Review of LiDAR, localization and object Processing for safe autonomous systems

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Outline

Key Take Away Points

Autonomous Systems

LiDAR

- Basics
- Players
- LiDAR Architectures from main players (Waymo, Scala, Continental, Innoviz, Panasonic, Blackmore FMCW)
- Receiver Architectures for Pulsed LiDAR

Integrated Perception (work by Apollo AI)

Sources: Various public sources

Key Take Away from 1st presentation: LiDARs making into commercial cars

Sensor Maker	Design Win for commercial deployment	Design Win Size and timeframe
Waymo	Waymo-Chrysler Waymo-Jaguar [Robo car]	62,000 20,000 [by 2022]
Valeo	Audi [ADAS for consumer car]	~3000, 2017 ~100K, 2021
Innoviz	BMW [ADAS for consumer car]	~100K, 2021
Continental	Volvo [ADAS for consumer car]	~100K,2021

Key Take Away from 2nd presentation: Integrated Perception is important for LiDAR and is provided by Apollo AI.

- Expertise in simultaneous localization and mapping, object detection, tracking and classification, decision making and path optimization. Patent pending IP. Working with several LiDAR companies and car OEMs.

- **Currently available software for licensing**

  Mapping Stack:
  - ✓ Real-time SLAM using LiDAR and feature map generation
  - ✓ Real-time localization with LiDAR(+GPS+IMU+wheel odometry for robustness)

  SLAM Demo: Video embedded on www.apolloaisystems.com

  Object processing Stack:
  - ✓ LiDAR, Camera, RADAR
  - ✓ LiDAR+Camera

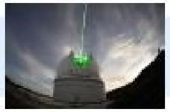
- Apollo AI's self-driving stack is developed for low cost SoC such as Renesas, ST, Texas Instruments, Visteon which has both ARM and Vector processors. Very amenable to hardware accelerator IP implementation for FPGA also.
- Please email contact@apolloaisystems.com

Autonomous Systems

The idea of sensing the atmosphere using light appeared before the invention of the laser.
Slowly, the LiDAR is spreading across applications.

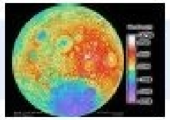
LIDAR (light detecting and ranging)

In the 1960s, atmospheric research was the first application of LiDAR.



Atmosphere: altitude and spectroscopy

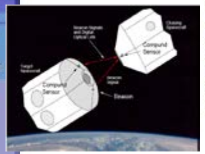
In 1971, the Apollo 15 mission used a LiDAR to map the surface of the moon



From laser range measurements made during Apollo missions 15, 16 and 17 in 1971-72, Prof. John Junkins developed a precise model for the shape of the moon.

In the 1930's, EH Synge conceived the LiDAR.

In 1960, TH Maiman conceived the first laser.



Since 2000, unmanned aerial refueling, space craft docking and archaeology

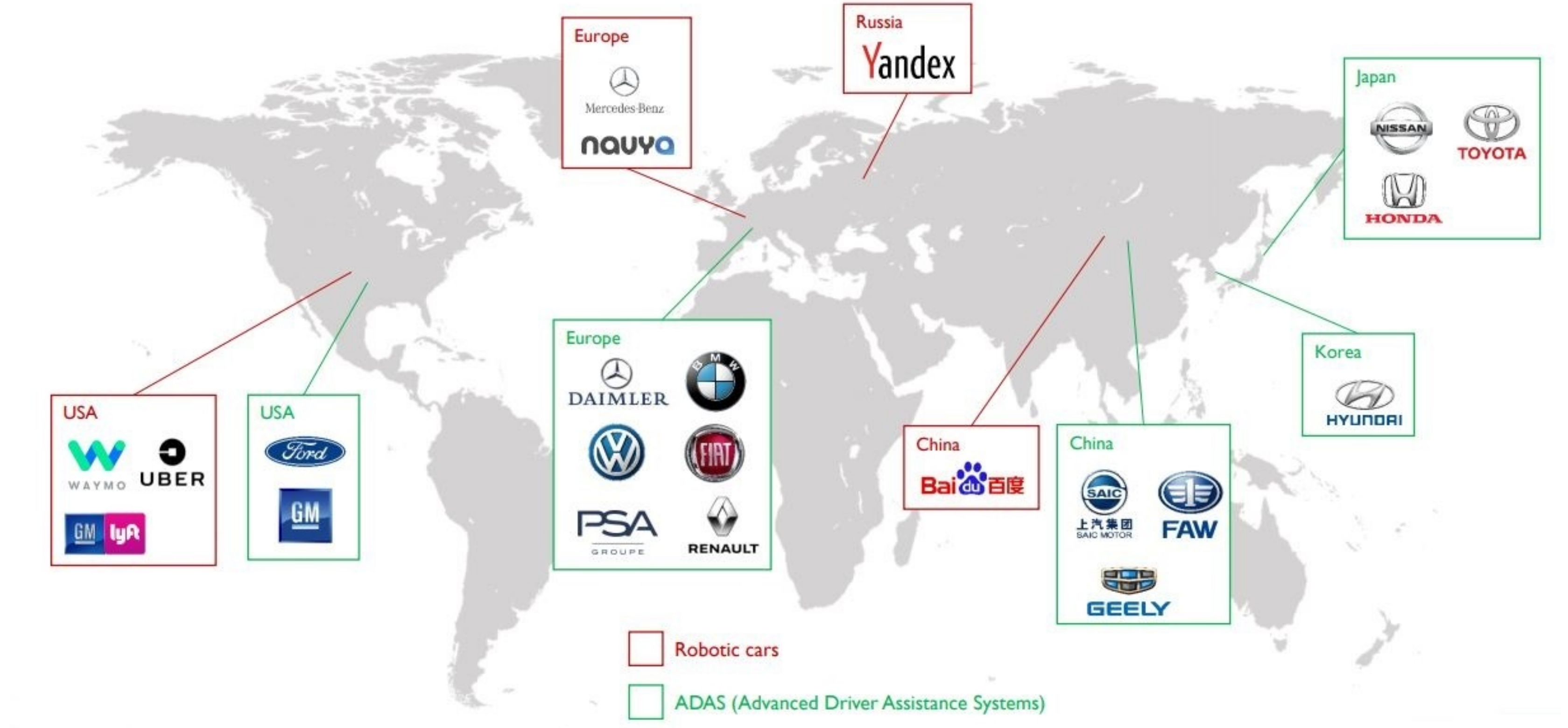
Topology
Transportation
Industrial robots
Consumer
Wind

1930 1975 2020

[1] *Gunnam, K., Hughes, D., Junkins, J. L., and Ketharnaraz, N., "A Vision Based DSP Embedded Navigation Sensor," IEEE Journal of Sensors, October 2002.*
[2] *Valasek, J., Gunnam, K., Kimmett, J., Tandale, M. D., Junkins, J. L., and Hughes, D., "Vision-Based Sensor and Navigation System for Autonomous Air Refueling," The Journal of Guidance Control and Dynamics, April 2005.*
VISion based NAVigation (Visnav) technology[1,2] commercialized for autonomous aerial refueling applications through Sargent Fletcher. Also licensed to NASA for space craft docking.
Sargent Fletcher is a subsidiary company of Cobham plc. which makes aircraft equipment, including aerial refueling systems, external fuel tanks, and special purpose pods.

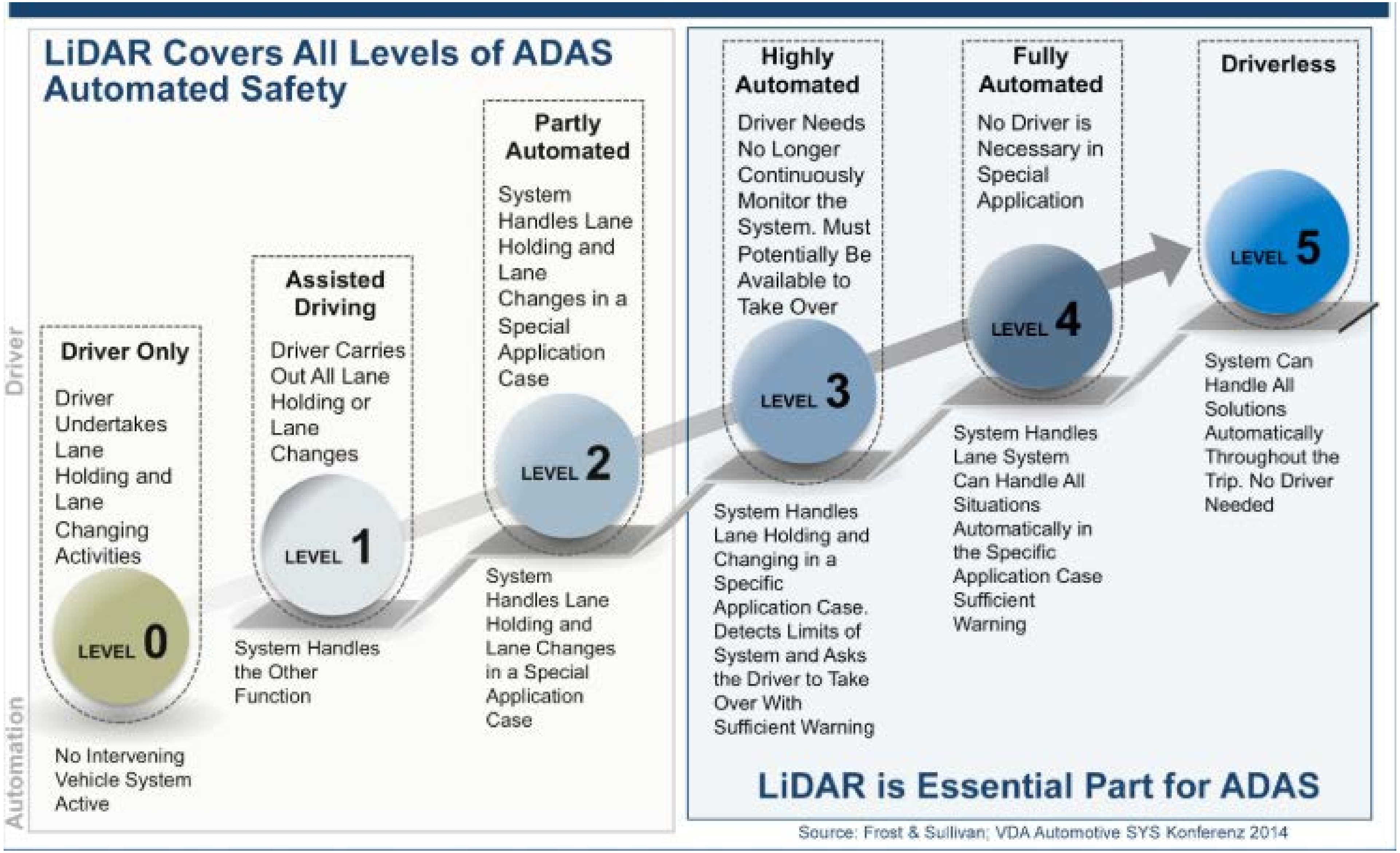
source: Yole with updates

Autonomous Systems- Ground Transportation [Cars, Trucks]



Source: Yole

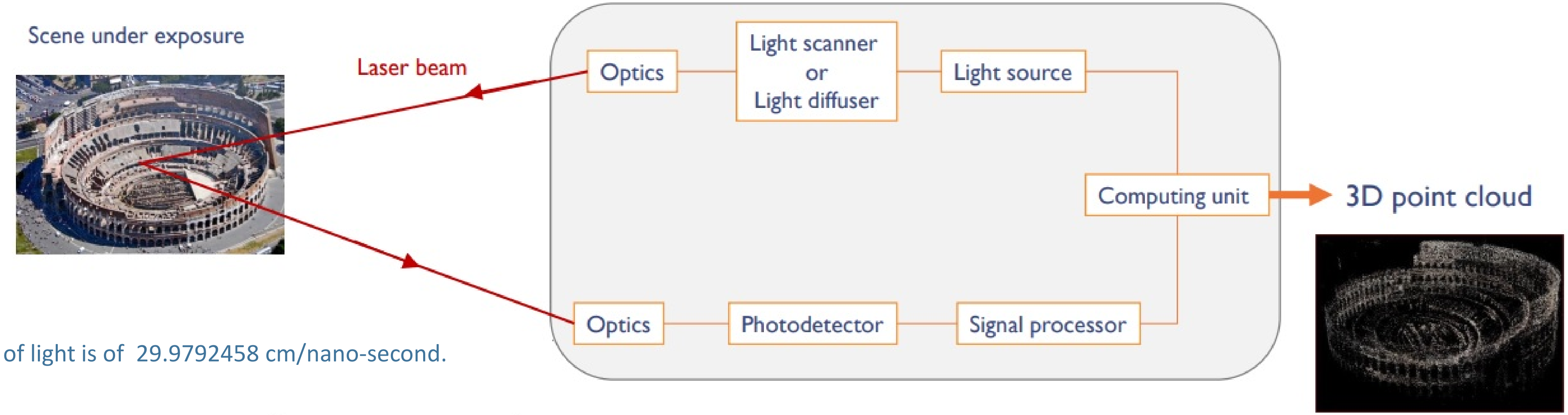
Why LiDAR



LiDAR Covers All Levels of ADAS Automated Safety
Driver
Automation
Driver Only
Driver Undertakes Lane Holding and Lane Changing Activities
LEVEL 0
No Intervening Vehicle System Active
Assisted Driving
Driver Carries Out All Lane Holding or Lane Changes
LEVEL 1
System Handles the Other Function
Partly Automated
System Handles Lane Holding and Lane Changes in a Special Application Case
LEVEL 2
System Handles Lane Holding and Lane Changes in a Special Application Case
Highly Automated
Driver Needs No Longer Continuously Monitor the System. Must Potentially Be Available to Take Over
LEVEL 3
System Handles Lane Holding and Changing in a Specific Application Case. Detects Limits of System and Asks the Driver to Take Over With Sufficient Warning
Fully Automated
No Driver is Necessary in Special Application
LEVEL 4
System Handles Lane System Can Handle All Situations Automatically in the Specific Application Case Sufficient Warning
Driverless
LEVEL 5
System Can Handle All Solutions Automatically Throughout the Trip. No Driver Needed
LiDAR is Essential Part for ADAS
Source: Frost & Sullivan; VDA Automotive SYS Konferenz 2014

LiDAR basic principle

The basic working principle of the LiDAR is very simple.
A light source illuminates a scene. The light scattered by the objects of the scene is detected by a photodetector.
Measuring the time it takes for the light to travel to the object and back from it, allows to know its distance.



speed of light is of 29.9792458 cm/nano-second.

LiDAR system

Tof LiDAR systems

Pulsed-modulation systems: measures the time-of-flight directly.

Allows long-distance measurements.

The arrival time must be detected very precisely.

Needs very short light pulses with fast rise and fall-times and with high optical power lasers or laser diodes. Typical pulse duration 5ns.

Multi-pulse systems with random signatures provide cross talk immunity.

Does not suffer from the phase ambiguity problem;

Technology of choice in a number of outdoor applications under adverse conditions: surveying (static and mobile), autonomous driving, cultural heritage, planetary missions.

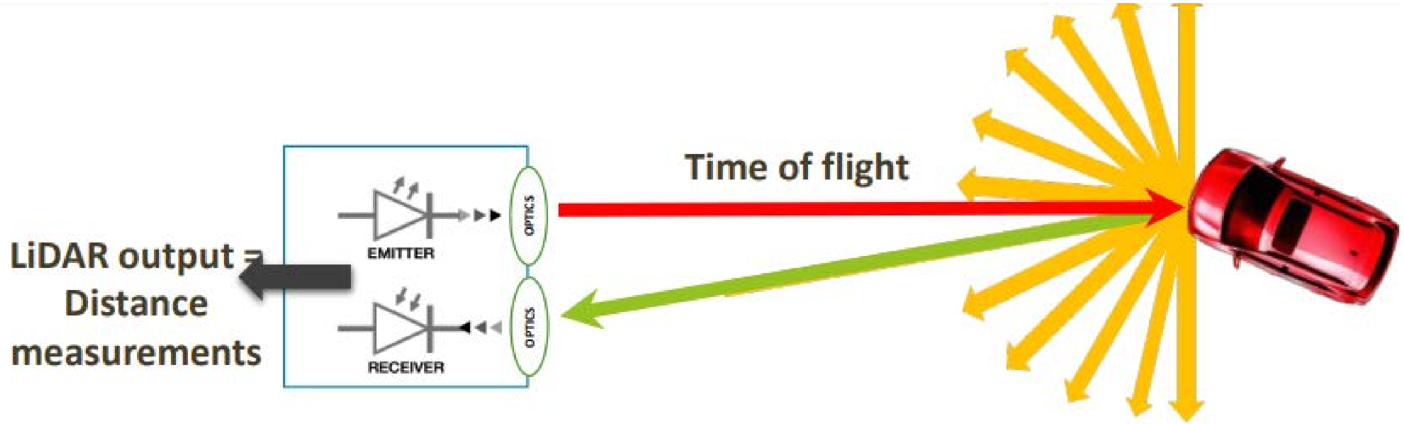
CW-modulation measures the phase difference between the sent and received signals.

Different shapes of signals are possible, e.g., sinusoidal, square waves, etc.

Cross-correlation between the received and sent signals allows phase estimation which is directly related to distance if the modulation frequency is known.

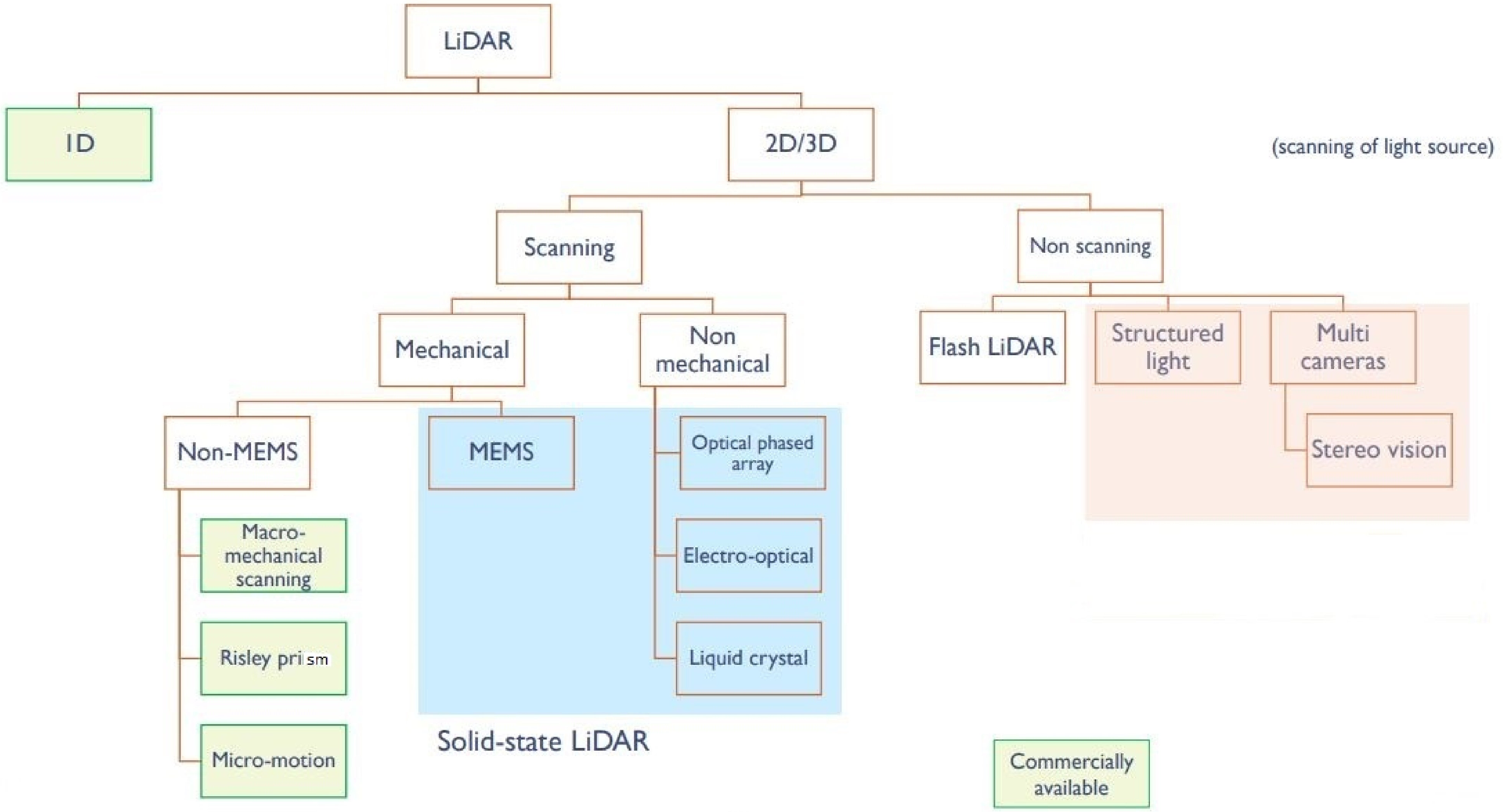
Elements affecting Tof LiDAR systems

- Object types (color, reflectivity, size)
- Weather conditions
- Sensor placement
- Refresh rate
- Resolution
- Lidar Illumination methods
- Lidar detection methods (indium gallium arsenide (InGaAs) for 1550nm, silicon APD for 905nm, receive architectures etc.)



