LiDAR and Other Techniques
Measuring Distance with Light for Automotive Industry

Slawomir Piatek
Technical Consultant, Hamamatsu Corp.
Introduction

• There is a great interest in the automotive industry to develop on-vehicle systems which make driving safer.

• In addition, motivated by market demand, a longer-term goal is development of a completely autonomous (self-driving) vehicle.
Introduction

• Such a self-driving vehicle must have an ability to create a 3D map of its surroundings up to about 300 m at a video rate.

This webinar discusses techniques and challenges of measuring distance with light for automotive applications emphasizing time-of-flight LiDAR
Outline

- Time of flight (ToF) LiDAR (emphasis of this webinar)
  - Basic concept
  - Challenges in designing ToF LiDAR
  - Types of ToF LiDAR: mechanical, flash, optical phase array
- FMCW radar (concept)
- FMCW LiDAR (heterodyne optical mixing)
- Summary and conclusions
Basic layout of ToF LiDAR

- "start" pulse
- "fast" photodetector
- laser
- beam splitter
- emission optics
- timer
- "stop" pulse
- collection optics
- returned pulse after Δt
- emitted pulse
- \( w = c\tau \)
- to target
ToF LiDAR distance

Measure $\Delta t$

$$R = \frac{1}{2}c\Delta t$$

If $\Delta t = 0.67 \, \mu s$, $R = 100 \, m$

or 6.7 ns per 1 m of distance
Distance uncertainty

\[ \delta_R = \frac{1}{2} c \delta_{\Delta t} \]

- \( \delta_R \) – Distance uncertainty

- \( \delta_{\Delta t} \) – Uncertainty in measuring \( \Delta t \) (mostly due to photodetector jitter)
Distance uncertainty

\[ \delta_R = \frac{1}{2} c \tau = \frac{1}{2} w \]

- \( \delta_R \) – Distance uncertainty
- \( \tau \) – Pulse duration
- \( w \) – Pulse width \((c \tau)\)

Laser spot large compared to target features

Propagating divergent pulse

\[ w = c \cdot \tau \]
Beam Divergence

Diffraction causes beam divergence: $\theta \approx 1.22\lambda/D$

$S_t$ – Minimum resolvable transverse size at distance $R$
Beam Divergence

Radar: 77 GHz $\rightarrow$ $\lambda = 0.3$ cm.

If $D = 20$ cm $\rightarrow \theta \approx 1^\circ$ $\rightarrow S_t \approx 1.8$ m + 0.2 m = $2$ m @ $R = 100$ m

LiDAR: 1550 nm

If $D = 5$ mm $\rightarrow \theta \approx 0.02^\circ$ $\rightarrow S_t \approx 3.7$ cm @ $R = 100$ m

For high-resolution 3D map, we need LiDAR
**ToF LiDAR: timing**

- **Start pulse**
- **Stop pulse**
- **$\Delta t$**
- **Trigger level**

**T** – repetition period

$T$ must be $> \Delta t$
ToF LiDAR: maximum distance

\[ R_{\text{max}} = \frac{1}{2} c T = \frac{1}{2} \frac{c}{f} \]

\( f \) – Repetition frequency or sampling frequency

Photon budget imposes another limit on \( R_{\text{max}} \)
ToF LiDAR: minimum distance (ideal case)

There is no limit on the smallest distance

\[ \tau \]

\[ T > \tau \]

\[ B = \infty \]

\[ t_r = \tau \]
ToF LiDAR: minimum distance (realistic)

Signal pileup limits the smallest measurable distance

\[ T > \tau \]

\[ B \text{ finite} \]

\[ t_\text{r} > \tau \]
ToF LiDAR: maximum sampling rate

\[ f_{\text{max}} = \frac{1}{\Delta t_{\text{max}}} = \frac{c}{2R_{\text{max}}} \]

\[ f_{\text{max}} = 1.5 \text{ MHz} \ @ \ R = 100 \text{ m} \]

Larger the range, more time it takes to produce a 3D map
ToF LiDAR: challenges

Challenges and considerations in designing ToF LiDAR
ToF LiDAR challenges: surround view

Would like
100 m range minimum
360° azimuthal coverage
20° declination coverage
0.2° resolution (~35 cm @ 100 m)
Video rate, 20 frames/s
ToF LiDAR challenges: sampling rate

To meet the challenge, we need $3.6 \times 10^6$ samplings/s (3.6 MHz)

Can do 1.5 MHz with one light source and photodetector @ $R = 100$ m

Need to compromise and/or invent different approaches
ToF LiDAR challenges: light source

Safe for human vision

Short-duration pulses (can get 2 - 5 ns) at high repetition

High peak power per pulse Must comply with *admissible exposure limit (AEL)*, which is a complex function of wavelength, repetition rate, and energy per pulse.

