Zhang et al. 2002]

Phase-shifting [Zhang et al. 2004]

Pseudorandom and M-arrays [Griffin 1992]

“Single-shot” patterns (N-arrays, grids, random, etc.)
Kinect

- IR Emitter
- Color Sensor
- IR Depth Sensor
- Tilt Motor
- Microphone Array
Kinect

Projected IR Pattern
Kinect

Depth Map

RGB Image
Kinect

infrared speckle pattern about 3 feet from kinect

How the Kinect Depth Sensor Works in 2 Minutes

http://www.youtube.com/watch?v=uq9SEJxZiUg
http://users.dickinson.edu/~jmac/selected-talks/kinect.pdf
Kinect

Shotton, Fitzgibbon, Cook, Sharp, Finocchio, Moore, Kipman, Blake,
Real-Time Human Pose Recognition in Parts from a Single Depth Image, CVPR
Active Scanner Issues

- Material properties (dark, specular)
Triangulation Scanner Issues

- Material properties (dark, specular)
- Subsurface scattering
Triangulation Scanner Issues

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

- Small working volume (baseline too large...)
- Triangulation angle: non-uniform resolution if too small, shadowing if too big (useful range: 15°-30°)
- Two-line-of-sight problem (shadowing from either camera or laser)
Outline

• 3D scanning methods
• 3D scan processing
• Example applications
3D Scan Processing Pipeline
3D Scan 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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Example Application: 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)

ugnetto
Why Capture Chisel Marks as Geometry?

Day (Medici Chapel)
Who?

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Domi Pitturo

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Dottssa Franca Falletti
Alessandra Marino
Matti Auvinen

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

In Pisa
Roberto Scopigno

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

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

side face
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
Summary

• Advantages of active scanning
  – Usually higher accuracy

• Disadvantages of active scanning
  – Need to project light into scene
  – Limits on working volume, lighting conditions, etc.
  – Sometimes slower