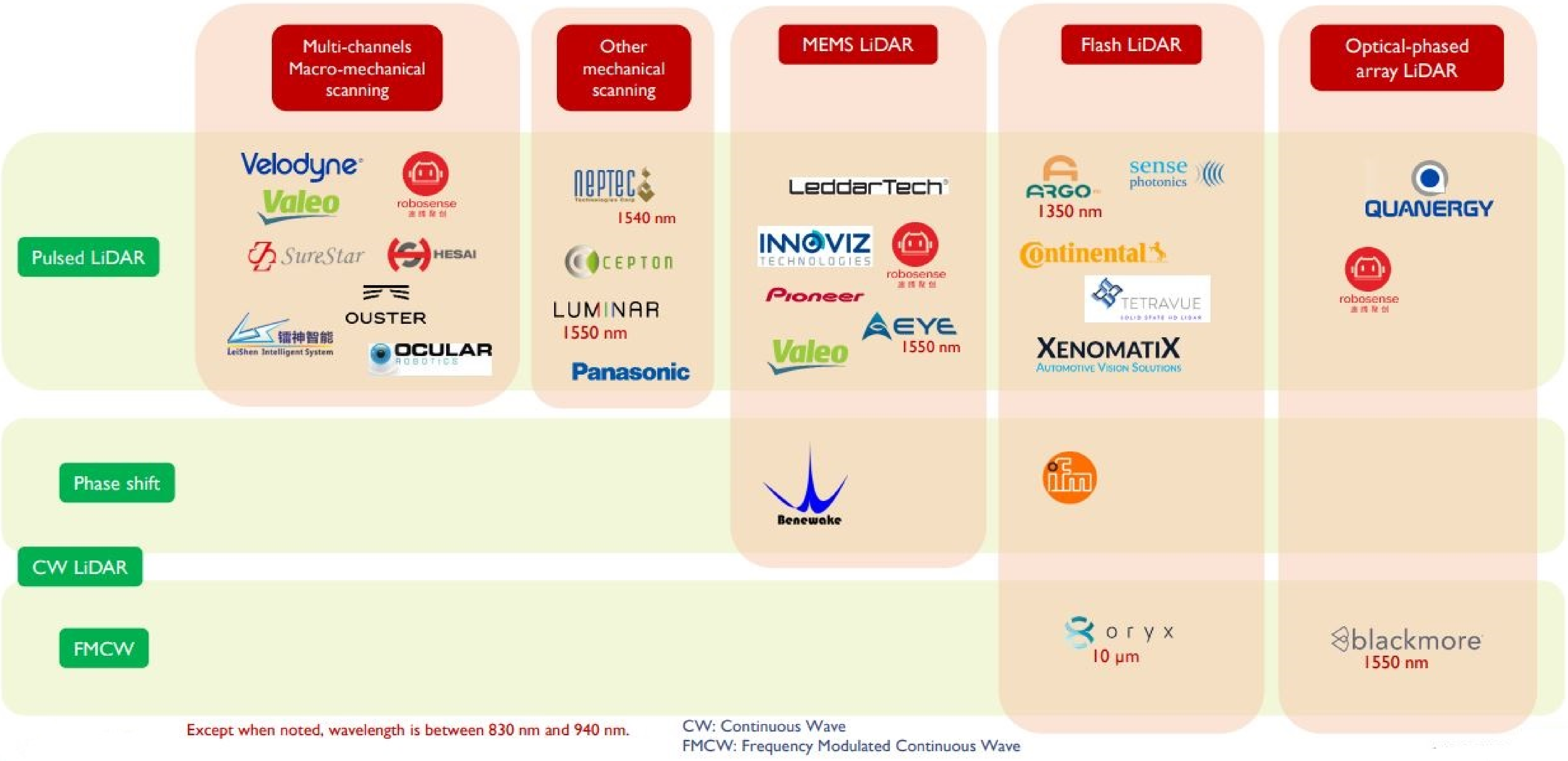
Source: Ibtta

Many LiDARs!



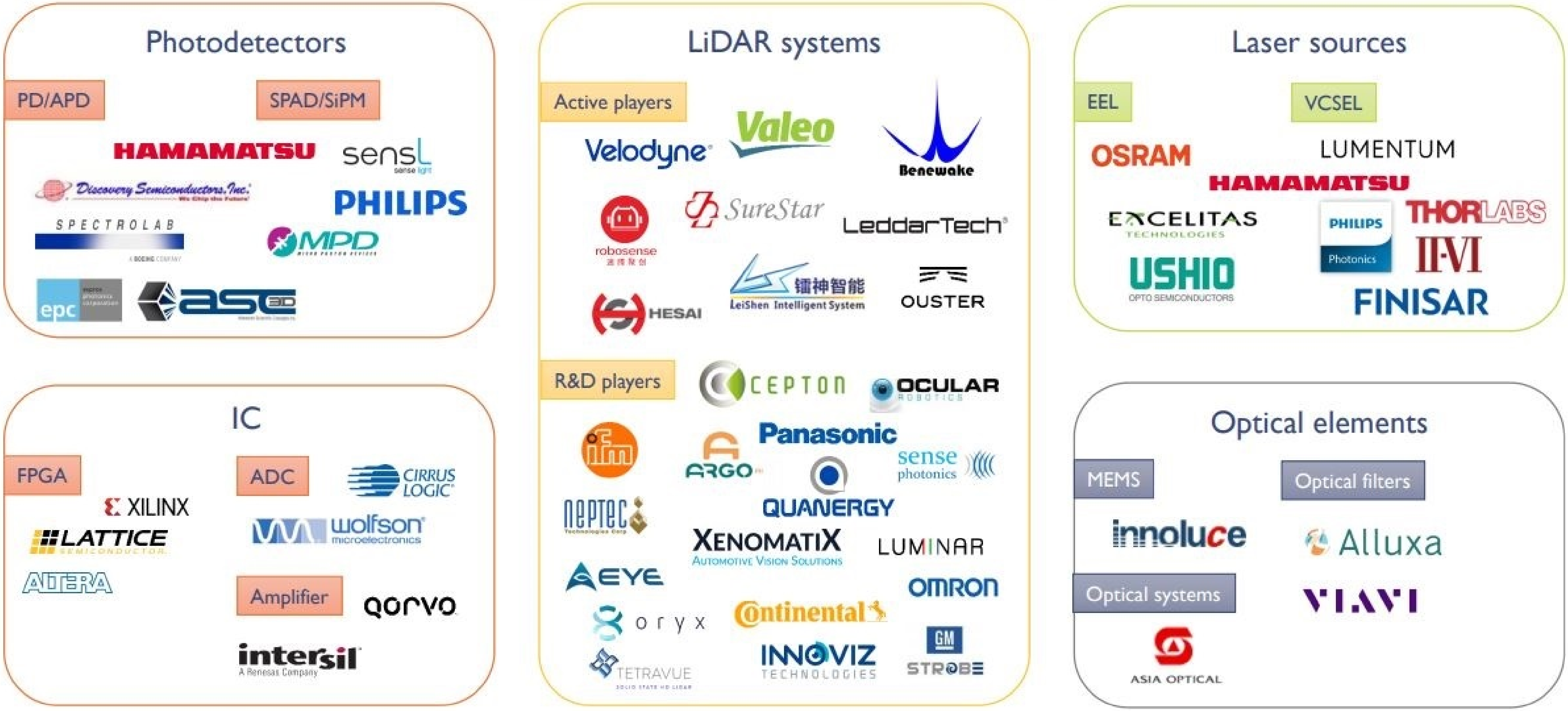
Source: Yole
with few changes.

Many LiDARs!



Source: Yole

LiDAR component and system makers [does not include car OEMS]



ADC: Analog Digital Converter
APD: Avalanche Photodiode
EEL: Edge-Emitting Laser
FPGA: Field-Programmable Gate Array
IC: Integrated Circuit
MEMS: Micro-Electro-Mechanical System
PD: Photodiode
SiPM: Silicon Photomultiplier
SPAD: Single-Photon Avalanche Diode
VCSEL: Vertical Cavity Surface-Emitting Laser

Source: Yole

LiDAR Makers, partial list (does not include car OEMs)

Source: Yole

LiDAR component and system makers in China

Photodetectors

IR Sensors

中国兵器工业集团有限公司
CHINA NORTH INDUSTRIES GROUP CORPORATION LIMITED

IC

FPGA

深圳市国微电子有限公司
SHENZHEN STATE MICROELECTRONICS CO.,LTD

SSMEC
(Shenzhen State Micro-electronics)

GOWIN

安路科技 ANLOGIC

华微电子 SINO-MICROELECTRONICS

Amplifier

SGMICRO

ADC

北京时代民芯科技有限公司

MXTronics

云芯微电子 YUNCHIP

LiDAR Systems

Mechanical

robosense

HESAI

SureStar

镭神智能 LeiShen Intelligent System

Solid-state

robosense

*MEMS and OPA

Benewake

Laser Sources

EEL

Accelink

O-Net Technologies

VCSEL

华芯半导体 SINOSEMIC

LiDAR Users

*R&D phase

Delivery Robots

Bai du 百度

JD.COM 京东

Robotic Cars

Bai du 百度

ADAS

SAIC 上汽集团 SAIC MOTOR

FAW

GEELY

Optical Elements

MEMS Scanners

ZhiSENSOR

WIO TECH 微奥科技

Optical Systems

水晶光电

Zhejiang Crystal-Optech

ADC: Analog Digital Converter
EEL: Edge-Emitting Laser
FPGA: Field-Programmable Gate Array
IC: Integrated Circuit

IR: Infrared
MEMS: Micro-Electro-Mechanical System
OPA: Optical Phased Array
VCSEL: Vertical Cavity Surface-Emitting Laser

Source: Yole

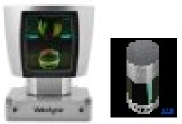
OEMs also became LiDAR Makers through M&A or internal R&D

Source: Yole

Solid-State LiDARs

Solid-state LiDAR is a broad name to describe LiDAR which are not using conventional motors but semiconductor solutions to scan or steer light through a scene.

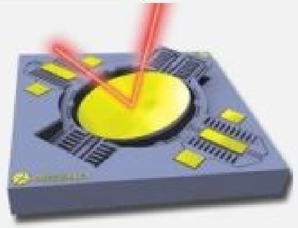
Macro-mechanical scanning — Current technology



MEMS LiDAR — 2018 – 2019

OPA LiDAR — 2022 – 2023

MEMS LiDAR

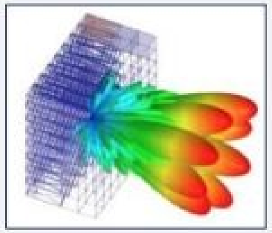


Courtesy of Preciseley Microtechnology Corp.

In a MEMS LiDAR, a micro-scanner integrated with actuators on silicon steers the laser beam during illumination.

- Batch production ⇒ Cheaper.
- Automotive robustness is under test.

OPA LiDAR (Optical Phased Array)



Courtesy of Quanergy

In a OPA LiDAR, steering of the illumination is obtained by controlling the phase of an array of lasers.

- No moving parts ⇒ More robust.
- Still difficult to design due to poor SNR

MEMS LiDAR players

- USA: AEYE
- Europe: Valeo
- Israel: INNOVIZ TECHNOLOGIES — Design win with BMW In partnership with Magna
- China: robosense, Benewake
- Canada: LeddarTech

OPA LiDAR players

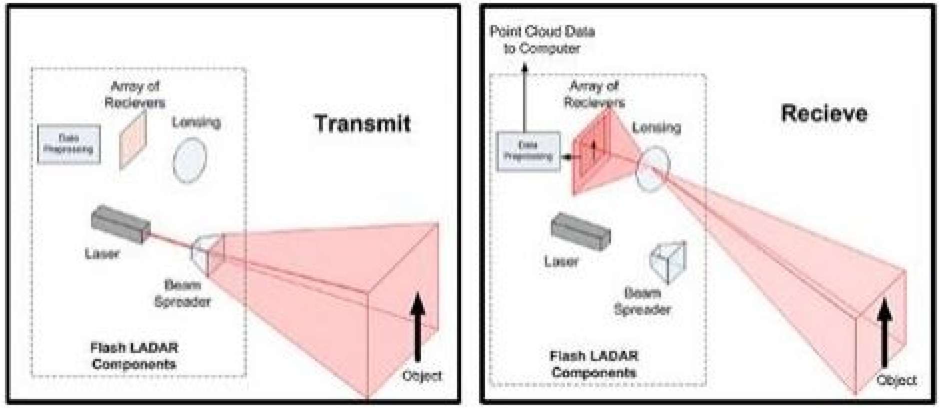
- USA: QUANERGY, blackmore
- China: robosense

MEMS: Micro-Electro Mechanical Systems
OPA: Optical Phased Array

Source: Yole

Solid-State Flash LiDARs

In Flash LiDAR, a laser beam is not scanned over the scene, but this last is illuminated at once. As a result, no moving part is needed. On the other hand, an array of photodetector is needed to form an image.



Courtesy of Advanced Scientific Concepts, Inc.

Pros and cons of Flash LiDAR

Pros	Cons
• No moving parts. • Potentially better spatial resolution.	• Photodetector array needed. • More photons are needed.

Photodetector arrays

PIN photodiodes

CCD or CMOS image sensor with time of flight capability.

APD

Higher gain than PIN photodiodes.

SPAD

Single photon detection but limited to digital one bit operation.

SiPM

High gain and high sensitivity. CMOS technology.

Flash LiDAR players

USA

sense photonics

ARGO

TETRAVUE SOLID STATE HD LIDAR

Europe

Design win with Volvo

Continental

ifm

XENOMATIX AUTOMOTIVE VISION SOLUTIONS

Israel

oryx

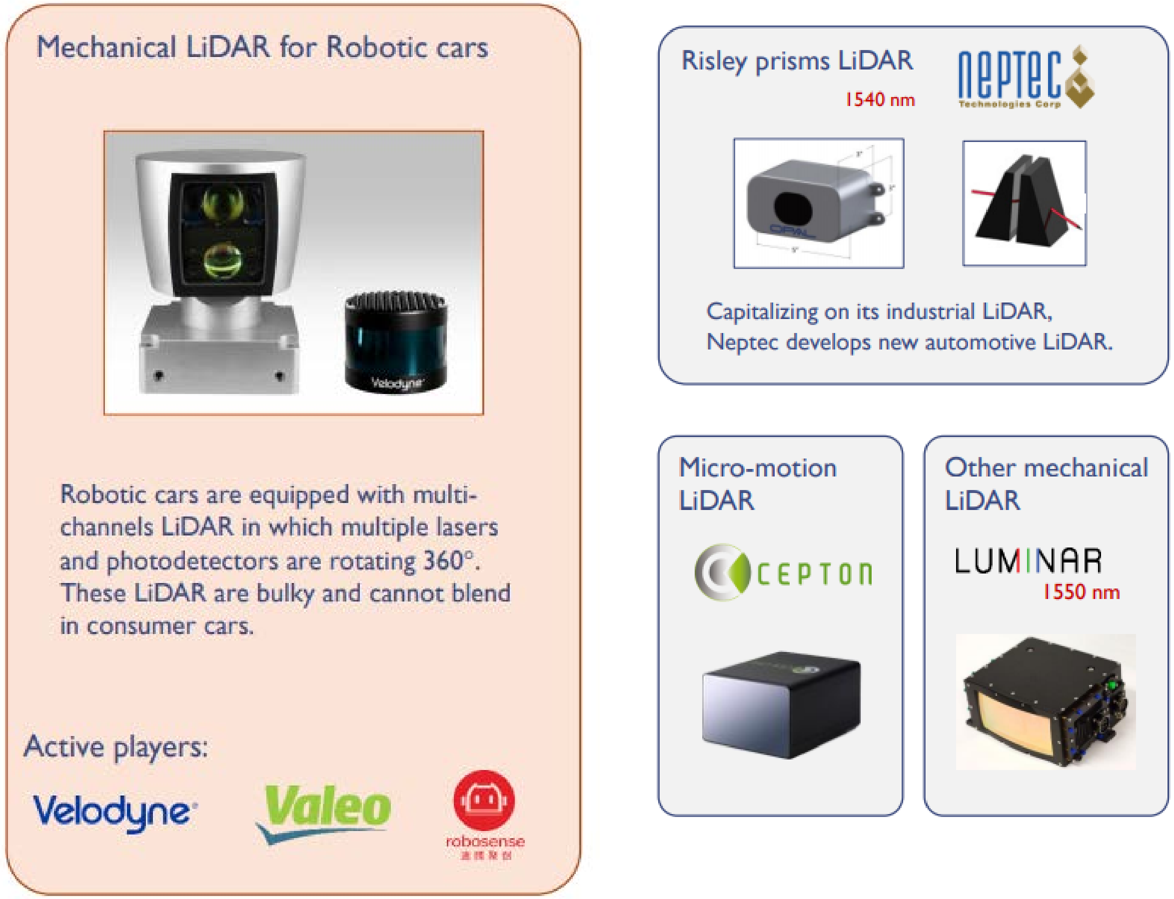
10 µm

APD: Avalanche Photodiode
PD: Photodiode

SiPM: Silicon Photomultiplier
SPAD: Single-Photon Avalanche Diode

Source: Yole

Mechanical lidars in research cars for testing



Source: Yole

Use rotating mirrors or turrets to steer the light beam across the field of view

- ❑ Pros: good performance and resolution
- ❑ Cons: expensive, less robust, weather sensitive. Not automotive grade
- Very limited volume
- Huge manufacturing cost
- razor-thin profit margins
- still partial automation-

more than 50% employees of lidar companies are in manufacturing

- Cutthroat competition from Chinese companies.

