Three-Dimensional Sensors
Lecture 4: Time of Flight Cameras
(Pulse Light Modulation)

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Lecture Outline

- Principles of pulsed-light TOF cameras
- 3D flash lidar cameras
- Space applications
- 2D and 3D scanners

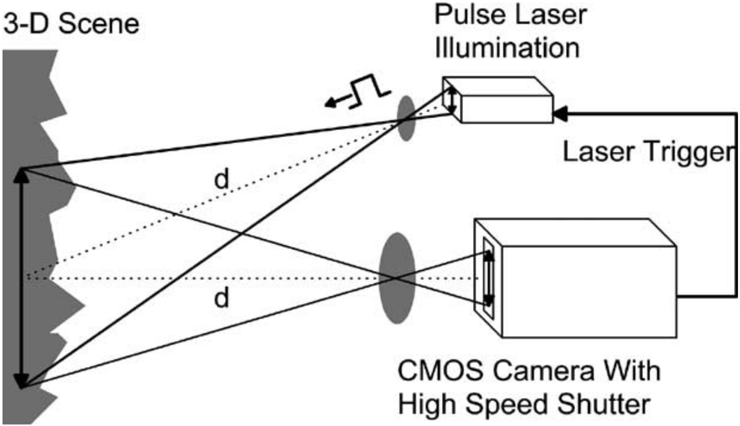
Time of Flight with Pulsed Light

- A light pulse of a few *nanoseconds* is generated by a laser;
- Distance is determined directly from the *time delay* between emitted light pulse and its reflection;
- It can use very short pulses with high optical power: The pulse irradiance is much higher than the background irradiance;
- The emitted laser energy remains low (class 1);
- Does not suffer from the phase ambiguity problem;
- It is the technology of choice in a number of outdoor applications under adverse conditions: surveying (static and mobile), autonomous driving, cultural heritage, planetary missions.

Sensor Types

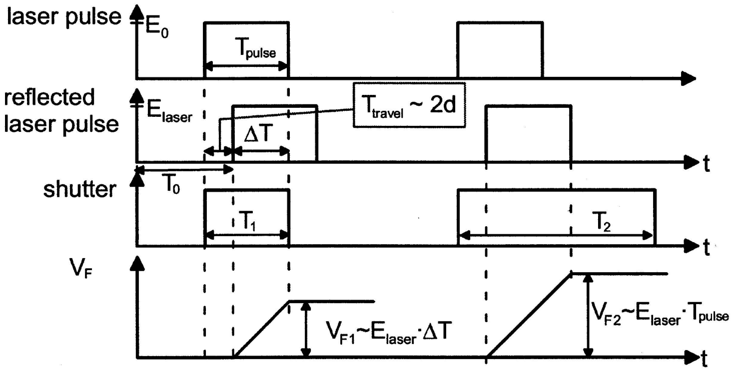
- Laser scanners use a rotating mirror;
- 2D (line) scanners (horizontal or vertical);
- 3D scanners (horizontal and vertical);
- Multiple-laser 2D line scanners (horizontal and vertical);
- 3D flash Lidar cameras (provide a depth image without any rotating mechanism).

The Principle of 3D Flash Cameras



Elkhalili et al. (2004). IEEE Transactions on Solid-State Circuits. Vol. 39. No 7, pages 1208–1212

Time-to-Amplitude Conversion from Elkhalili et al. (2004)



Elkhalili et al. (2004). IEEE Transactions on Solid-State Circuits. Vol. 39. No 7, pages 1208–1212

The *Double Short-Time Integration* Principle

- The output voltage (V_F) is proportional to the amount of photons reaching the sensor in a time interval.
- V_F is dependent on the laser power, background illumination, and of the object reflectance.
- T_{pulse} is the constant width of the laser pulses emitted at regular intervals.
- The reflected pulses are shifted by T_{travel}.
- The shutter is perfectly synchronized with the emitted pulses. Two different shutter times are used:
    - The first voltage measurement is performed with a shutter time $T_1 = T_{\text{pulse}}$
    - The second voltage measurement is performed with a longer shutter time T_2 that exceeds T_{pulse}