Narrow bandwidth
ToF LiDAR challenges: photon budget

- Specular reflection
- Diffuse reflection

Illumination $A_0$
ToF LiDAR challenges: photon budget

$$P(R) = P_0 \rho \frac{A_0}{\pi R^2} \eta_0 \exp(-2\gamma R)$$

- $P(R)$ – Power received
- $P_0$ – Peak power transmitted
- $\rho$ – Target reflectivity
- $A_0$ – Aperture area of the receiver
- $\eta_0$ – Receiving optics transmission
- $\gamma$ – Atmospheric extinction coefficient

This LiDAR equation assumes normal incidence, Lambertian reflection, flat beam profile and negligible divergence, laser spot smaller than the target, and $\gamma$ independent of $R$. 
ToF LiDAR challenges: photon budget

Number of photons (λ = 1550 nm) expected from a target as a function of its range using 1, 10, 100, and 1000 nJ pulses.

The figure assumes target reflectivity of 30%, 70% optical efficiency, 30-mm diameter receiver, 0.5 mrad laser beam divergence, and 70% optical efficiency.

50-nJ 4-ns pulse (12.5 W) has: \( \sim 4 \times 10^{20} \) photons @ 1550 nm
ToF LiDAR challenges: photon budget

$$\text{SNR}(R) = \frac{P(R)S_\lambda M}{\sqrt{2eB[(P(R)+P_B)S_\lambda + I_D]FM^2 + \frac{4kTB}{R_0}}}$$

$S_\lambda$ – Detector’s sensitivity  
$M$ – Detector’s intrinsic gain  
$I_D$ – Detector’s dark current  
$F$ – Detector’s excess noise factor  

$B$ – Detection bandwidth  
$P_B$ – Background light optical power  
$e$ – elementary charge; $k$ – Boltzmann constant; $T$ – temperature
ToF LiDAR challenges: what wavelength?

1550 nm

+ Best eye safety
+ Lower background
- Requires IR (non-silicon) photodetectors

905 nm

+ Better transmission in atmosphere
+ Silicon-based photodetector
ToF LiDAR challenges: what wavelength?

P_B @ 1550 nm < P_B @ 905 nm

Figure from Matson et al. 1983
ToF LiDAR challenges: what wavelength?

$\gamma_{\text{water}} (905 \text{ nm}) = 0.075 \text{ (cm}^{-1})$

$\gamma_{\text{water}} (1550 \text{ nm}) = 10.8 \text{ cm}^{-1}$

H$_2$O absorption @ 1550 nm > (100 × ) @ 905 nm
905 nm versus 1550 nm

Wet surface reflects more poorly @1550 nm versus @ 905 nm

Adapted from Wojtanowski et al. 2014
ToF LiDAR challenges: photodetector

- High photosensitivity
- High gain
- Small jitter
- Small excess noise
Importance of jitter

$t_1, t_2, t_3, \ldots$ transit times. Jitter represents variation in transit times.

Jitter is the main contributor to $\delta_{\Delta t}$ which affects distance resolution. 100 ps jitter implies 1.5 cm depth uncertainty.
Importance of detector gain

signal + electronic noise = Output

Arb.

photodetector electronics

No Gain
Importance of detector gain

The diagram illustrates the relationship between the output signal and detector gain. The signal from the photodetector is amplified by the electronics, which adds electronic noise. The amplified signal, along with the noise, is output as a waveform. Increasing the gain can enhance the signal-to-noise ratio, making the signal more pronounced. Thus, the detector gain plays a crucial role in improving the performance of the system.
Importance of excess noise

**Signal**

Waveform 1

Waveform 2

**time**

\[ \Delta t_1 \neq \Delta t_2 \] ✗

Fixed trigger level gives different round-trip-times

\[ \Delta t_1 = \Delta t_2 \] ✓

Constant-fraction trigger gives the same round-trip-times
ToF LiDAR challenges: photodetector

APD is the most commonly used photodetector

✔ Gain up to ~100 (ok, but not great)
✔ High quantum efficiency
✗ Large excess noise

Could SiPM be the detector of choice?
ToF LiDAR challenges: photodetector

SiPM is an array of microcells connected in parallel. Each is a series combination of APD in Geiger mode and quenching resistor.

\[ V_{\text{BIAS}} \sim 10\text{'}s\ V; \ a \ few \ volts \ above \ breakdown \ voltage \]