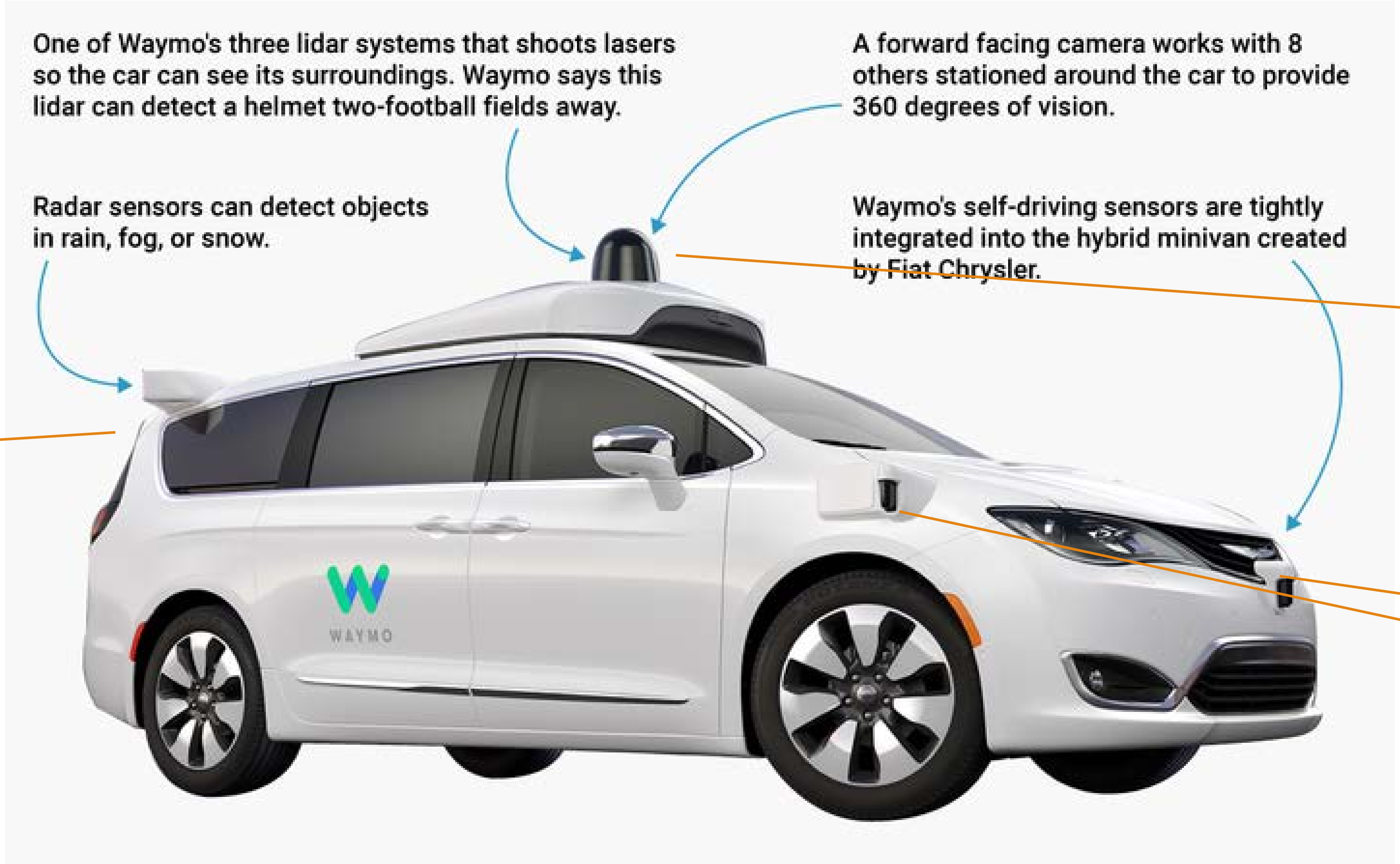
Google is making their custom and better LiDAR systems.

Source: Yole

LiDARs making into commercial cars

Sensor Maker	Design Win for commercial deployment	Design Win Size and timeframe
Waymo	Waymo-Chrysler Waymo-Jaguar [Robo car]	62,000 20,000 [by 2022]
Valeo	Audi [ADAS for consumer car]	~3000, 2017 ~100K, 2021
Innoviz	BMW [ADAS for consumer car]	~100K, 2021
Continental	Volvo [ADAS for consumer car]	~100K,2021

First laser scanner for the mass-production robo taxi



short range LiDAR

Two LiDARs housed in the same package with dividing structure for optical isolation.
905nm 64-beam LiDAR, 100m range (top)
1550nm single beam LiDAR, 300m range (bottom)

Short range LiDAR

LiDAR glass housing is also a optical filter.

Chrysler Pacifica Hybrid minivan is Waymo's first vehicle built on a mass-production platform with a fully-integrated hardware suite, for the purpose of full autonomy. Limited testing on-going in Arizona.

Source: Google, Google patents

Waymo LiDARs

Master-Slave LiDAR: (cost $7500 at limited volume, expected to cost less than $2000 in 100K volumes)
Master Mid range Lidar: 360° (horizontal)×20° (vertical) FOV of the environment. Range 100m. Uses 905nm lidar. Houses its APD in sealed chamber with inert nitrogen gas. 0.2° (horizontal)×0.3° (vertical) angular resolution.
Slave Steerable long range Lidar: Uses 1550nm lidar. Range is 300m.Single beam. Steerable over 360° about vertical axis as well as steerable about a horizontal axis. Can zoom into objects on the road based on the processing results for Midrange LiDAR. Preferred FOV of 8° (horizontal)×15° (vertical), a refresh rate of 4 Hz. 0.1° (horizontal)×0.03° (vertical) angular resolution.
Mounted with a rotational bearing configured to allow the LIDAR system to rotate about a vertical axis. The laser beam is steered about a horizontal axis such that the beam can be moved up and down with a resonant spring.
Range Enhancement: Though long range LiDAR is steerable, its default FoV is focused on the lane it is driving an. It main purpose is to detect debris on the road in the path of the car up to 300m.
Resolution Enhancement: Since the Master LiDAR range is limited to 100m and if the Master LiDAR detects pedestrians or cyclists or any other objects of concern within 100m, long range LiDAR can be steered to get more resolution of the concerning object. Here the long range LiDAR is providing more resolution than the range.
Advantages: Avoids using 128-beam lidar. Avoids using 120 degree FoV 1550nm LiDAR. Both are super expensive and costs more than 100K in limited units based on industry estimates.

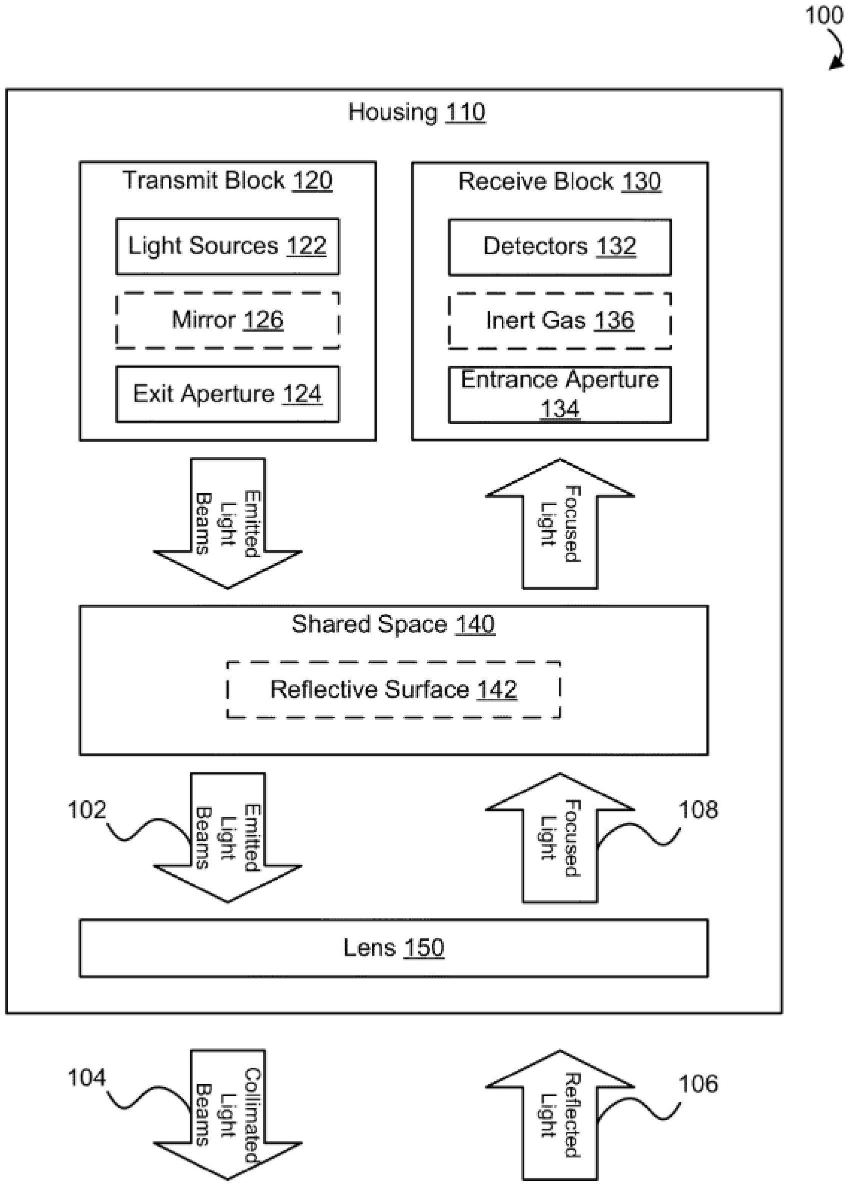
Source: Google patents

Waymo LiDARs

	Long-range LiDAR	Medium-range LiDAR	Short-range LiDAR
Range	300m	100m	30m
Laser	1550nm	905nm	905nm
Special features	Steerable over 360° about vertical axis as well as steerable about a horizontal axis. Operates based on processing from medium-range LiDAR	APD housed in sealed Chamber filled with nitrogen gas	No limitation on how close is the object.
Operating FoV	8° (horizontal)×15° (vertical)	360° (horizontal)×20° (vertical)	270°
Refresh rate	4 Hz	10 Hz	4Hz
Beam steering	Assembly movement + spring	Laser and diode array movement	Solid-state beam steering
Number of beams	1	64	1
Lens	1	1	1

Source: Google patents

Waymo LiDAR



Source: Google patents

Waymo LiDARs, Lens

Shared Lens (250): Receives the light beams via the transmit path. Have an aspheric surface 252 facing outside of the housing 210 and a toroidal surface 254 facing the shared space 240.

Collimate the light beams for transmission into an environment of the LIDAR device. (224 mirror, 202a-c lasers)

Collect light that includes light from one or more of the collimated light beams reflected by one or more objects in the environment of the LIDAR device

Focus the collected light onto the detectors (232a-c) via a receive path that extends through the shared space and the entrance aperture of the receive block.
244 wall for optical isolation of transmit and receive.
220- transmit block 226 –exit aperture. 234- entrance aperture. 228 –curved focal surface 210-housing

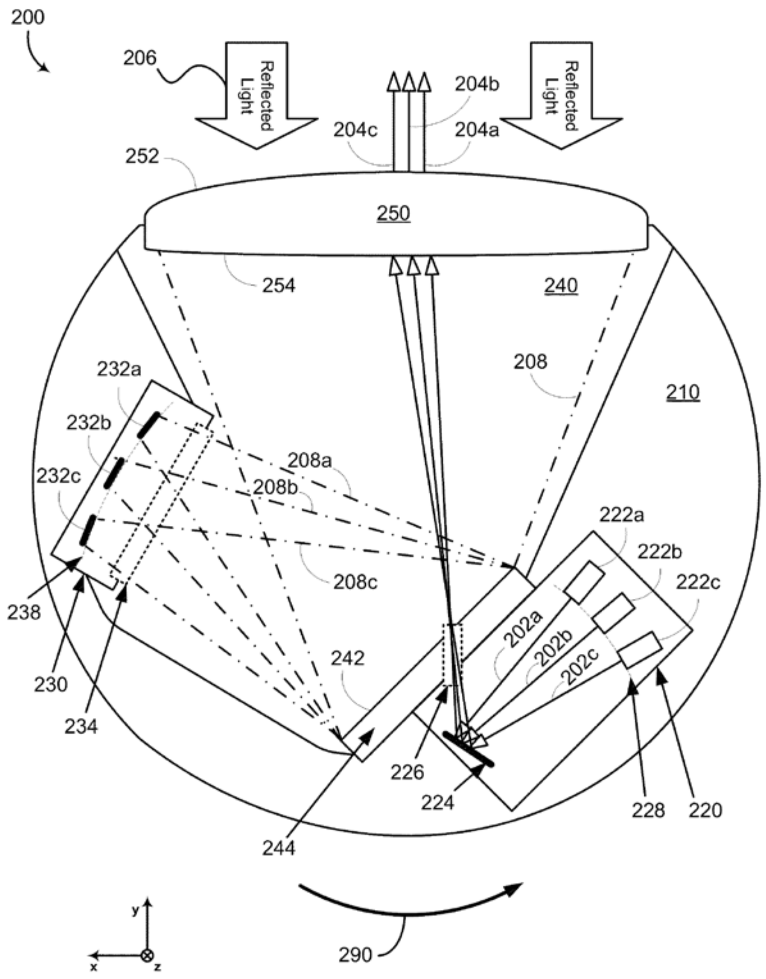
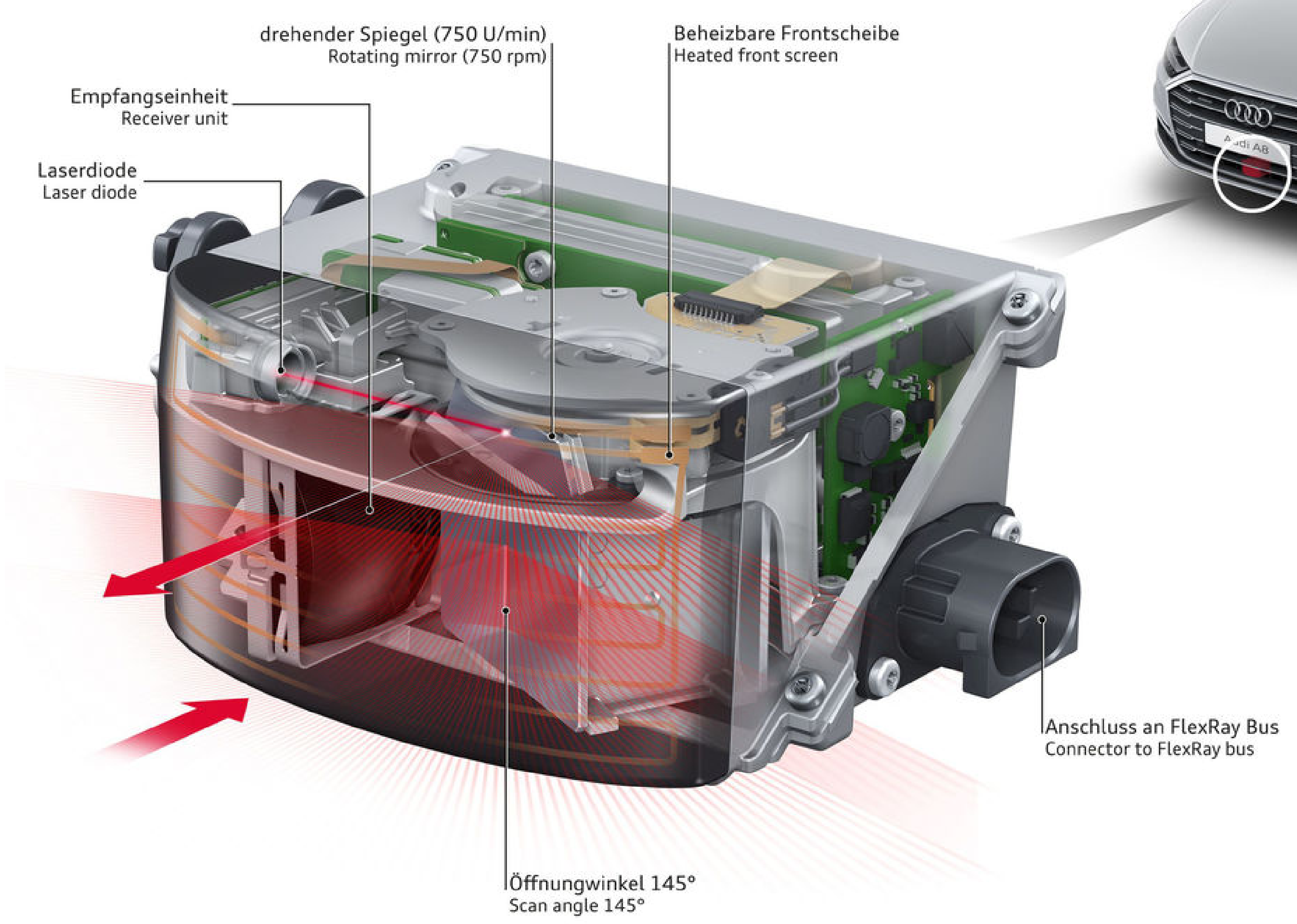


FIG. 2

Source: Google patents

First laser scanner for the automotive volume production, Scala



Limited to ADAS

Source: Ibeo

Leddar Tech LiDAR

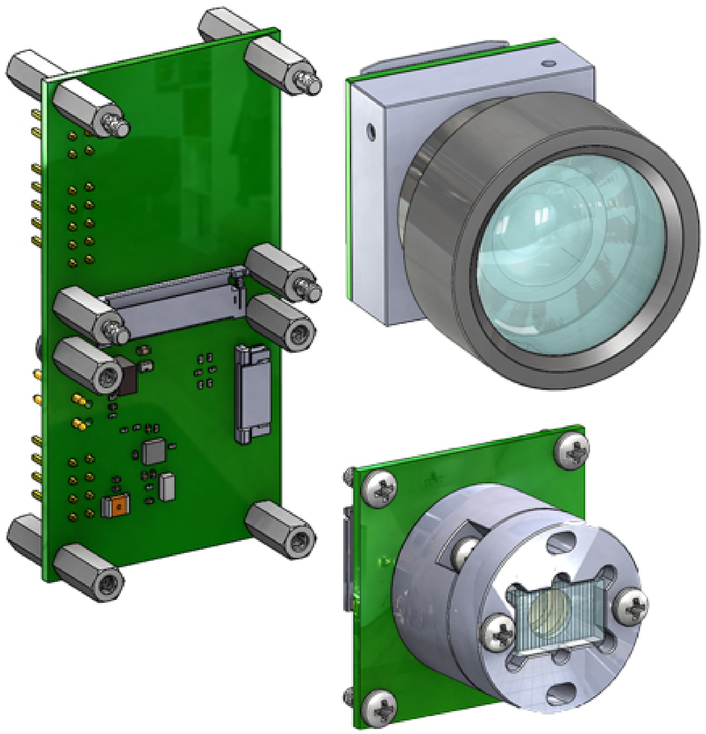
Vu8 module- 8 beam LiDAR

A carrier board to host the electrical and communications interface)

An infrared laser emitter

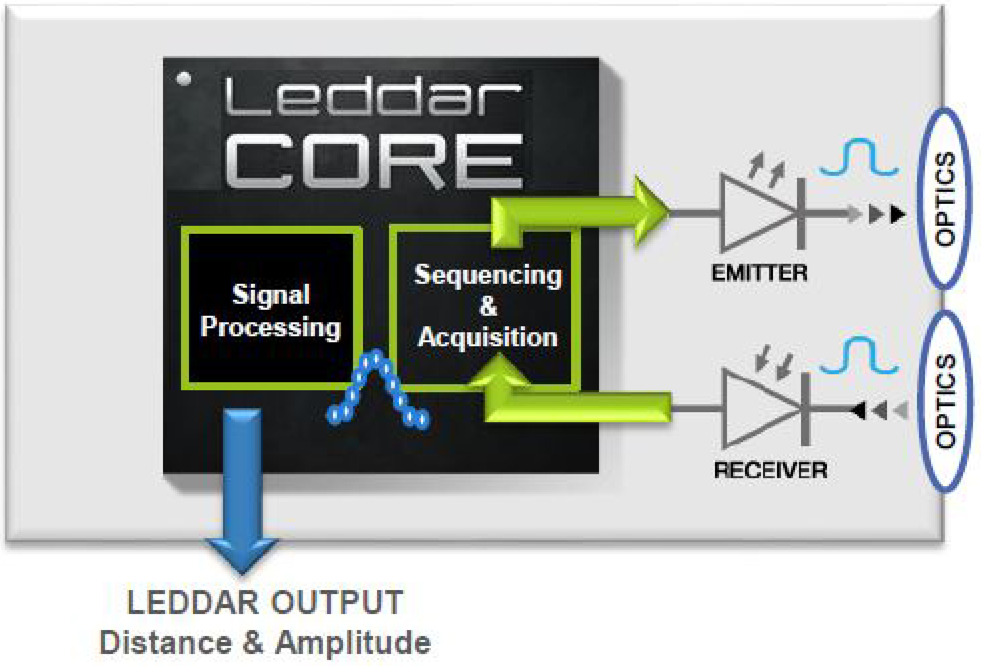
An optical receiver assembly

An internal processor (called the LeddarCore IC)



Source: LeddarTech

Leddar Tech LiDAR



LEDDAR KEY DIFFERENTIATORS

Rather than working directly on the analog signal, Leddar samples the receive echo for the complete detection range of the sensor.