Travel Time Estimation

- During the first shutter time the output voltage is proportional to $\Delta T = T_{\text{pulse}} - T_{\text{travel}}$:

$$V_{F1} \propto E_{\text{laser}} \Delta T$$

- During the second shutter time the whole laser energy is located within the shutter window:

$$V_{F2} \propto E_{\text{laser}} T_{\text{pulse}}$$

- Hence:

$$\Delta T = \frac{V_{F1}}{V_{F2}} T_{\text{pulse}}$$

Precise Depth Estimation

$$d = \frac{c}{2} T_{\text{travel}} = \frac{c}{2}(T_{\text{pulse}} - \Delta T) = \frac{c}{2} T_{\text{pulse}} \left(1 - \frac{V_{F1}}{V_{F2}}\right)$$

- This measurement cycle can be repeated n times and the resulting voltages are accumulated in an analog memory.
- This *multiple double short-time integration* increases the signal to noise ratio by $n^{1/2}$.
- It also increases the range accuracy by the same factor.

Maximum and Minimum Depth Measurements

- The above method consists in measuring ΔT which is equal to 0 for $T_{\text{travel}} = T_{\text{pulse}}$
- Hence, the maximum range is:

$$d_{\max} = \frac{c}{2} T_{\text{pulse}}$$

- With $T_{\text{pulse}} = 30\text{ns}$ the maximum depth is 4.5m.
- The maximum range can be increased in 2 ways:
  - Increasing the duration of the light pulse,
  - Introducing a delay between the firing of the laser pulse and the opening of the shutter – this results in a minimum depth $d_{\min} > 0$.

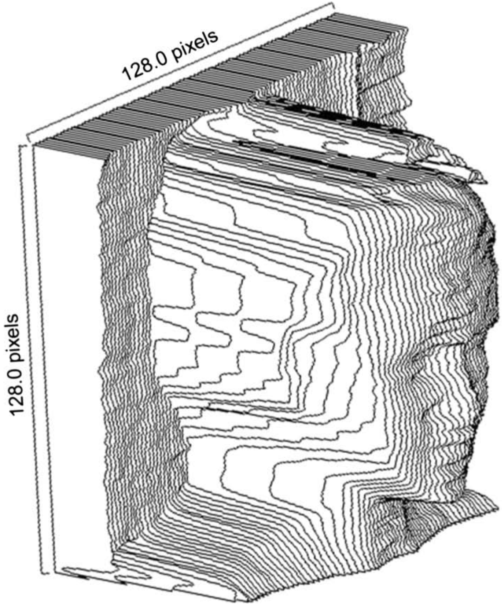
Typical Results Using the Time-to-Amplitude Method

Number of pixels:	4×64
Pixel size:	130×300 μm^2
Laser wavelength:	$850 - 910nm$
Depth accuracy (1 pulse):	$< 5cm$
Depth accuracy (100 pulses):	$< 1cm$

Single Photon Image Sensors

- It enables 128×128 images using SPAD (single photon avalanche diodes) and TDC (time-to-digital converters).
- The measured voltage transition carries the arrival time of a photon which is digitally encoded with picosecond resolution by a 10 bit TDC.
- Minimum and maximum depth: 20cm to 375cm.
- Accuracy in depth: $5 - 9$mm.

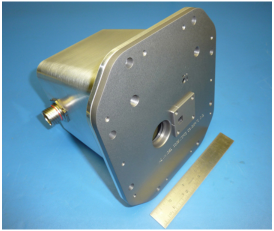
Example from Niclass et al. (2008)



3D Flash Lidar Cameras from Advanced Scientific Concepts Inc.