Output of SiPM: Superposition of current pulses
SiPM

✔ Gain $(10^5 - 10^6) F \approx 1.3$ ✔

✓ Photosensitivity at 905 nm
SiPM

~ Recovery time

~ Linearity
LiDAR

Types of ToF LiDAR
ToF LiDAR: Mechanical scanning

Velodyne LiDAR system: 64 channels (beams) 905 nm, 1.3 or $2.2 \times 10^6$ points per second, 5 - 20 Hz rotation, APD photo-sensors.
ToF LiDAR: Rotating multi-facet mirror

- six-facet polygonal mirror; each mirror has a different tilt angle

Reference: Niclass et al. 2014
ToF LiDAR: Rotating multi-facet mirror

3D map in full daylight

Sensor: SPAD 2D array

10 frames/s

FOV: 55° × 9°

Reference: Niclass et al. 2014
ToF LiDAR: Scanning with MEMS mirrors
Combining electrostatic and magnetic actuations allows 2D scanning (two axis rotation).
Light projectors: MEMS mirrors

\[ \theta_{\text{max}} \] – Total scan angle

\[ \delta_\theta \] – Beam divergence (produced by the mirror ×)

\[ N = \frac{\theta_{\text{max}}}{\delta_\theta} \] – Number of resolvable spots (resolution)

Reference: Patterson et al. 2004

\[ \text{incident laser beam} \]

\[ \text{MEMS mirror} \]
Light projectors: MEMS mirrors

✔ Low cost

✔ Almost no moving parts

✖ Limited field of view

~ Size/frequency tradeoff

~ Frequency/beam divergence tradeoff
Flash LiDAR

- Scene object
- Short (10’s ns) pulse of illumination
- Illumination optics
- Timing circuit
- APD or SPAD array
- Detection optics
Flash LiDAR

✔ Resolution limited by the detector
✔ No moving parts
✖ Small field of view
✖ Starved for photons, limited range
Optical phase array (OPA)

Each element (pixel, \(\sim 30 \times 30 \mu m^2\)) receives and re-emits light with changed phase and amplitude.

Due to interference, the emitted far field radiation can be shaped into variety of patterns, for example beams.
Optical phase array (OPA)

- No moving parts
- Lobes and beam divergence
- Slow (due to cell tuning)

Figure from Abediasl & Hashemi 2015
Another approach?

Designing ToF LiDAR at reasonable cost is very challenging.

What about a different approach borrowed from radar technology?

Frequency modulated continuous wave (FMCW) LiDAR
Advantages of FMCW LiDAR

• Photon shot noise limited detection
• Immune to photon background
• Distance and velocity information in frequency domain
• Lower-bandwidth electronics
FMCW Radar

Chirp-modulation (triangular) of frequency
FMCW Radar

\[ f_{B1} = \frac{2BR}{cT} - \frac{2V_r}{\lambda_0} \]

\[ f_{B2} = -\frac{2BR}{cT} - \frac{2V_r}{\lambda_0} \]
FMCW Radar

Larger bandwidth gives better distance resolution
FMCW Radar

Shorter T gives better resolution

\[ \Delta f_1 \]
\[ \Delta f_2 \]

\[ f_0 \]
\[ f_{\text{max}} \]
FMCW LiDAR (heterodyne optical mixing)

optical mixing occurs on the detector

detector

collimator

tunable laser

f_{LO}

BS

M

frequency shifter

f_{PO} = f_{LO} + f_{offset}

to target

M

M

M

M

M

M

receiving optics

returned light

f_a = f_{LO} + f_{offset} + \Delta f

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55
FMCW LiDAR (heterodyne optical mixing)

\[ |E_{\text{tot}}|^2 = |E_a + E_{\text{LO}}|^2 = |A_a \cos(2\pi f_a t + \phi_a) + A_{\text{LO}} \cos(2\pi f_{\text{LO}} t + \phi_{\text{LO}})|^2 \]

\[ |E_{\text{tot}}|^2 = |E_a|^2 + |E_{\text{LO}}|^2 + A_a A_{\text{LO}} \cos[2\pi(f_a - f_{\text{LO}})t + (\phi_a - \phi_{\text{LO}})] \]

\[ P_{\text{sig}} = P_a + P_{\text{LO}} + 2\sqrt{P_a P_{\text{LO}}} \cos[2\pi(f_a - f_{\text{LO}})t + (\phi_a - \phi_{\text{LO}})] \]

\[ i_{\text{sig}} = \frac{\eta e P_{\text{sig}}}{hf} = i_a + i_{\text{LO}} + 2\sqrt{i_a i_{\text{LO}}} \cos[2\pi(f_a - f_{\text{LO}})t + (\phi_a - \phi_{\text{LO}})] \]

\[ f_a - f_{\text{LO}} = \Delta f + f_{\text{offset}} \]