Through patented methods, Leddar iteratively expands the sampling rate and resolution of this sampled signal.

Utilizing sophisticated software-based algorithms, it analyzes the resulting discrete-time signal and recovers the distance for every object in its field of view.

Source: LeddarTech

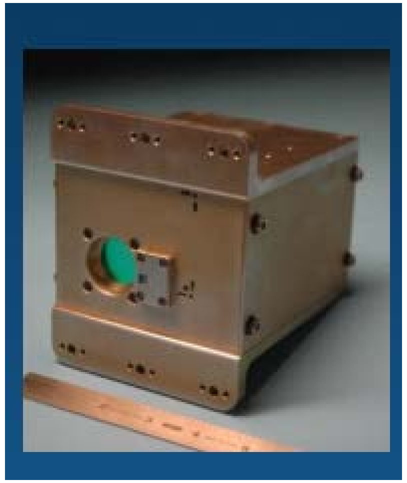
Continental Flash LiDAR

- •No moving parts – solid state
- •Scalable fields of view and range
- •Contiguous pixels – no gaps
- •High vertical resolution
- •Co-registered range & intensity
- •No motion blur
- •High sensitivity
- •a single laser pulse per frame of data delivers range data and black-and-white video back to the LiDAR sensor, where they are captured by a focal plane array of smart pixels.

•3D Flash LIDAR can provide an accurate image of the traffic light in 3D and show how far away it is. The synergy of these two technologies makes the system even more robust and reliable.

Source: Continetnal

Continental Flash LiDAR, previous generation



Quantities Measured:	Range and Intensity
Detectors:	128 x 128 ROIC/ InGaAs APD array.
Performance:	1 meter (5 cm precision) to 4 km (60 cm precision).
Optical/Mechanical Design:	12 mm aperture f/1.6 telescope, aluminum construction.
Field of View:	45 by 45°
In-Flight Calibration:	Single time of flight optical reference.
Mounting Orientation:	Fixed to spacecraft.
Thermal Requirements:	Operating 10° C to +40° C.
	Storage -20° C to +60° C.
Frame Rate:	20 Hz
On-board Data Processing:	Virtex 4 FPGA
Mass:	3 kg
Size:	12 x 12 x 12 cm
Power:	30 W 100% duty cycle (28 -32 Vdc)

Source: Continetnal

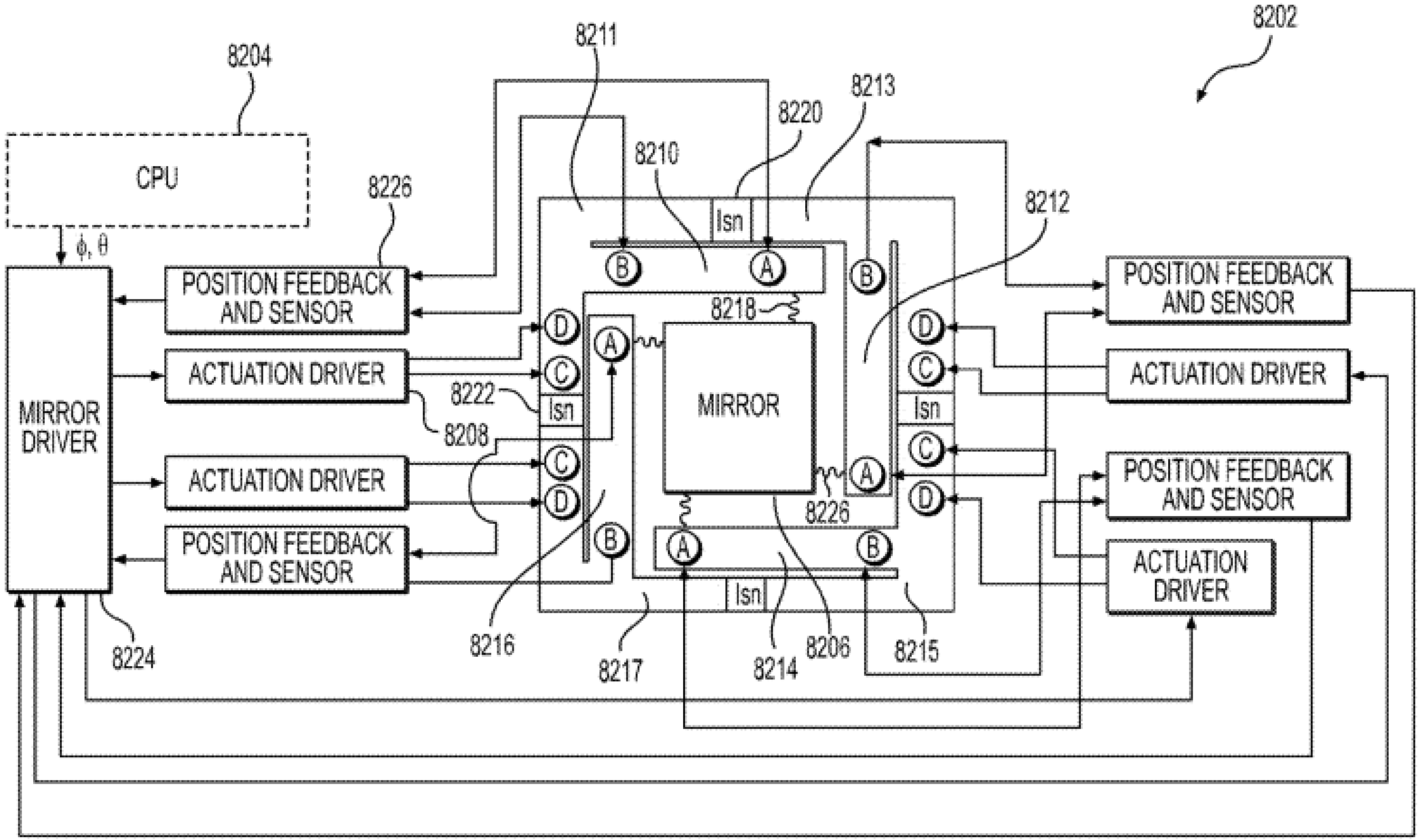
Innoviz Solid State LiDAR

microelectromechanical (MEMS) mirror for deflecting the light.

Actuators and interconnect elements are mechanically connected.

Each actuator comprises a body and a piezoelectric element.

The piezoelectric element is configured to bend the body and move the MEMS mirror when subjected to an electrical field.



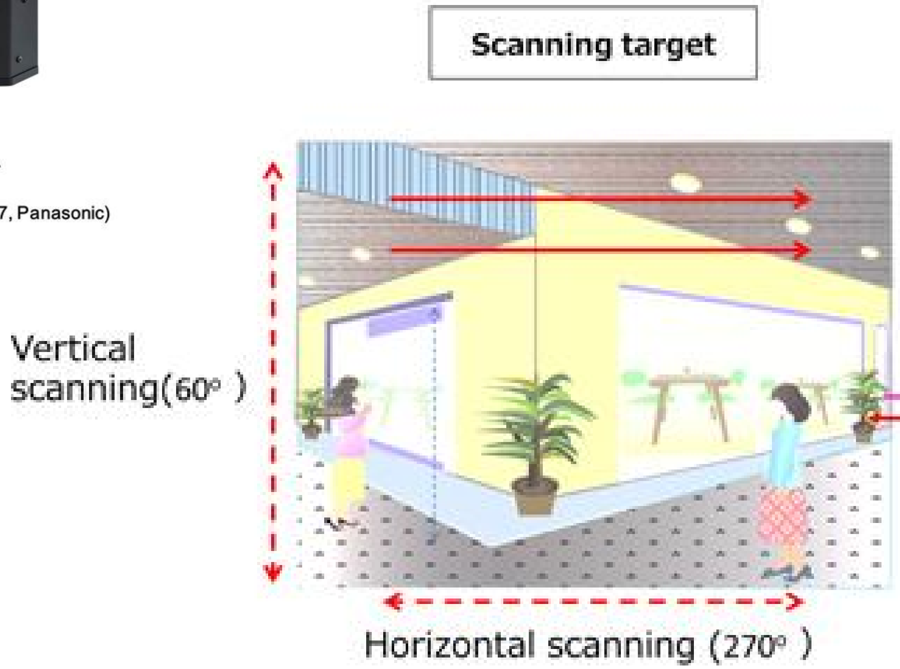
Source: Google patents

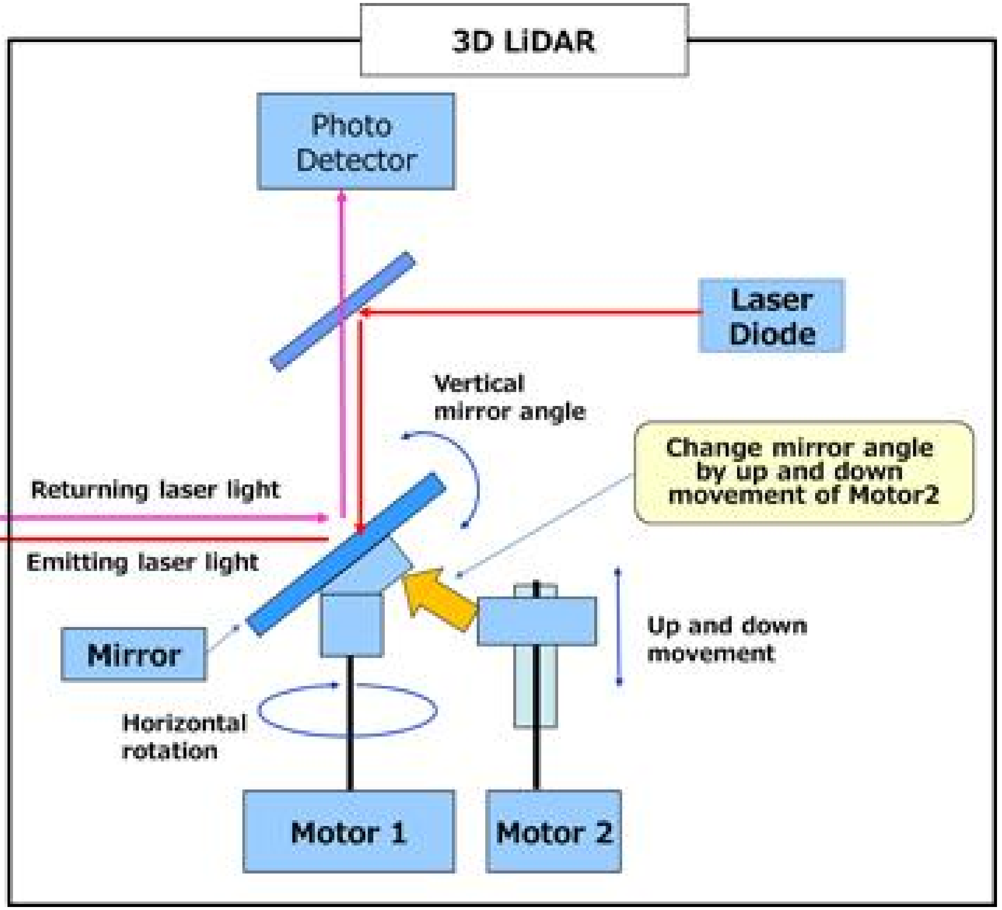
Panasonic 3D LiDAR

A light source illuminates a scene.
The light scattered by the objects of the scene is detected by a photodetector.
Measuring the time it takes for the light to travel to the object and back from it, allows to know its distance.

3D LiDAR sensor

(September 2017, Panasonic)



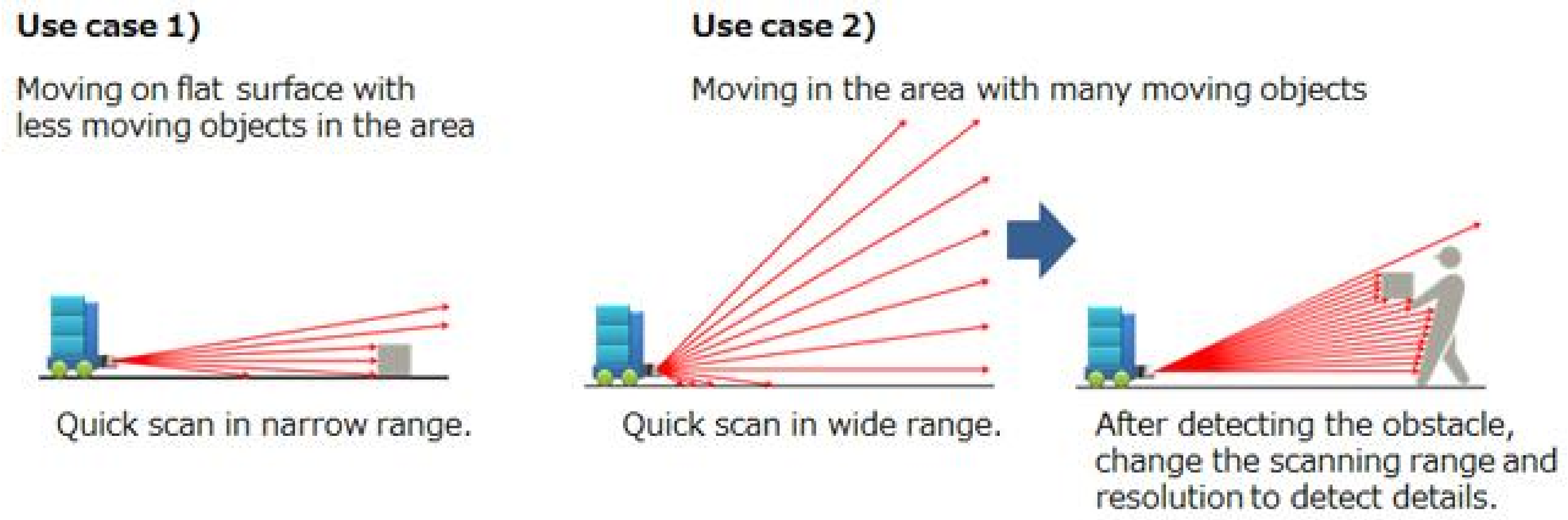


Source: Panasonic

3D LiDAR

3D LiDAR sensor

(September 2017, Panasonic)



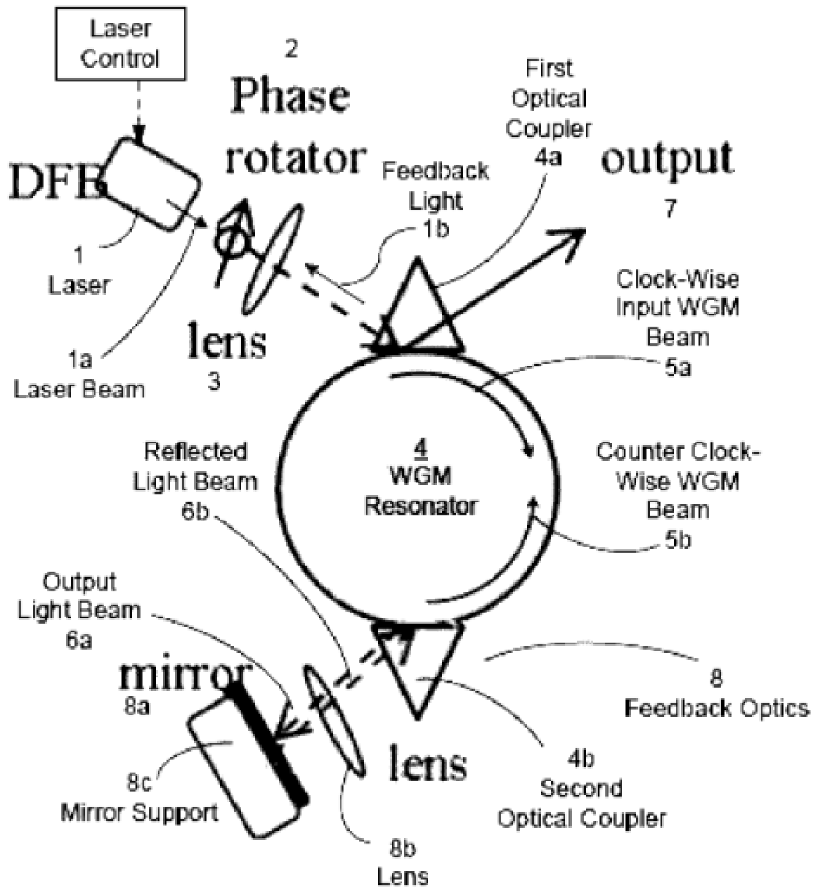
Source: Panasonic

Basic specifications of Panasonic's 3D LiDAR

Item	Performance
Scanning angle	270 degrees in horizontal and 0 to 60 degrees in vertical direction (variable)
Resolution in vertical angles	Can be chosen from three modes of 1.5 degrees, 3.0 degrees and 7.5 degrees.
Detectable distance	0.5 m to 50 m
Frame rate	5 fps to 25 fps
Ambient light immunity	Up to 100,000 lux (under sunlight)
Outside dimensions	130 mm (H) x 120 mm (W) x 140 mm (D)

Source: Panasonic

FMCW LiDAR,Blackmore

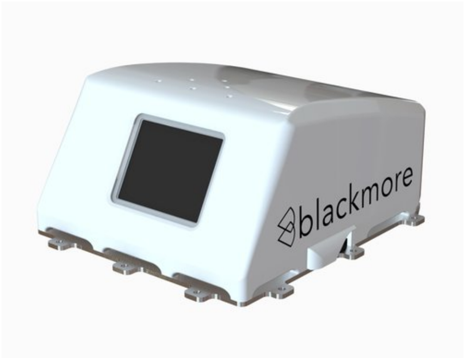


Blackmore claims the world's first FMCW lidar for automotive research vehicles:

- Long range performance (>200m)
- Velocity measurement (+/- 150m/s, 0.2m/s resolution)
- Calibrated reflectivity estimates
- Flexible 2D scanning over forward-look FOV
- Selectable point throughput of 300kpts/sec to 1.2Mpts/sec
- (Blackmore is funded by Toyota ventures and BMW i ventures)

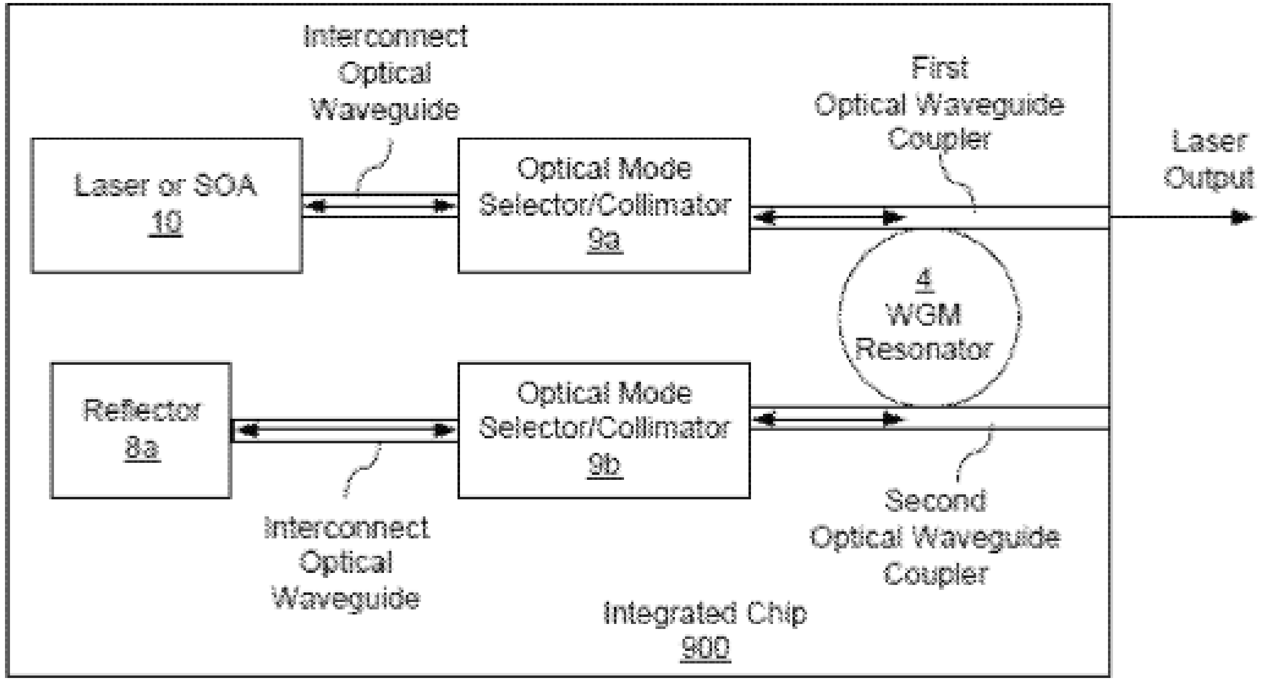
Laser linewidth 100 Hz.
Linear chirp with large bandwidth (B) of 15GHz
Range resolution (ΔR) of 1 cm.
c is speed of the light.

