Time of Flight Capture

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Range Acquisition Taxonomy

- **Range acquisition**
  - **Contact**
    - Mechanical (CMM, jointed arm)
    - Inertial (gyroscope, accelerom.)
    - Ultrasonic trackers
    - Magnetic trackers
  - **Transmissive**
    - Industrial CT
    - Ultrasound
    - MRI
  - **Reflective**
  - **Optical**
    - Non-optical
    - Radar
    - Sonar
Range Acquisition Taxonomy

Optical methods

Passive

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

Active

Active variants of passive methods
- Structured Light
- Active depth from defocus
- Photometric stereo

Triangulation (e.g., lasers)

Time of flight
Optical Range Scanning Methods

- **Advantages:**
  - Non-contact
  - Safe
  - Usually inexpensive
  - Usually fast

- **Disadvantages:**
  - Sensitive to transparency
  - Confused by specularity and interreflection
  - Texture (helps some methods, hurts others)
Stereo

- Find feature in one image, search along epipole in other image for correspondence
Stereo

- Advantages:
  - Passive
  - Cheap hardware (2 cameras)
  - Easy to accommodate motion
  - Intuitive analogue to human vision

- Disadvantages:
  - Only acquire good data at “features”
  - Sparse, relatively noisy data (correspondence is hard)
  - Bad around silhouettes
  - Confused by non-diffuse surfaces

- Variant: multibaseline stereo to reduce ambiguity
Shape from Motion

• “Limiting case” of multibaseline stereo
• Track a feature in a video sequence
• For $n$ frames and $f$ features, have $2 \cdot n \cdot f$ knowns, $6 \cdot n + 3 \cdot f$ unknowns
Shape from Motion

• Advantages:
  – Feature tracking easier than correspondence in far-away views
  – Mathematically more stable (large baseline)

• Disadvantages:
  – Does not accommodate object motion
  – Still problems in areas of low texture, in non-diffuse regions, and around silhouettes
Shape from Shading

- Given: image of surface with known, constant reflectance under known point light
- Estimate normals, integrate to find surface
- Problem: ambiguity
Shape from Shading

• Advantages:
  – Single image
  – No correspondences
  – Analogue in human vision

• Disadvantages:
  – Mathematically unstable
  – Can’t have texture

• Not really practical
  – But see photometric stereo
Shape from Texture

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

- Analogue to human vision
- Same disadvantages as shape from shading
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
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 (=Structured Light)
  - Provides features for correspondence
- Active depth from defocus
  - Known pattern helps to estimate defocus
- Photometric stereo
  - Shape from shading with multiple lights
Time of Flight

• A time-of-flight (TOF) camera works by illuminating the scene with a modulated light source, and observing the reflected light.
• The phase shift between the illumination and the reflection is measured and translated to distance
• Not new:
Time of Flight

• But being rediscovered and enabled by advances in hardware (since ~2000)
  – e.g., Swiss Ranger, ZCam, Canesta, Kinect (=ZCam+Canesta+MSFT$$)$

• Often uses ~850nm light (so not visible to humans)
Pulsed Time of Flight

- Ambient light
- Pulsed source
- Reflection
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.
Pulsed Time of Flight

• Send square waves
  – Easier to produce with digital circuits

• Start a counter to measure time delay
  – Achieving 1mm accuracy needs a pulse of 6.6 picoseconds in duration
  – Most possible, but still hard, is 5mm accuracy needing about 30 picoseconds
Pulsed Time of Flight

• How to measure the time it took the reflection to get back with photo-detectors?
• How to convert to distance?
Pulsed Time of Flight

- C1 window corresponding to light source
- C2 window corresponding to !C1
Pulsed Time of Flight

- $Q_1 = \text{time light is on and reflection is on}$
- $Q_2 = \text{time light is off and reflection is on}$

- $d = ?$
- $d = \text{function}(Q_1, Q_2)$

- $d = \frac{1}{2} c \Delta t \left( \frac{Q_2}{Q_1 + Q_2} \right)$
Continuous Wave ToF

- Four samples phase stepped by $\pi/2$
Continuous Wave ToF

- What is phase angle \( \phi \) between light and reflection?
Continuous Wave ToF

- $\phi = \arctan\left(\frac{Q_3 - Q_4}{Q_1 - Q_2}\right)$
Continuous Wave ToF

\[ d = \frac{c}{(4\pi f)} \phi \]
Continuous Wave ToF

- Amplitude

\[ A = \frac{1}{2} \sqrt{((Q_1 - Q_2)^2 + (Q_3 - Q_4)^2)} \]
Continuous Wave ToF

- Offset $B = \frac{1}{4} (Q_1 + Q_2 + Q_3 + Q_4)$
Continuous Wave ToF

- Variance $\sigma = \frac{c}{4\sqrt{2\pi f}} \frac{\sqrt{(A+B)}}{c_d A}$ where $c_d$ is modulation contrast
Continuous Wave ToF

• Ambiguity distance $d_{amb} = \frac{c}{2f}$