active 3D scanning

Jason Lawrence (most slides by Szymon Rusinkiewicz)
3d scanning applications

- computer graphics
- product inspection
- robot navigation
- as-built floorplans
- product design
- archaeology
- fashion
- art history
industrial inspection

- determine whether manufactured parts are within tolerance
medicine

- plan surgery on computer model, visualize in real-time
medicine

* plan surgery on computer model, visualize in real-time
medicine

plan surgery on computer model, visualize in real-time
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- plan surgery on computer model, visualize in real-time
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 mall
range acquisition taxonomy

Range acquisition

- Contact
  - Mechanical (CMM, jointed arm)
  - Inertial (gyroscope, accelerometer)
  - Ultrasonic trackers
  - Magnetic trackers
  - Industrial CT
  - Ultrasound
  - MRI
- Transmissive
- 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

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

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

Active

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 scenes (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 eliminate defocus
- photometric stereo
  - shape from shading w/ multiple known light positions
pulsed time of flight

- basic idea: send out pulse of light (usually laser), time how long it takes to return
pulsed time of flight

✦ advantages:
  - large working volume (up to 100 m.)

✦ disadvantages:
  - not-so-great accuracy (at best ~5mm)
  - requires timing to ~30 picoseconds
  - does not scale w/ working volume

✦ often used for scanning buildings, rooms, archaeological sites, etc.
Scanning Monticello

- joint project between UVA and UNC led by Dave Luebke
- goal: obtain 3D model of Jefferson’s home
- uses:
  - education / architectural studies
  - virtual environments
  - dissemination
  - archival
Scanning Monticello

http://www.cs.virginia.edu/Monticello/

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Scanning Monticello

http://www.cs.virginia.edu/Monticello/
AM modulation time of flight

* modulate a laser at frequency $\nu_m$, it returns with a phase shift $\Delta \phi$

$$d = \frac{1}{2} \left( \frac{c}{i_m} \right) \left( \frac{\Delta \phi \pm 2\pi n}{2\pi} \right)$$

* note the ambiguity in the measured phase shift!
AM modulation time of flight

- accuracy / working volume tradeoff (e.g., noise \( \sim 1/500 \) 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 (typically ~1000:1)
- scales down to small working volume (e.g., 5cm 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. auto ICP of all overlapping pairs
  4. global relaxation to spread out error
  5. merging using volumetric method
range processing pipeline

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applications of 3d scanning

✦ The Pieta Project
IBM Research

✦ The Digital Michaelangelo Project
Stanford University

✦ The Great Buddha Project
University of Tokyo
why scan sculptures?

- interesting objects to look at
- introduce scanning to new disciplines
  - art: studying working techniques
  - art history
  - cultural heritage preservation
  - archaeology
- 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 technology
  - practical: physical access, time
- type of data
  - high-res 3d data vs. coarse 3d + normal maps
  - influenced by eventual application
- intellectual property (security)
IBM’s Pieta Project

- Michelangelo’s “Florentine Pieta”
- 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 at 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
data

- range data has 2mm spacing, 0.1mm noise
- each range image: 10,000 points, 20x20 cm
- color data: 5 images with controlled lighting, 1280x960, 0.5mm 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 11x11 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)
who? (or who not?)

Faculty and staff
- Prof. Brian Curless
- Jelena Jovanovic
- Lisa Pacelle
- Dr. Kari Pulli
- Prof. Marc Levoy
- Domi Pitturo
- John Gerth

Graduate students
- Sean Anderson
- James Davis
- Lucas Pereira
- Jonathan Shade
- Daniel Wood
- Barbara Caputo
- Dave Koller
- Szymon Rusinkiewicz
- Marco Tarini

Undergraduates
- Alana Chan
- Jeremy Ginsberg
- Unnur Gretarsdottir
- Wallace Huang
- Ephraim Luft
- Semira Rahemtulla
- Joshua Schroeder
- David Weekly
- Kathryn Chinn
- Matt Ginzton
- Rahul Gupta
- Dana Katter
- Alex Roetter
- Maisie Tsui

In Florence
- Dottssa Cristina Acidini
- Dottssa Licia Bertani
- 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

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

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

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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
scanning a large object

- calibrated motions
  - pitch (yellow)
  - pan (blue)
  - horiz. translation (orange)

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

- manual initial alignment
- pairwise ICP, then global registration
- VRIP (parallelized across subvolumes)
- use hi-res geometry to discard bad color data, perform inverse lighting calculations
statistics about the scan of David

- 480 individually aligned 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
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  Ko Nishino
Takeshi Ooishi    Takashi Tomomatsu
Taku Nishikawa   Yutaka Takase
Ryusuke Sagawa   Katsushi Ikeuchi
Cyrax range scanner by Cyra Technologies
- laser pulse time-of-flight
- accuracy: 4mm
- range: 100m
processing

- 20 range images (a few million points)
- simultaneous all-to-all ICP
- variant of volumetric merging (parallelized)
results