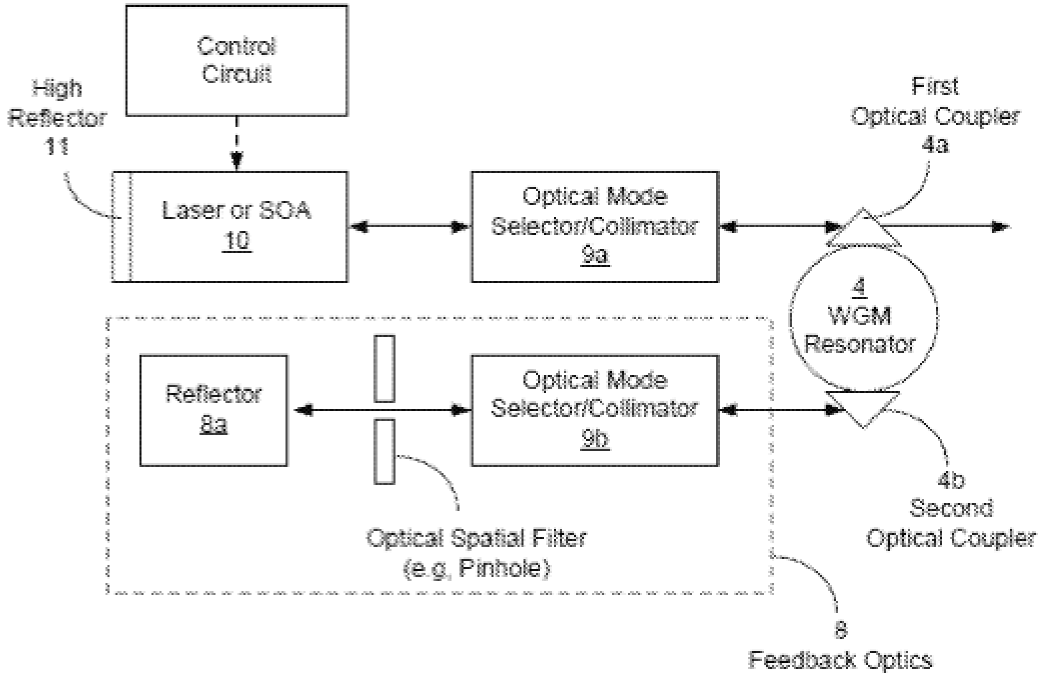
$\Delta R = c/2B$

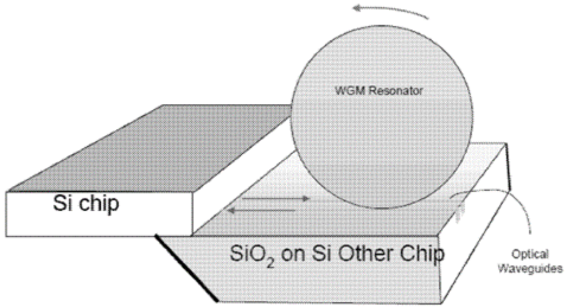


Source: Google patents, Blackmore

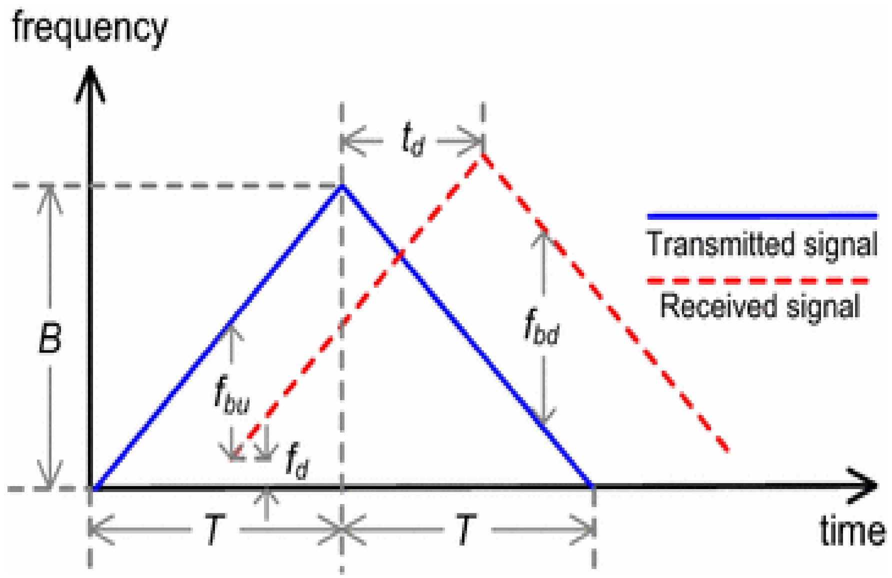
FMCW LiDAR, two other alternate implementations







FMCW LiDAR operating principle



The received and transmitted frequencies of a triangular waveform for the FMCW radar system. And these are mixed.

f_{bu} and f_{bd} denote the up ramp beat frequency and down ramp beat frequency, respectively.

the transmitted signal of an FMCW radar system can be modeled as

$$s_T(t) = A_T \cos\left(2\pi f_c t + 2\pi \int_0^t f_T(\tau)d\tau\right), \quad (1)$$

where $f_T(\tau) = \frac{B}{T} \cdot \tau$ is the transmit frequency as a linear function of time, f_c is the carrier frequency, B is the bandwidth, A_T represents the transmitted signal amplitude, and T is the time duration. Considering a reflected signal with a time delay $t_d = 2 \cdot \frac{R_0 + vt}{c}$ and Doppler shift $f_D = -2 \cdot \frac{f_c v}{c}$, the receive frequency can be expressed as

$$f_R(t) = \frac{B}{T}(t - t_d) + f_D, \quad (2)$$

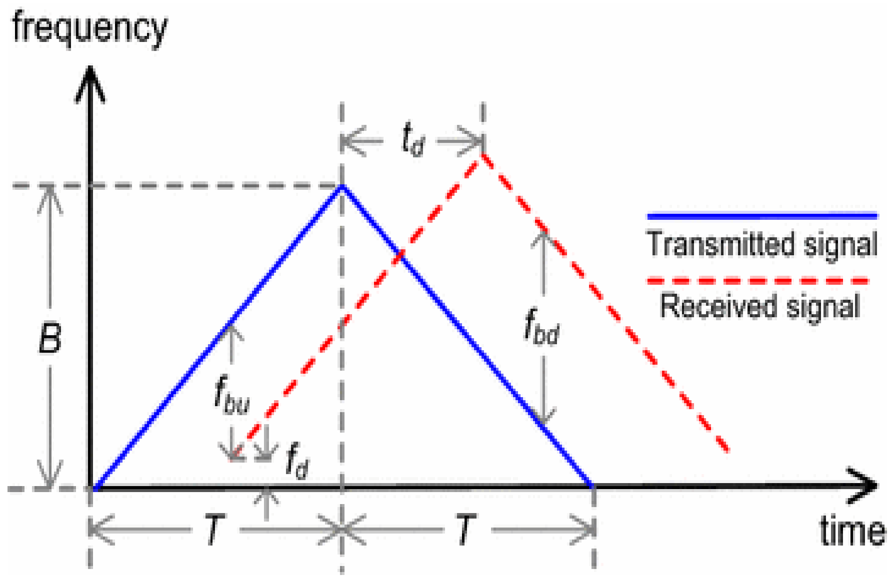
where R_0 is the range at $t = 0$, v is the target velocity, and c is the speed of light. The received signal can be described as

$$\begin{aligned} S_R(t) &= A_R \cos\left(2\pi f_c (t - t_d) + 2\pi \int_0^t f_R(\tau)d\tau\right) \\ &= A_R \cos\left\{2\pi \left(f_c (t - t_d) + \frac{B}{T}\left(\frac{1}{2}t^2 - t_d \cdot t\right) + f_D \cdot t\right)\right\}. \end{aligned} \quad (3)$$

Here, A_R represents the received signal amplitude, which is dependent on antenna gains, transmitted power, and the target's distance and radar cross section (RCS).

Source: https://springerplus.springeropen.com/articles/10.1186/s40064-015-1583-5

FMCW LiDAR operating principle



The received and transmitted frequencies of a triangular waveform for the FMCW radar system

f_{bu} and f_{bd} denote the up ramp beat frequency and down ramp beat frequency, respectively.

To obtain information of the Doppler frequency and beat frequency, $S_T(t)$ and $S_R(t)$ are mixed by multiplication in the time domain, and passed to a low-pass filter (LPF). The intermediate frequency (IF) signal $S_{IF}(t)$ of the LPF output is then obtained for the up ramp as

$$S_{IF}(t) = \frac{1}{2}\cos\left(2\pi\left(f_c \cdot \frac{2R_0}{c}\right) + 2\pi\left(\frac{2R_0}{c} \cdot \frac{B}{T} + \frac{2f_c v}{c}\right)t\right). \quad (4)$$

Similarly, the IF signal $S_{IF}(t)$ of the LPF output can be obtained for the down ramp as follows

$$S_{IF}(t) = \frac{1}{2}\cos\left(2\pi\left(f_c \cdot \frac{2R_0}{c}\right) + 2\pi\left(-\frac{2R_0}{c} \cdot \frac{B}{T} + \frac{2f_c v}{c}\right)t\right). \quad (5)$$

Hence, two time-dependent frequency terms called beat frequency appear in the spectrum of the baseband signal

$$\begin{cases} f_{bu} = \frac{2R_0}{c} \cdot \frac{B}{T} + \frac{2f_c v}{c} \\ f_{bd} = -\frac{2R_0}{c} \cdot \frac{B}{T} + \frac{2f_c v}{c} \end{cases}. \quad (6)$$

We can then use these frequencies to solve for v and R_0.

Source: https://springerplus.springeropen.com/articles/10.1186/s40064-015-1583-5

Receiver Architectures for Pulse LiDAR

Detection for Pulse LiDAR using ADC and Matched Filter

- Range resolution is inversely proportional to the combined rise time of the laser, TIA and detector, while the maximum range is proportional to peak laser power and the combined sensitivity of the TIA and detector for the given optics.

- This indicates that to achieve high resolution over long distances, the system should have a high-peak-power laser with a fast rise time measured by a high bandwidth, low-noise photo diode, TIA, and detector.

- Additionally, the system must account for the return signal amplitude, which decreases proportionally to the square of the measured distance. The finite rise time of the measured return must also be accounted for in the detector to prevent level-dependent triggering errors.

- A high-speed ADC digitizes the return signal (instead of simply measuring time), signal processing can be employed to implement sophisticated detection schemes that not only have better performance than the TDC.

- These also provide additional information for target identification. This result allows for the relaxation of the laser rise time or improvement in range resolution for the same rise time. The wide dynamic range of the ADC eases and in some systems even eliminates the requirement for AGC in the receive path.

Source: Texas Instruments Application Notes

Detection for Pulse LiDAR using ADC and Matched Filter

$$P_s(R) = P_\ell \frac{\rho_t A}{\pi R^2} \eta_o \eta_a^2$$

P_s = received signal power from transmitted laser pulse after scattering/reflecting from target

P_ℓ = power of the laser pulse

ρ_t = "effective Lambertian" reflectivity of the target

A_r = effective collection area of the optical receiver

R = slant range to the target from "sensor"

η_o = optical transmission efficiency of all optical components in the ALS

η_a = transmission efficiency of the atmosphere between sensor and target (at range R)

= exp (-σR) (e.g. σ ≃ 0.3/km for 10 km visibility)

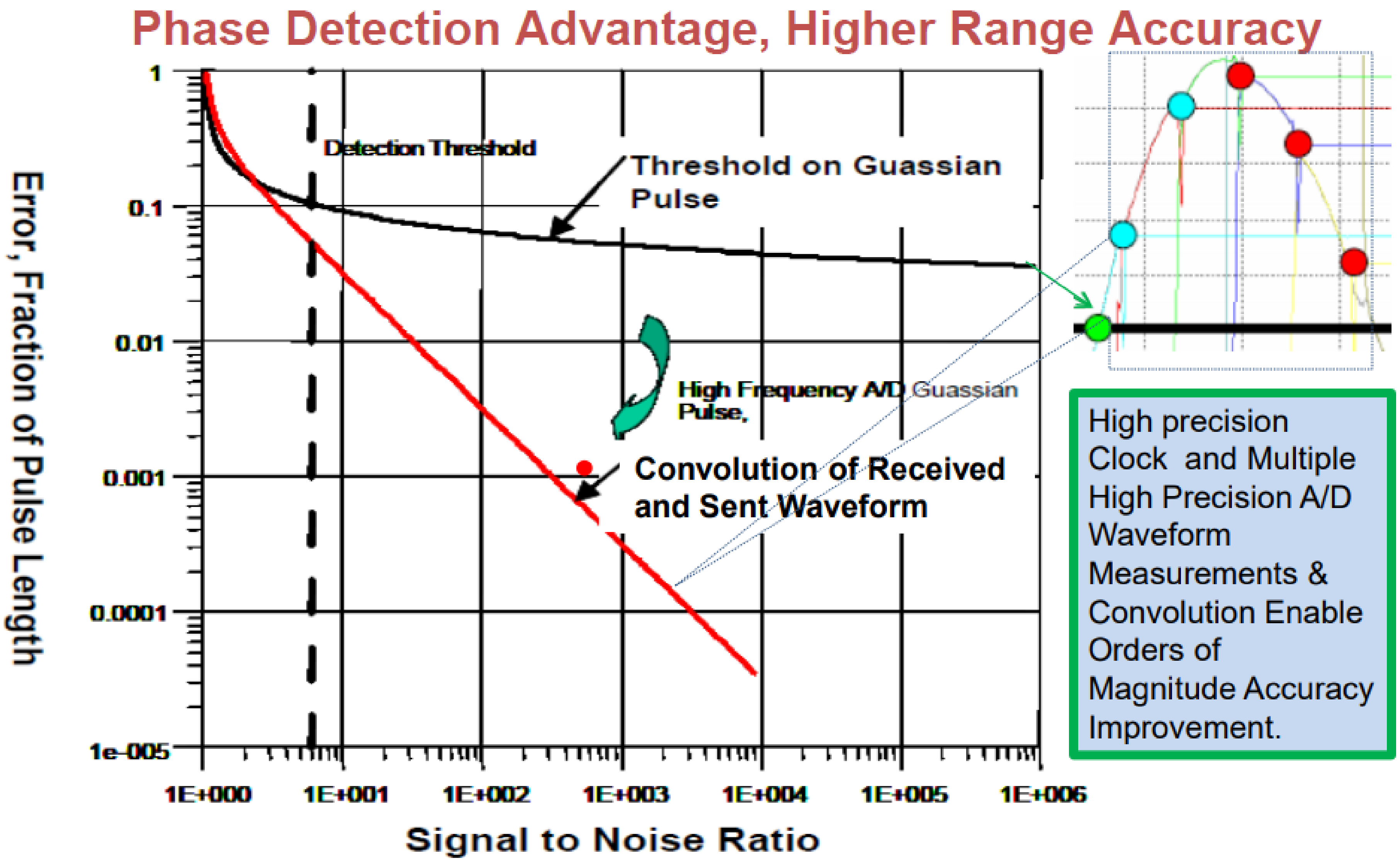
Note:

P_ℓ, A_r, η_o → system hardware parameters

ρ_t, η_a, R → operating environment parameters

Source: Texas Instruments Application Notes

Matched Filter



High precision Clock and Multiple High Precision A/D Waveform Measurements & Convolution Enable Orders of Magnitude Accuracy Improvement.

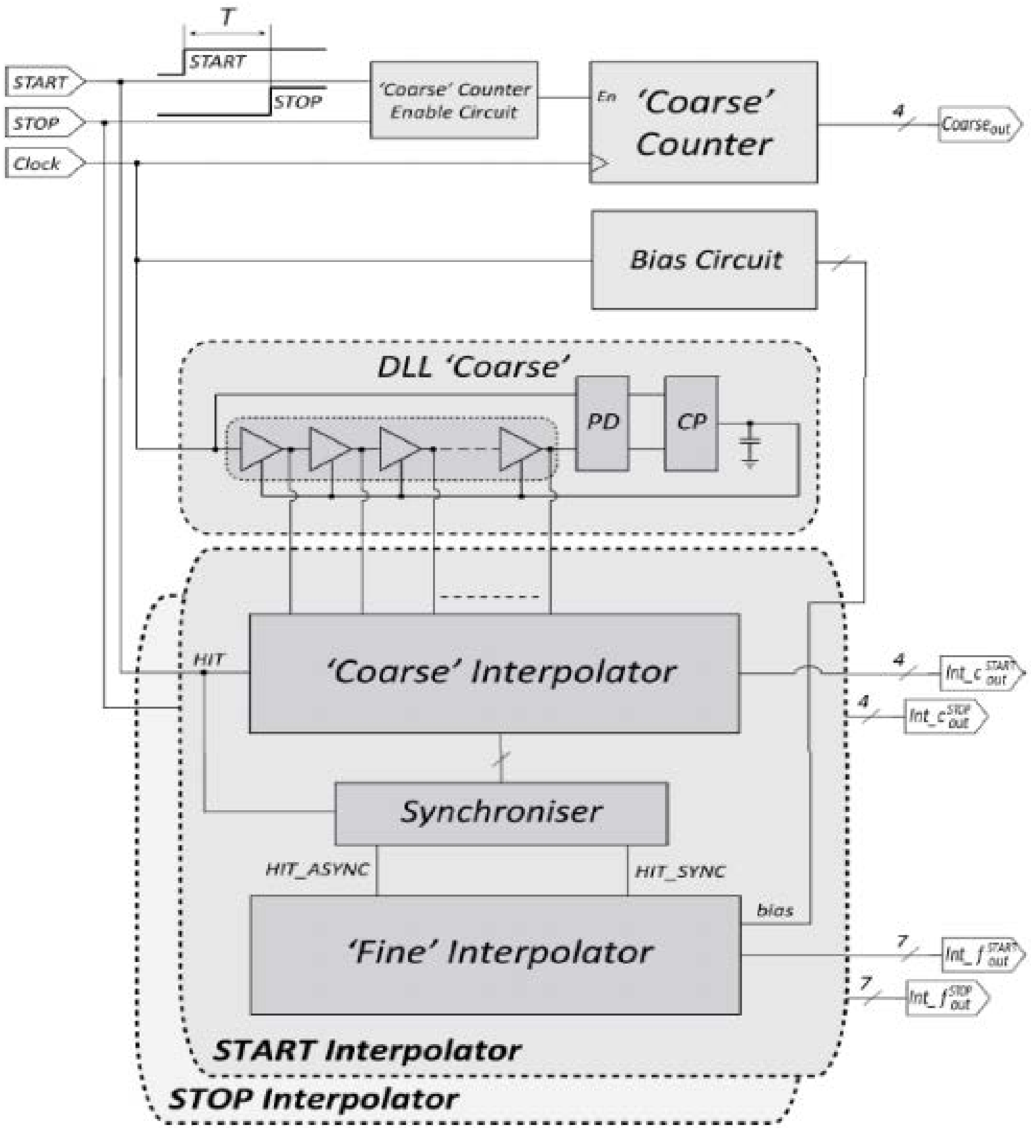
Source: Dr. John Junkins's presentation

Detection for Pulse LiDAR using TDC

- Range resolution is inversely proportional to the combined rise time of the laser, TIA and detector, while the maximum range is proportional to peak laser power and the combined sensitivity of the TIA and detector for the given optics.
- This indicates that to achieve high resolution over long distances, the system should have a high-peak-power laser with a fast rise time measured by a high bandwidth, low-noise photo diode, TIA, and detector.
- Additionally, the system must account for the return signal amplitude, which decreases proportionally to the square of the measured distance. The finite rise time of the measured return must also be accounted for in the detector to prevent level-dependent triggering errors.
- TDC-based systems must solve the previously mentioned problems directly in the analog domain, which implies that fast rise time pulses and high receive bandwidth are required.
- The receive path also generally requires automatic gain control (AGC) to account for the return signal level and a time discriminator to ensure triggering occurs at a constant point in the rise of the return signal.