Tiger Eye

Portable 3D



Dragon Eye

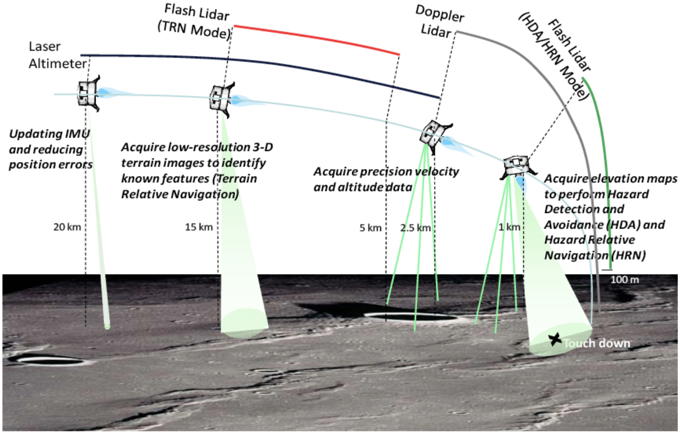
TigerEye 3D Video Camera

- 128 x 128 pixels APD (avalanche photo diode); 30Hz
- 1570 nm eye-safe laser
- 3^0 field of view (actual full FOV $= 3^0$ x 3^0); Range up to 1100 meters
- 9^0 field of view (actual full FOV $= 8.6^0$ x 8.6^0); Range up to 450 meters
- 45^0 x 22^0 field of view; Range up to 150 meters
- 45^0 field of view; Range up to 60 meters

DragonEye 3D Flash LIDAR Space Camera

- 128×128 pixels; 10FPS; Range and intensity video Camera
- 45^0 x 45^0 field of view (17mm)
- Range up to 1.5km inclusive (greater depending on diffuser/lens choice)
- Tested and used by NASA

Use of Lidar Technology for Planetary Exploration



Landing on Moon and Mars

- NASA's Autonomous Landing and Hazard Avoidance (ALHAT)
- Lidar sensors: 3-D Imaging Flash Lidar, Doppler Lidar, and Laser Altimeter
- Five sensor functions: Altimetry, Velocimetry, Terrain Relative Navigation (TRN), Hazard Detection and Avoidance (HDA) and Hazard Relative Navigation (HRN)
- The Inertial Measurement Units (IMU) suffer from drastic drift over the travel time from the Earth. The IMU drift error can be over 1 km for a Moon-bound vehicle and over 10 km for Mars

ALHAT Sensors Performance Requirements

Sensor	Function	Operational Altitude Range	Precision/Resolution
Flash Lidar	HDA/HRN	1000 m – 100 m	5 cm/40 cm
	TRN	15 km – 5 km	20 cm/6 m
	Altimetry[1]	20 km – 100 m	20 cm
Doppler Lidar	Velocimetry	2500 m – 10 m	1 cm/sec
	Altimetry	2500 m – 10 m	10 cm
Laser Altimeter	Altimetry	20 km – 100 m	20 cm
	TRN[1]	15 km – 5 km	20 cm

3D Flash Lidar Technology Advancement

Component Technology	Description	Lead Organization	Status
Transmitter laser	High pulse energy optimized for Flash Lidar, compact and rugged design suitable for space	Fibertek	Complete
Detector Array	Low noise InGaAs Avalanche Photodiode Detector array	Optogration	Complete
Image reconstruction and enhancement processor	3-D Super-resolution algorithm, real-time implementation in high-speed HDW	NASA LaRC	2012
Fiber optic delivery unit	High pulse energy fiber cable for transmitter beam, rugged designed for space	NASA GSFC	2012
256X256 Sensor Engine	Low noise HgCdTe APD detector with advanced ROIC including control/interface electronics	Raytheon	2012
256X256 Sensor Engine	Advanced high sensitivity ROIC hybridized with Optogration APD array including control/interface electronics	ASC	2013
Receive/Transmit Optics	Variable Field of View	NASA LaRC	2013

Examples of 2D and 3D Scanners

- Riegl Laser Measurements Systems: http://www.riegl.com/nc/products/mobile-scanning/
- Optech Mobile Mappers: http://www.optech.ca/lynx.htm
- Zoller-Frohlich laser scanners (based on CW modulation): http://www.zf-laser.com/Home.91.0.html?&L=1

Multiple-Laser 3D Scanner: Velodyne

- 32/64 fixed-mounted lasers, each mechanically mounted to a specific vertical angle, with the entire unit spinning
- 1.3 million points per second
- More details: `http://velodynelidar.com/lidar/hdlproducts/hdl64e.aspx`

Discussion

- The geometry of 3D flash lidar cameras is similar to lock-in TOF cameras
- Amplitude image not available but it is possible to get the image of the background light (intensity)
- 3D Flash cameras have no moving parts and hence they are not sensitive to vibrations, they can provide 3D videos.
- 2D and 3D laser scanners (equipped with mirrors and motors) provide 360^0 views. They can be used in combination with standard cameras to yield RGB-D data.