We get \( \Delta f \), and thus \( R \) and \( V_R \)
Coherent detection

For maximum signal:

- the beams must overlap (ideally $g = 1$)
- wavefronts must have the same shape
- polarization is the same
- spatial coherence
Coherent detection

\[ \frac{S}{N} = \frac{i^2}{(i_{SN})^2} \approx \frac{g\eta P_s}{2hfB} \]

- \( g \) – overlap factor;
- \( \eta \) – photodetector quantum efficiency;
- \( B \) – detection bandwidth

By making \( P_{LO} \) large enough, one can make the detection photon-shot noise limited.

Photodiode can be used for the photodetection.
Balanced detection

Excess noise of LO (through the DC part) can reduce S/N. Remedy: use balanced detection.

\[ I_1 = \left( \eta e/\hbar f \right) \left[ \frac{1}{2} P_{lo} + \frac{1}{2} P_s \right] + (P_s P_{lo})^{1/2} \sin(\Delta \omega t + \phi) \]

\[ I_2 = \left( \eta e/\hbar f \right) \left[ \frac{1}{2} P_{lo} + \frac{1}{2} P_s \right] - (P_s P_{lo})^{1/2} \sin(\Delta \omega t + \phi) \]

\[ I_1 - I_2 = 2 \left( \eta e/\hbar f \right) (P_s P_{lo})^{1/2} \sin(\Delta \omega t + \phi) \]

+- are due to \( \pi/2 \) shifts when light reflects from the BS
Balanced photodiodes by Hamamatsu

Balanced photodiode module offered by Hamamatsu

Hamamatsu also offers matched bare photodiodes
Coherent detection: working example

\[ \lambda = 1549.54 \text{ nm} \]

B = 4.3 GHz

Gao & Hui 2012
## Is there a perfect LiDAR?

<table>
<thead>
<tr>
<th>LiDAR System</th>
<th>Range</th>
<th>Reliability</th>
<th>Cost</th>
<th>Size</th>
<th>Systems per car</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mechanical</td>
<td>Long</td>
<td>Good</td>
<td>Mid. to high</td>
<td>Bulky</td>
<td>1</td>
</tr>
<tr>
<td>MEMS based</td>
<td>Medium to long</td>
<td>Good</td>
<td>Low</td>
<td>Compact</td>
<td>1 – 4 or more</td>
</tr>
<tr>
<td>Flash</td>
<td>Short</td>
<td>Very good</td>
<td>Low</td>
<td>Compact</td>
<td>1 – 4 or more</td>
</tr>
<tr>
<td>Optical Phase Array</td>
<td>Advantages: solid state design with no moving parts</td>
<td>Disadvantages: loss of light that restricts the range</td>
<td></td>
<td></td>
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<tr>
<td>FMCW</td>
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<td></td>
</tr>
<tr>
<td></td>
<td>Advantages: immune to background, photon shot noise detection</td>
<td>Disadvantages: data processing intensive, still requires beam steering</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Not yet...
Summary & Conclusions

• Some form of LiDAR is likely to be needed on self-driving car
• ToF LiDAR is very challenging to design
  - Beam steering and photodetection are the most outstanding challenges
• There is a growing interest in FMCW LiDAR with optical mixing
• There is no default LiDAR design yet; work in progress
Upcoming Webinar (January 2018)

Silicon Photomultiplier: Operation, Performance, & Optimal Applications
Presenter: Slawomir Piatek
Host: Laser Focus World
Wednesday, January 10, 2018
Visit Booth #521 & Presentations at PW18

Development of an InGaAs SPAD 2D array for Flash LIDAR
Presentation by Takashi Baba, January 29, 2018 (11:00 AM - 11:30 AM)

Development of an InGaAs MPPC for NIR photon counting applications
Presentation by Takashi Baba, January 30, 2018 (5:50 PM - 6:10 PM)

Photodetectors, Raman Spectroscopy, and SiPMs versus PMTs
One-day Workshop with Slawomir Piatek, January 31, 2018 (8:30 AM - 5:30 PM) – Free Registration Needed

Development of a Silicon hybrid SPAD 1D array for LIDAR and spectrometers
Poster session with Shunsuke Adachi, January 31, 2018 (6:00 PM - 8:00 PM)
Thank you for listening!

• Speaker Contact – Slawomir Piatek (spiatek@physics.rutgers.edu)
• LiDAR Inquires to Hamamatsu – Jake Li (jli@Hamamatsu.com)