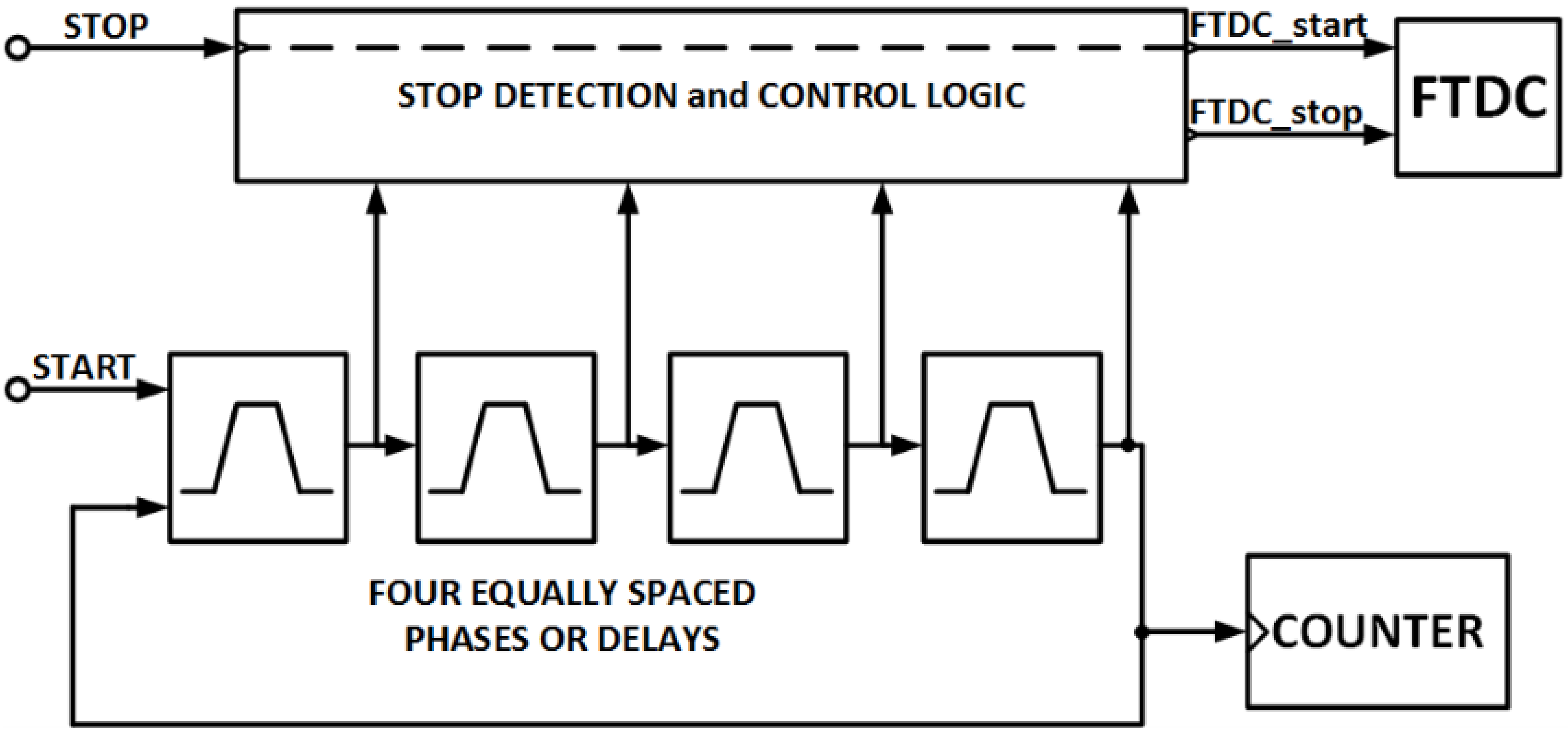
Source: Texas Instruments Application Notes

TDC for Pulse LiDAR, DLL based



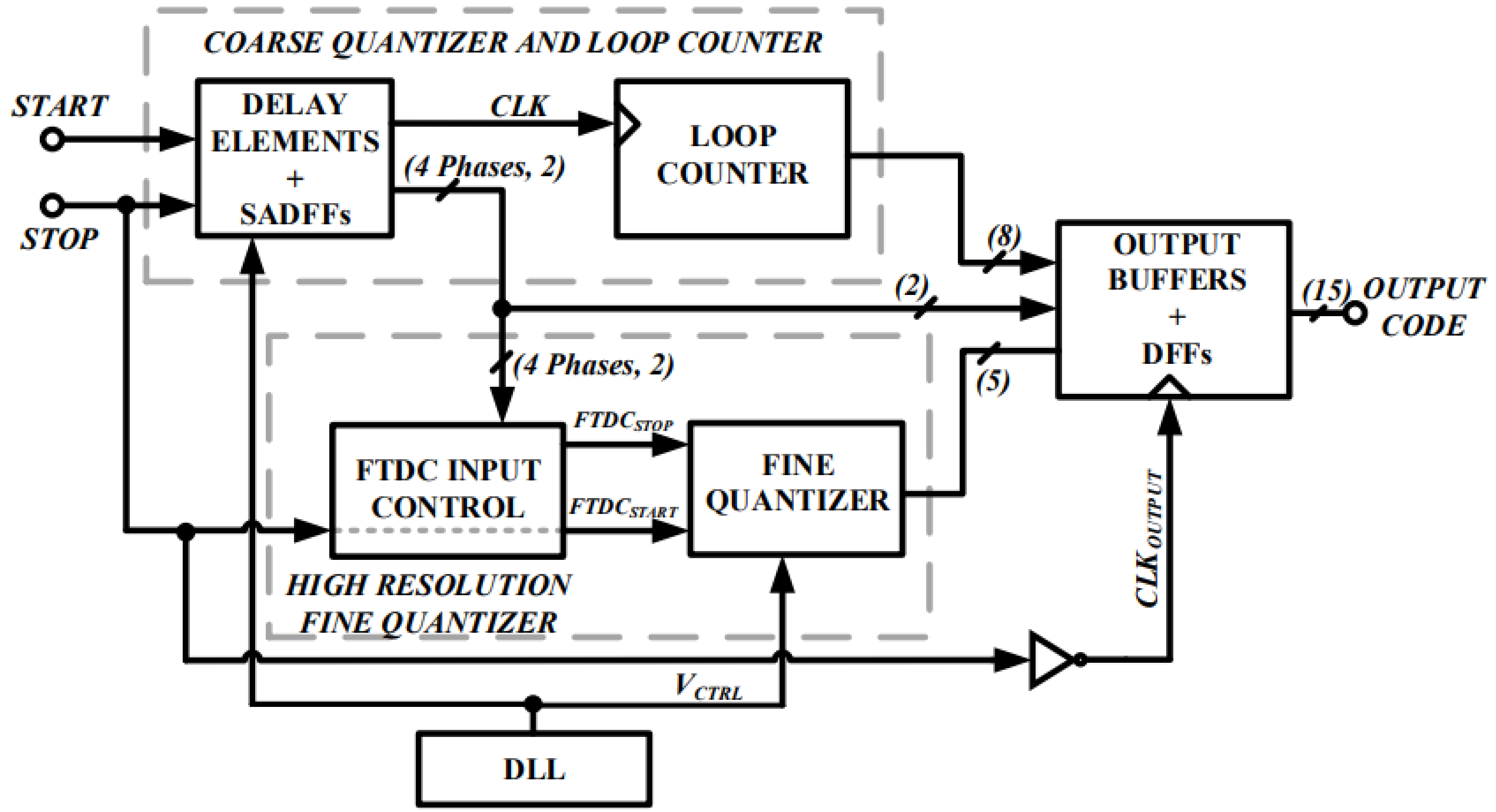
Source:
https://oaktrust.library.tamu.edu/bitstream/handle/1969.1/152478/NARKU-TETTEH-THESIS-2014.pdf?sequence=1

Hierarchical TDC with coarse looped TDC In 1st stage and fine TDC in 2nd stage



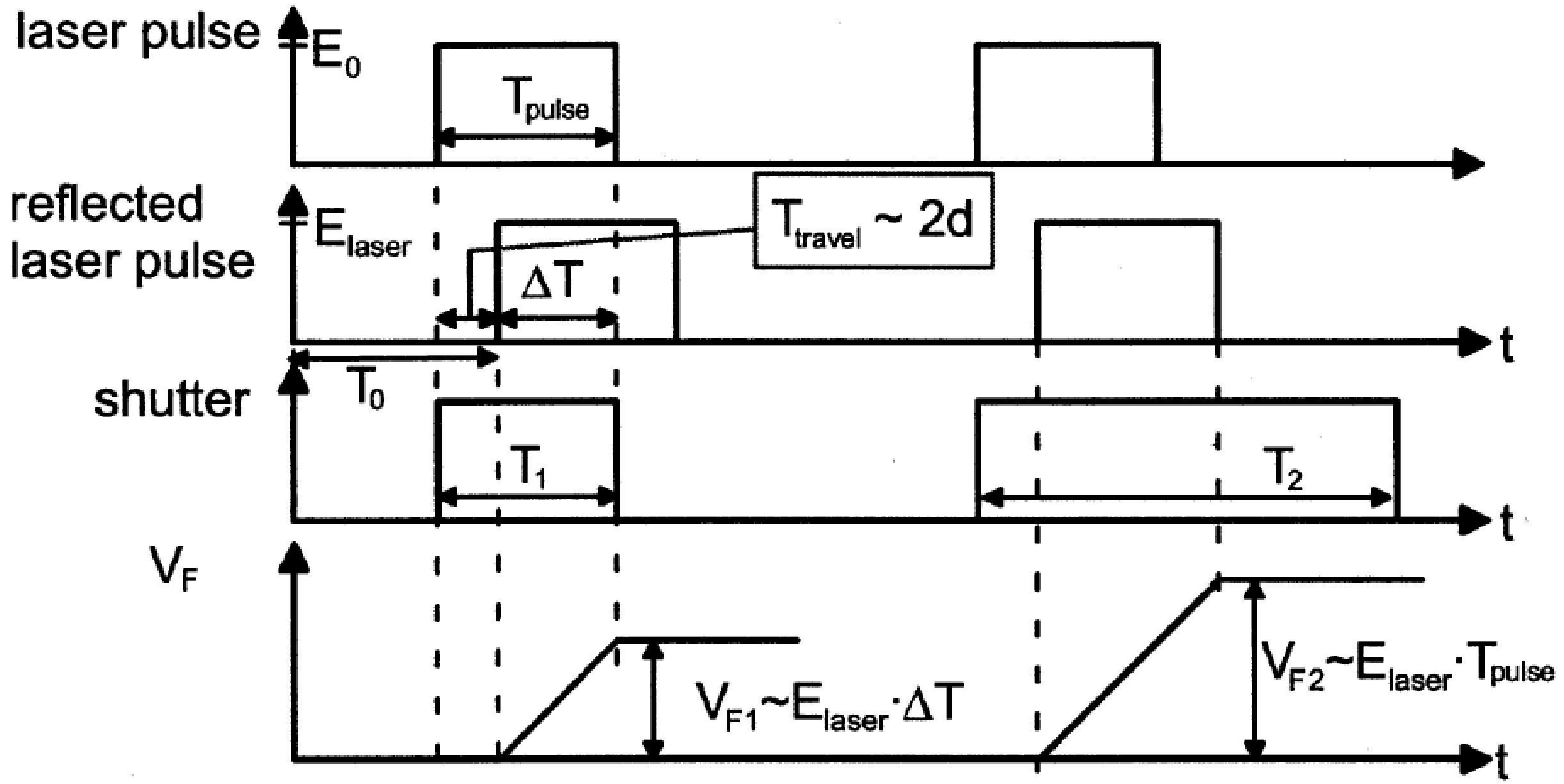
Source:
https://oaktrust.library.tamu.edu/bitstream/handle/1969.1/152478/NARKU-TETTEH-THESIS-2014.pdf?sequence=1

Hierarchical TDC with coarse looped TDC In 1st stage and fine TDC in 2nd stage



Source:
https://oaktrust.library.tamu.edu/bitstream/handle/1969.1/152478/NARKU-TETTEH-THESIS-2014.pdf?sequence=1

TDC for Pulse LiDAR based on time to voltage conversion



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

Double Short-time integration

- 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.

Integrated Perception by Apollo AI

Apollo AI

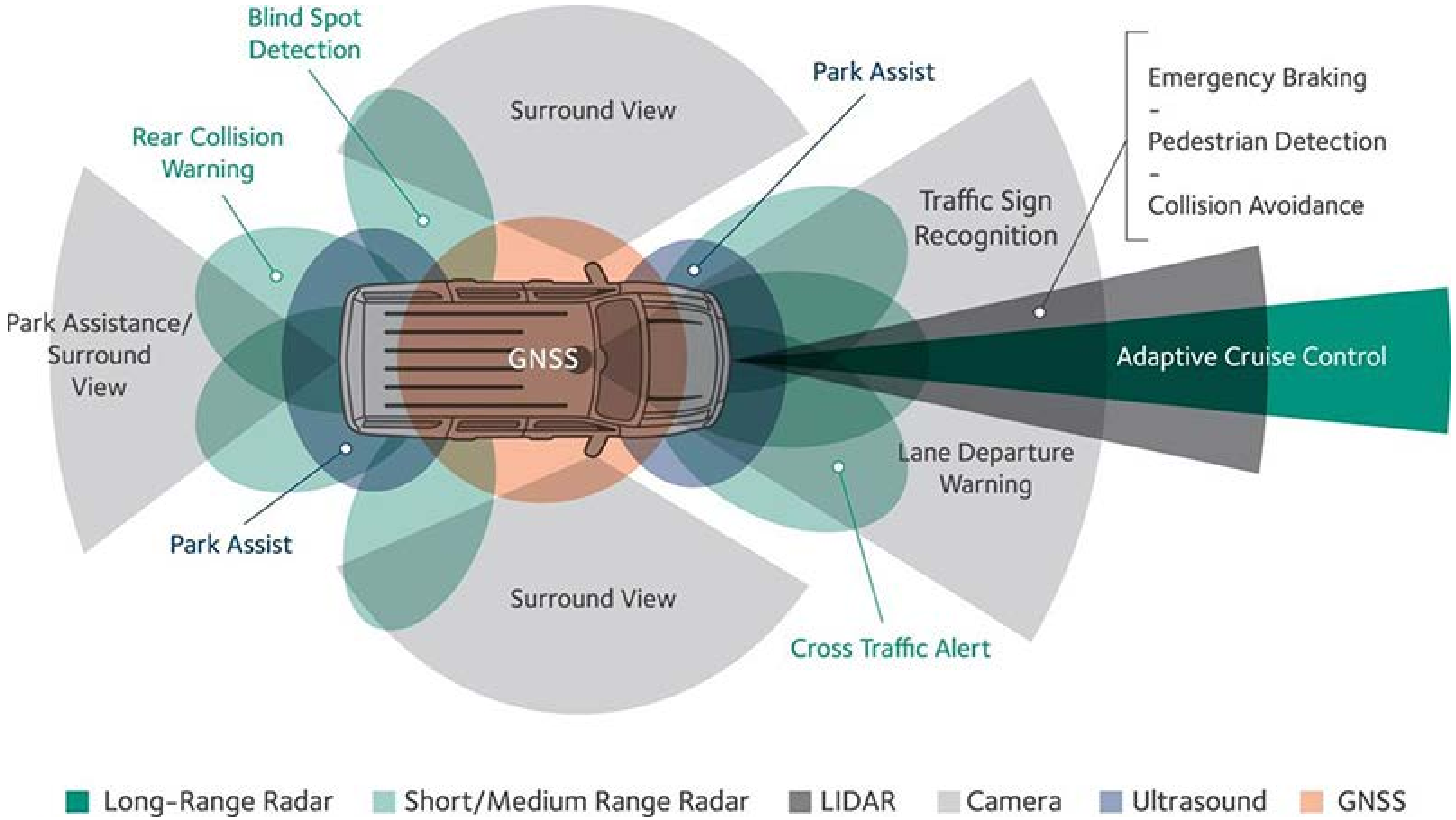
- Apollo AI is NSF-funded company based in Santa Clara.
- Expertise in simultaneous localization and mapping, object detection, tracking and classification, decision making and path optimization. Patent pending IP. Working with several LiDAR companies and car OEMs.
- Follow a judicious approach of mixture of classical techniques with modern deep learning based on more than 100 person years of experience in information theory, control systems, detection and estimation, machine learning, neural networks, communication and signal processing systems, systems design, navigation.
- Apollo AI provides Real-Time Perception Solutions for Autonomous Driving

  Mapping: Real-time SLAM using LiDAR only / LiDAR + Camera/ Camera only (+GPS+IMU for robustness)

  Object processing: Object Detection, Classification, and Tracking using LiDAR only/ Camera only / RADAR only / LiDAR+Camera

  LiDAR Sensor Auto-Calibration: Unsupervised automatic calibration using a consumer-grade IMU

Sensing for Autonomous Systems



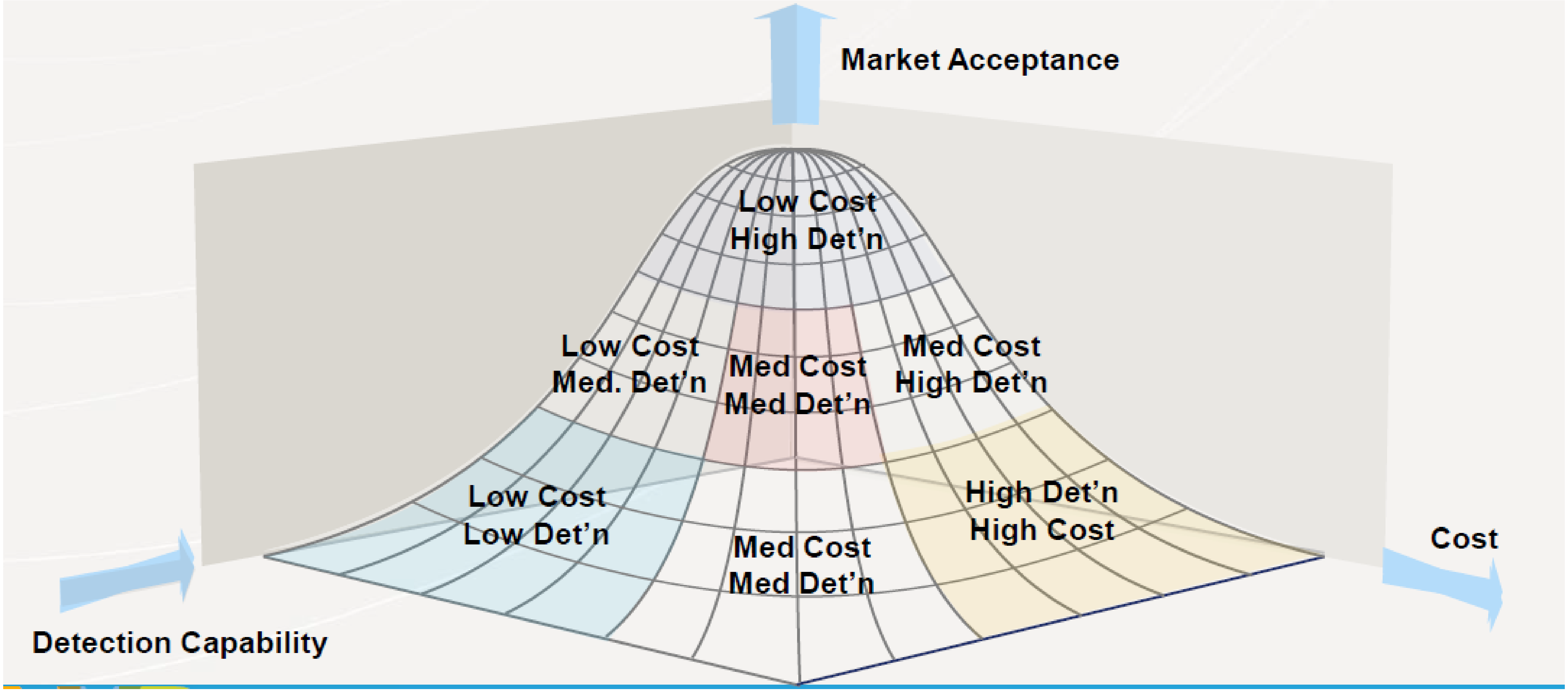
Source: NovAtel

Sensing Technology Comparison

Rating: H = High, M=Medium, L = Low	Camera	Radar	LiDAR	Autonomous Requirement
Object Detection	M	H	H	H
Classification	H	M	-	H
Density of Raw Data	H	M	L	H
Velocity Measurement	-	H	-	H
Lane Detection	H	-	-	H
Traffic Sign Recognition	H	-	-	H
Range of Sensor	M (150m)	H (250m)	M (100m)	Full range
Rain, Fog, Snow	L	H	L	H
Night	-	H	H	H
Sensor size	Small to Med	Small	Med	Mix
Cost	H (ADAS)	L	H	Mix

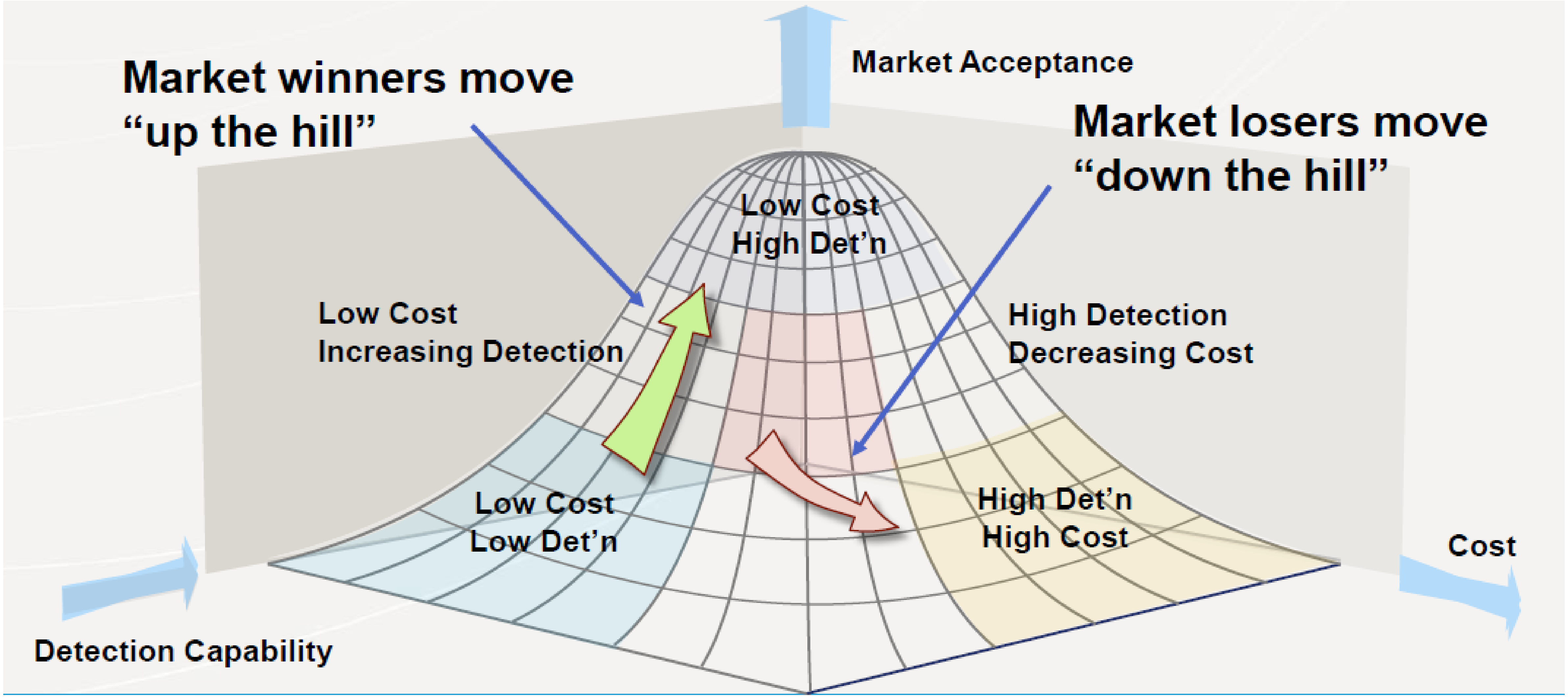
Source: NXP

Game of the "King of the Hill"



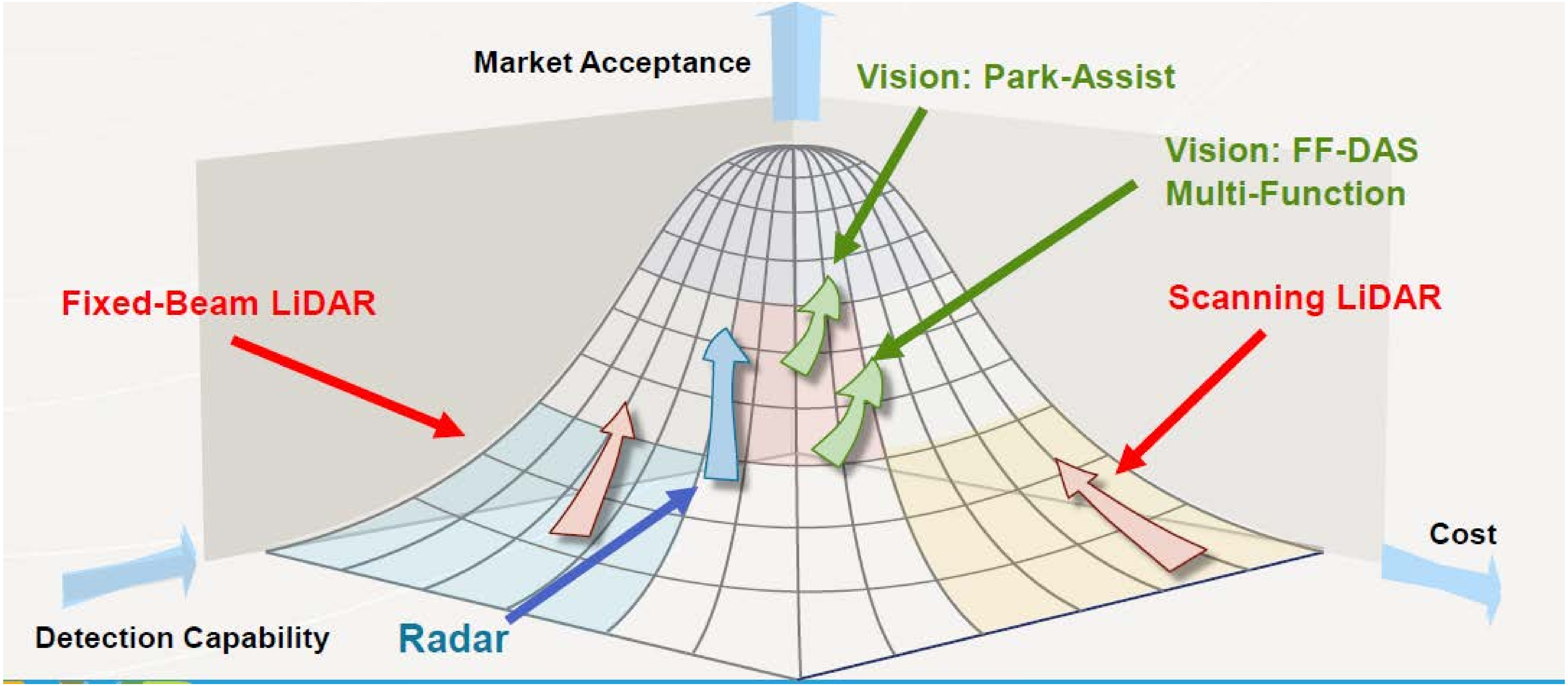
Source: NXP

Game of the “King of the Hill”



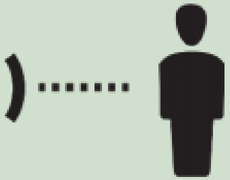
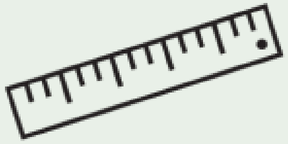
Source: NXP

Climbing the Autonomous Hill



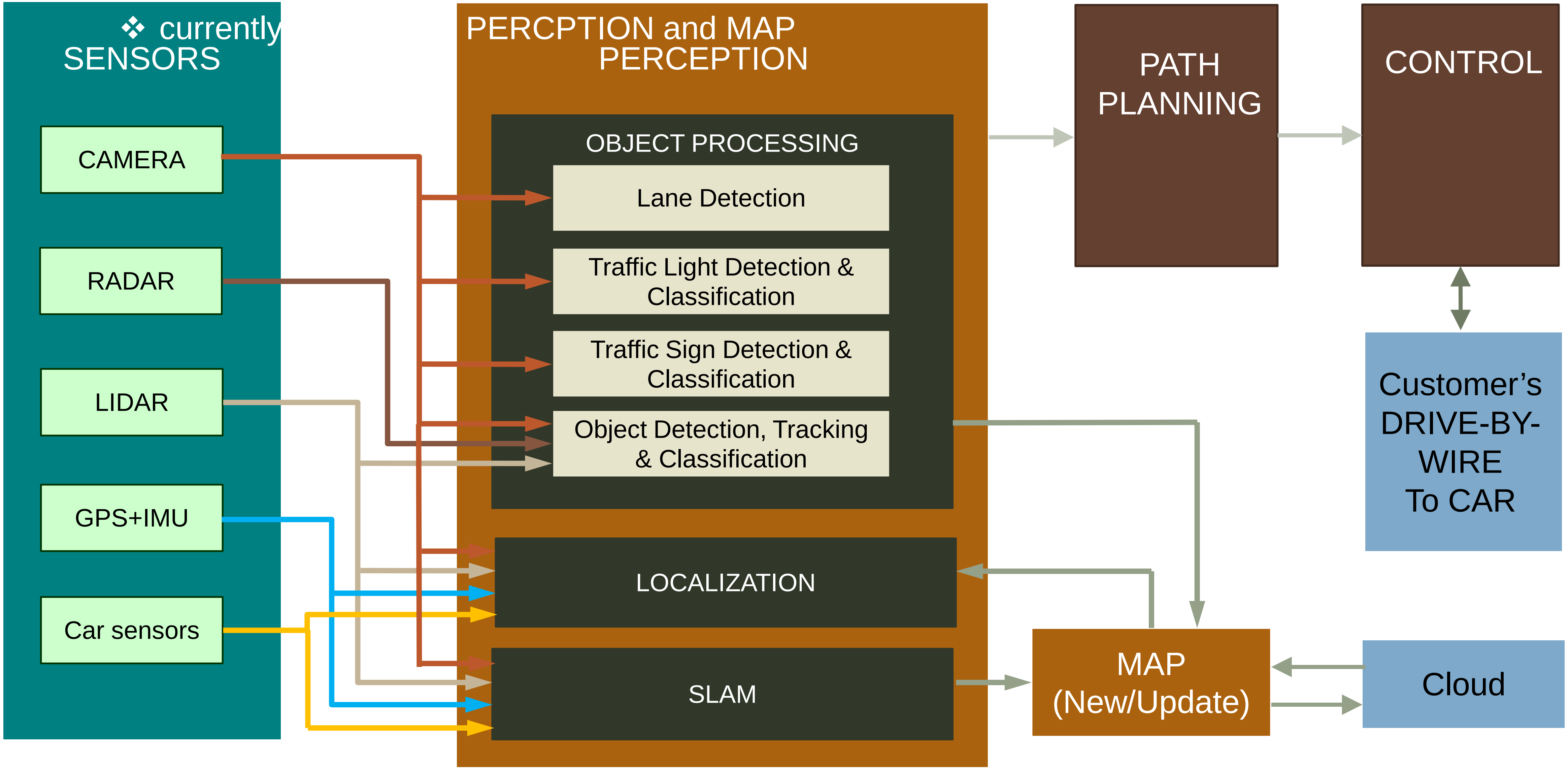
Source: NXP

LiDARs need Integrated Perception to climb the Autonomous Hill

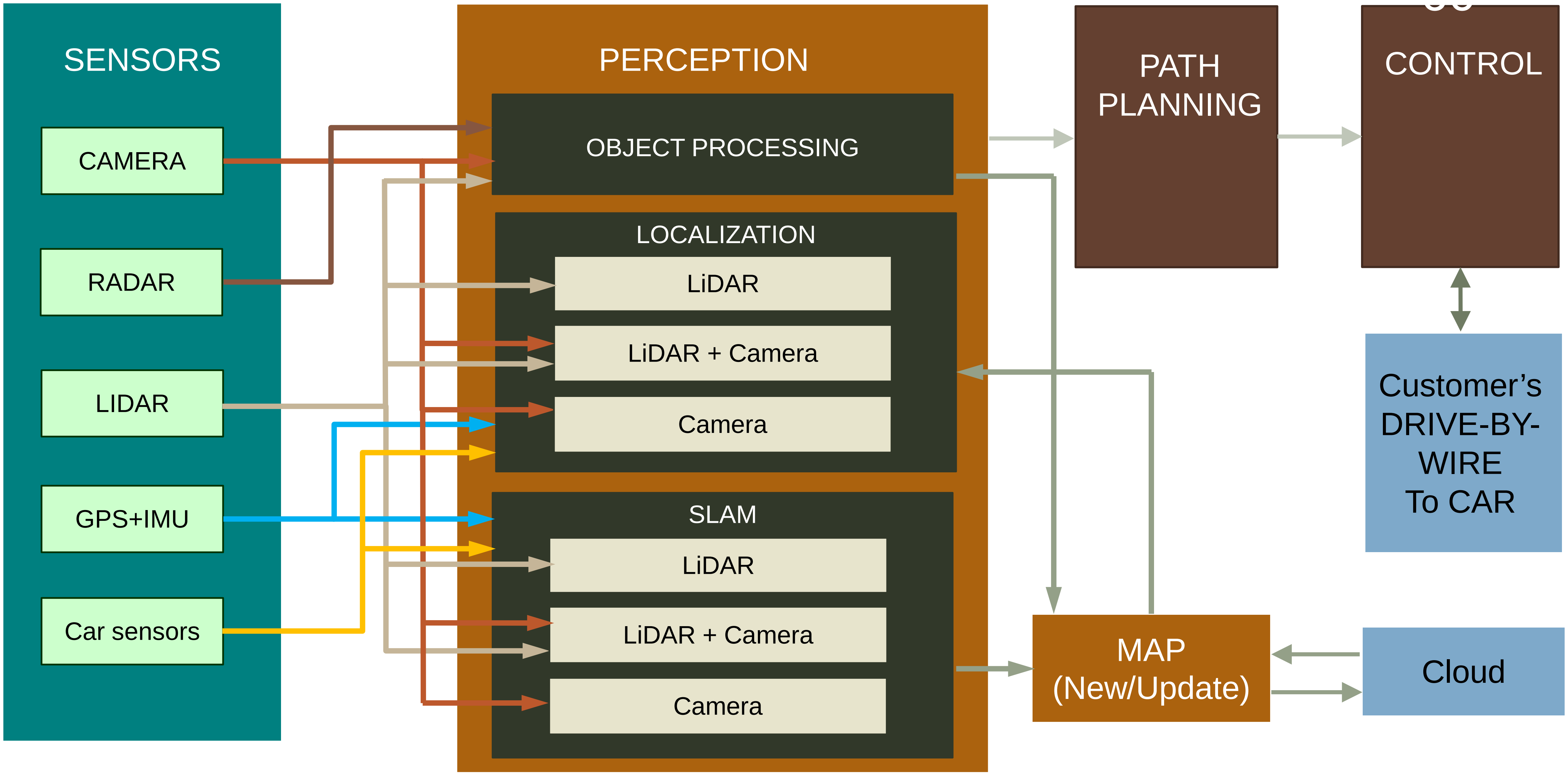
Detection		Detects the presence of one or more objects (Vehicles, bicycles, pedestrians, etc.) in a given area.
Measurement		Locates objects to determine their distance from a sensor and from each other. Can measure vehicle height or length.
Profiling and classification		Enables vehicle classification based on their dimensions and overall profile.
Tracking and speed		Tracks the displacement of an object in the sensor's field-of-view and determines/estimates its position and speed.

Source: ibtta

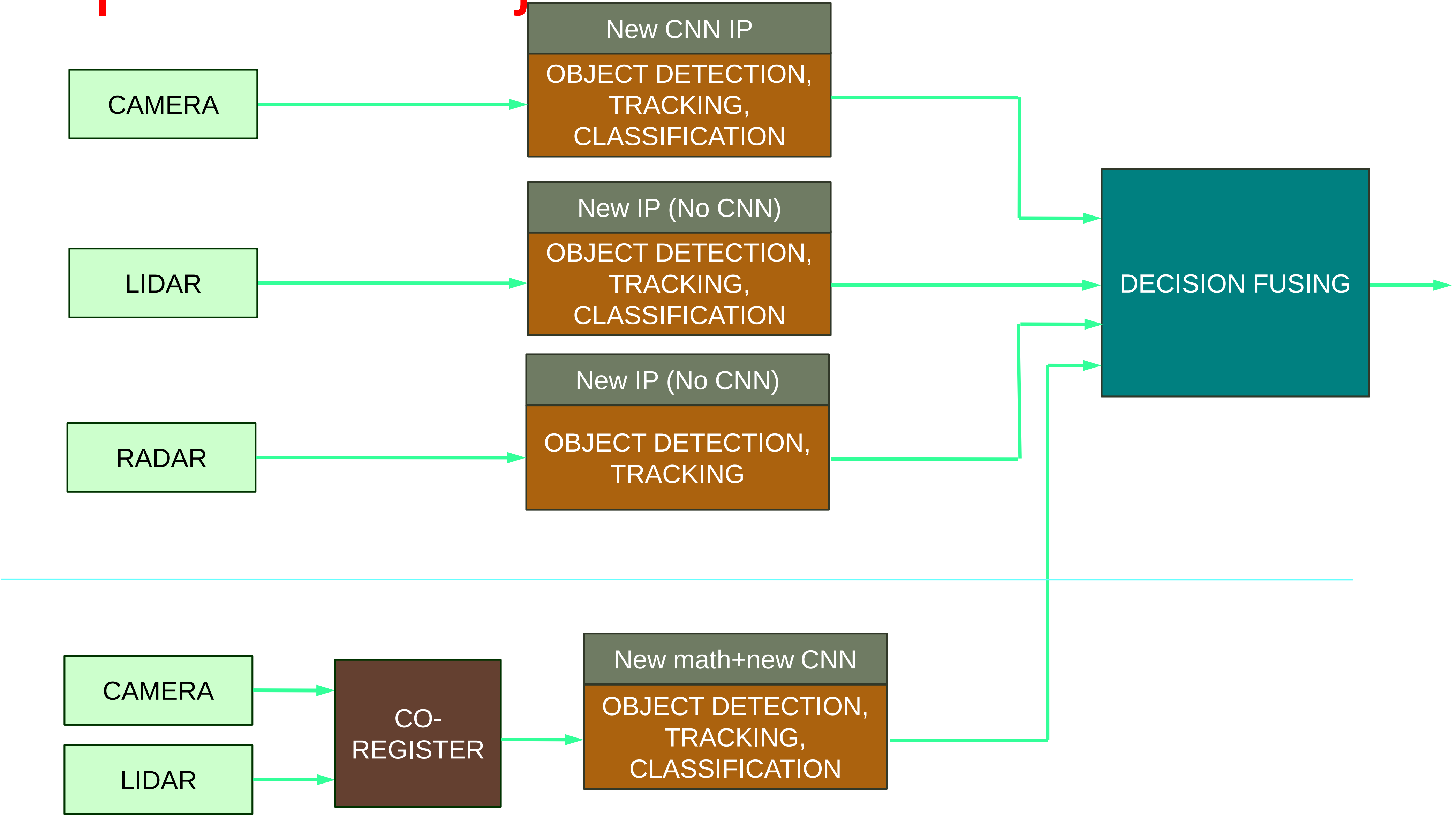
Apollo AI Technology Stack



Apollo AI Technology Stack



Apollo AI Object Detection



Development Status

- ❖ **Currently available software for licensing**

Mapping Stack:

- ✓ Real-time SLAM using LiDAR and feature map generation
- ✓ Real-time localization with LiDAR(+GPS+IMU+wheel odometry for robustness)

SLAM Demo: Video embedded on www.apolloaisystems.com

Object processing Stack:

- ✓ LiDAR, Camera, RADAR
- ✓ LiDAR+Camera

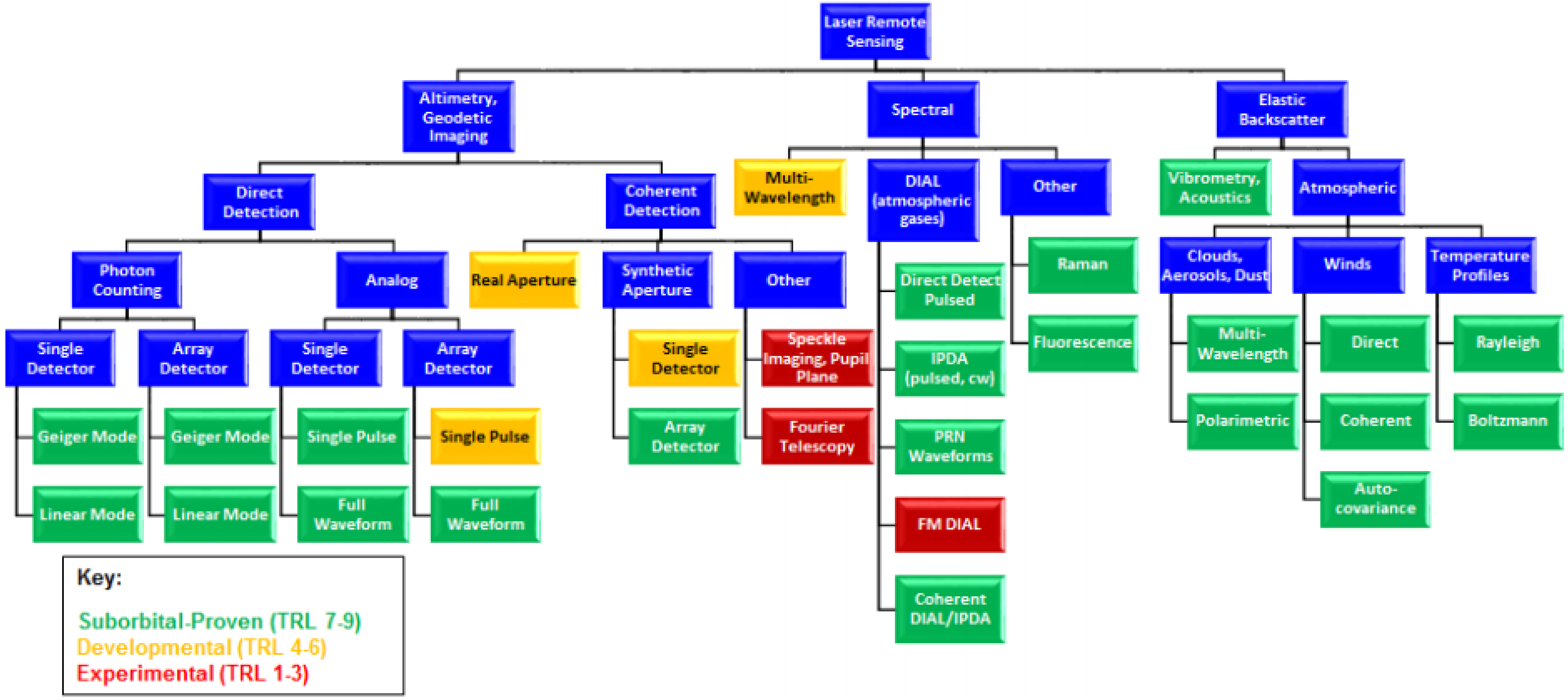
- ❖ Apollo AI's self-driving stack is developed for low cost SoC such as Renesas, ST, Texas Instruments, Visteon which has both ARM and Vector processors. Very amenable to hardware accelerator IP implementation for FPGA also.
- ❖ Please email contact@apolloaisystems.com

Demo: Video embedded on www.apolloaisystems.com

Thanks

Backup

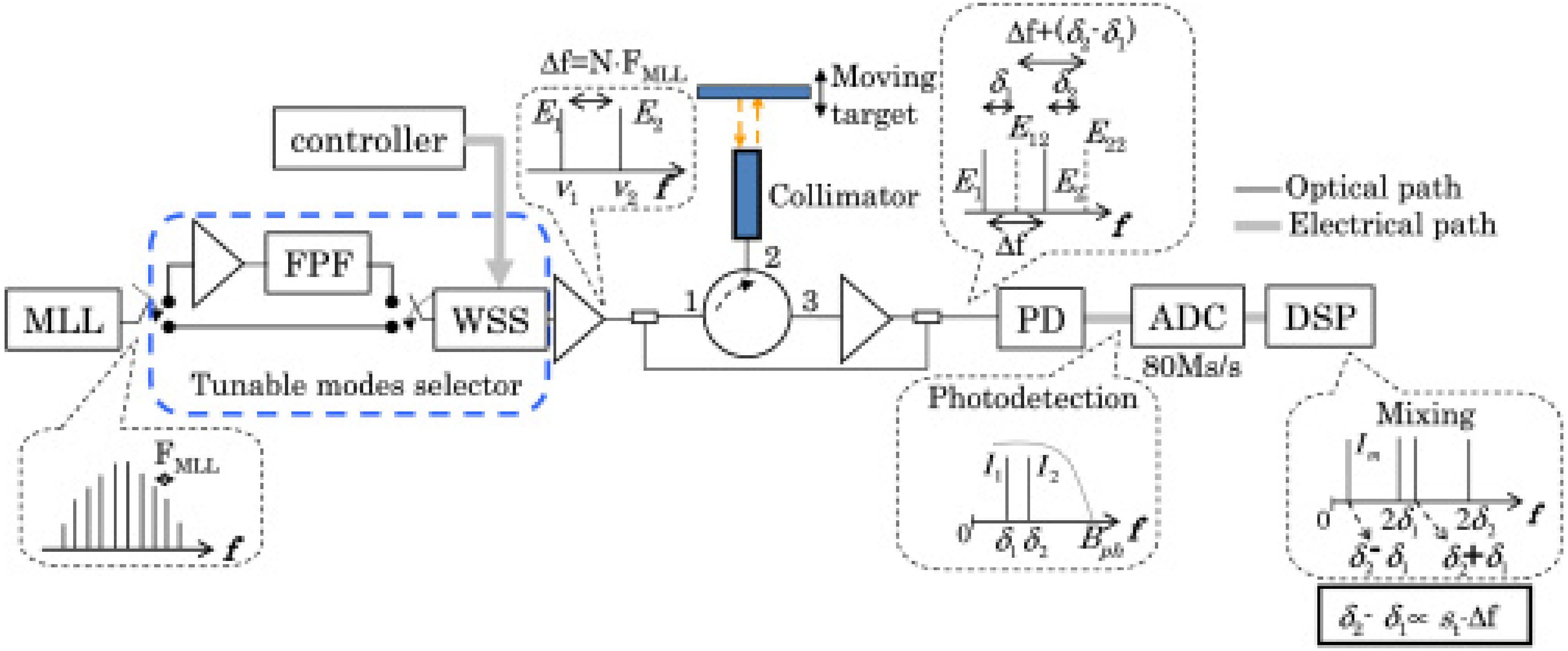
Complete taxonomy of sub-orbital lidar applications and sensor options



Source: NASA

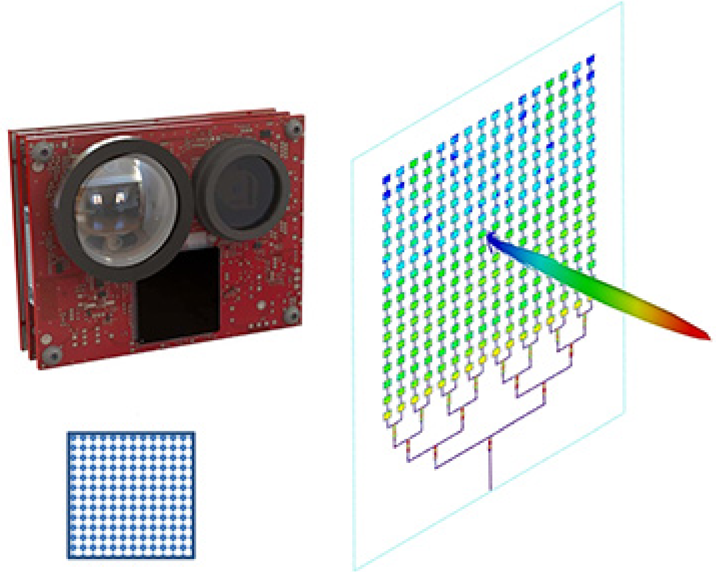
Dual-Frequency LiDAR

. Speed measurements for different tone separations equal to 10, 40, 80, and 160 GHz are demonstrated

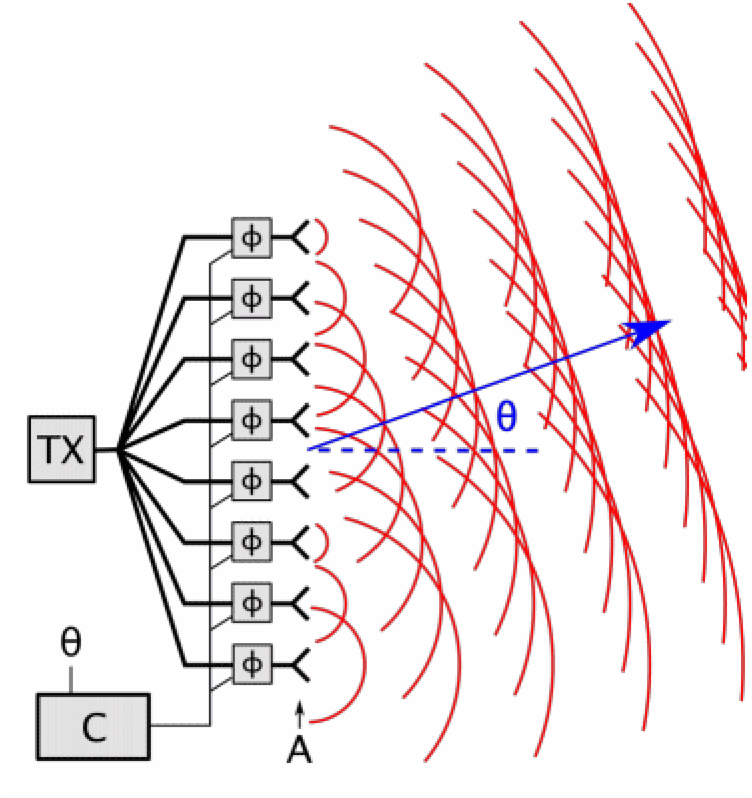


Source: https://www.osapublishing.org/ol/abstract.cfm?uri=ol-40-7-1358
http://www.ee.cityu.edu.hk/~scchan/all_papers/Dia07SPIE.pdf

Quanergy Optical Phase Array



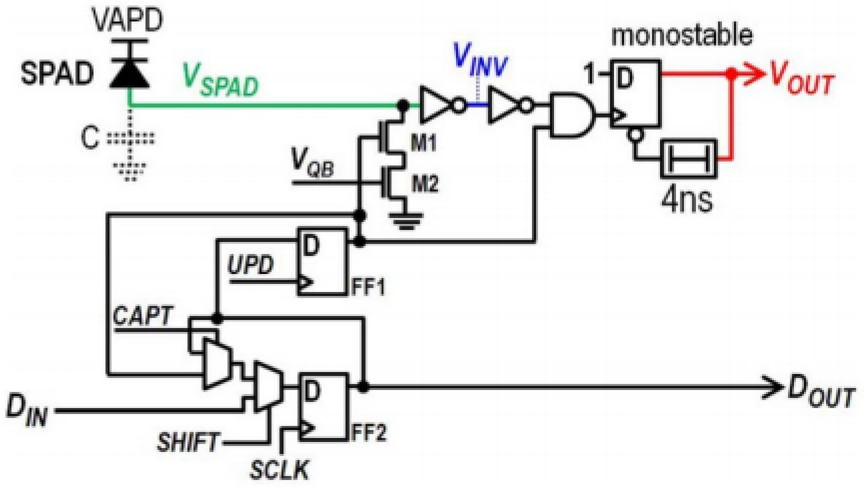
(Top) Quanergy S3 solid-state lidar inside view. (Lower left) Single-photon avalanche diode array, chip-to-chip attached to readout IC. (Lower right) Transmitter optical phased array Photonic IC with far-field radiation pattern.

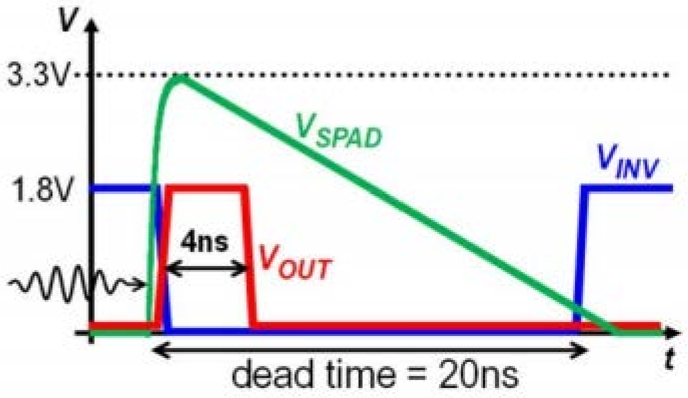


Transmitter optical phased array

source: Quanergy

Single photon avalanche diodes (SPAD)



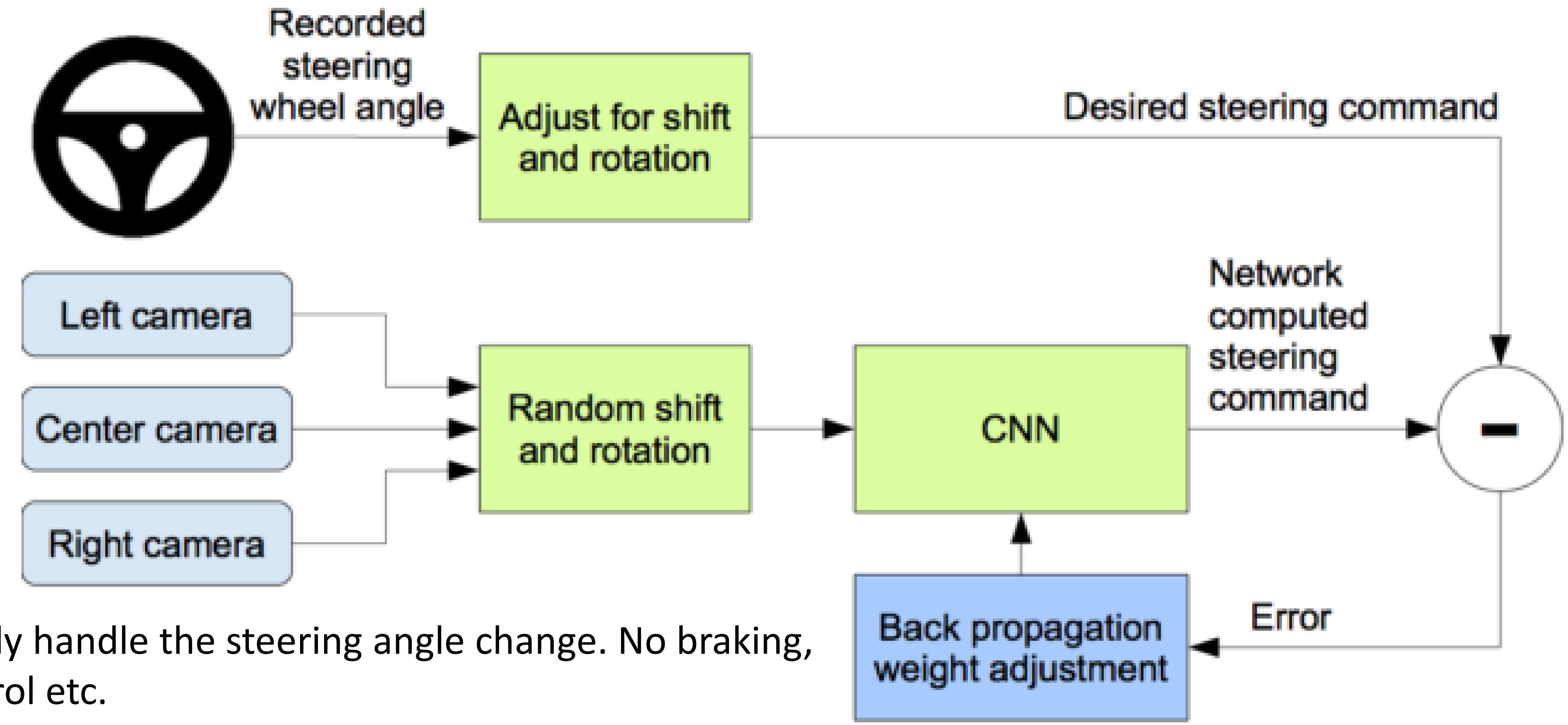


Photon counting histogram methods are used.

Issues with range as SNR is low.

source: Quanergy

Why not a CNN for entire self-driving?



This can only handle the steering angle change. No braking, speed control etc.

Source: Nvidia

Self-Driving System Modules

Source: GM Cruise