Sensor fusion for autonomous vehicles

December 15th, 2020
1. Introduction
2. Radar
3. The proliferation of camera modules
4. The emergence of LiDAR
5. The transformation of E/E architecture
6. Market forecasts for ADAS vehicles sensors
7. LiDAR for robotic and industrial applications
8. Sensor fusion
**CONTEXT**

**C.A.S.E., the acronym taking over the auto industry**

**Autonomous**
Sensor suite and computing developments for safer roads.

**Shared**
Owning, sharing, or renting, the mobility of the future offers greater flexibility.

**Connectivity**
Comfort, safety and entertainment in a new dimension.

**Electric**
Alternative drive systems to reduce CO₂ emissions.

Source: Daimler
Since 2018, many acquisitions, partnerships or fundraising have been made regarding ADAS and AD activities.

<table>
<thead>
<tr>
<th>Year</th>
<th>Event</th>
<th>Company(s)</th>
<th>Details</th>
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<tbody>
<tr>
<td>2018</td>
<td>Innoviz and Magna announces partnership for serial production with BMW</td>
<td>Innoviz, Magna</td>
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<td>2018</td>
<td>Volvo partners with Luminar</td>
<td>Volvo, Luminar</td>
<td>Volvo partners with Luminan</td>
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<td>2019</td>
<td>Blickfeld partners with Koito</td>
<td>Blickfeld, Koito</td>
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<td>2019</td>
<td>Velodyne lidar will provide core lidar technology to Veoneer</td>
<td>Velodyne, Veoneer</td>
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<tr>
<td>2019</td>
<td>Mercedes, NVIDIA announce partnership for AD</td>
<td>Mercedes, NVIDIA</td>
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<tr>
<td>2019</td>
<td>Faurecia acquires Clarion for $1.2B</td>
<td>Faurecia, Clarion</td>
<td>Faurecia acquires Clarion for $1.2B</td>
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<td>2019</td>
<td>ZF to acquire Wabco for $7B</td>
<td>ZF, Wabco</td>
<td>ZF to acquire Wabco for $7B</td>
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<td>2019</td>
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Actual AEB systems are based on camera and radar. Its penetration rate keeps increasing from 18% in 2017 to 38% in 2019.
In October 2019, the American Automobile Association (AAA) conducted a series of tests using vehicles with AEB and pedestrian detection alerts on a closed course with dummy pedestrians.

Several tests have been made at different speeds, mixing adult and children ‘pedestrians’ during daylight and night conditions.

Tests were performed on: Chevy Malibu, Honda Accord, Tesla Model 3 and Toyota Camry.

60% of the time, the vehicle struck the adult crossing the road during daylight at 20 mph.

89% of the time, the vehicle struck the child crossing the road during daylight at 20 mph.

100% of the time, the vehicle struck the adult after a right turn at 15 mph.

When encountering an adult pedestrian at night, these systems were ineffective.

New sensors like LiDAR or thermal cameras will need to be implemented.
CURRENT RADAR TECHNOLOGIES AND USE CASES

Which technology for which application?

The 77/79GHz frequency is opening more use cases for monitoring car surroundings.

The 77/79GHz frequency is opening more use cases for monitoring car surroundings.

**77/79GHz**

- **In-cabin**
  - CPD
  - CMOS

- **Rear**
  - CMOS/SiGe
  - BSD
  - RCTA
  - LCA
  - CMOS
  - PA

- **Front**
  - AEB
  - SiGe/CMOS (GaAs)
  - AEB
  - VRU
  - SiGe/CMOS
  - ACC
  - SiGe/CMOS (GaAs)
  - TJA
  - SiGe/CMOS
  - FCW
  - SiGe/CMOS

- **Side**
  - VEA
  - CMOS

**24GHz**

- **Rear**
  - GaAs/SiGe
  - BSD
  - LCA

- **Front**
  - AEB*
  - GaAs/SiGe

- **ACC**
  - Adaptive Cruise Control

- **AEB**
  - Automatic Emergency Braking

- **BSD**
  - Blind Spot Detection

- **CPD**
  - Child Presence Detection

- **FCW**
  - Forward Collision Warning

- **LCA**
  - Lane Change Assist

- **PA**
  - Park Assist

- **RCTA**
  - Rear Cross Traffic Alert

- **RCW**
  - Rear Collision Alert

- **TJA**
  - Traffic Jam Assist

- **VEA**
  - Vehicle Exit Assist

- **VRU**
  - Vulnerable Road User

* Limited range – supported at low speed
FUTURE RADAR TRENDS
Four steps towards super sensors

- **3D Measure height**
  - Future radar developments towards automated driving.
  - Started in 2019.

- **Elevation capability**
  - Phase in from 2021.

- **High resolution**
  - Imaging
  - Discriminate nearby objects

- **Availability interference mitigation**
  - Implementation from 2020.

- **Classification, labelling**
  - Image processing AI/deep learning
  - Ongoing on OEM side likely to follow imaging radar.

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Leveraging military and telecom technologies, advanced radar technology fully supports up to level-4 autonomy, with high resolution and radar imaging reaching the market with low C-SWAP.

**FUTURE RADAR TRENDS**

The road to high resolution

**C-SWAP:** cost, size, weight, and power

**2000**

Resolution, classification, and object-tracking capability

**2010**

2D ADAS basic

X,Y,Doppler

**2019**

2D ADAS improved

X,Y,Doppler

**2021**

Ultra-high resolution X,Y,Z,Doppler,depth

AI/Deep Learning

**LRR 4th gen**

**ARS 5th gen**

**Bosch**

**Continental®**

**Bosch**

**Continental®**

**Bosch**

**Continental®**

**Bosch**

**Continental®**

**Yole Développement © April 2020**
The top five companies capture 83% of the market. The merging players are progressing well. Waymo’s market share has started to become visible.
THE PROLIFERATION OF CAMERA MODULES

The ‘Ten-plus cameras per car’ roadmap

The market is driven by camera proliferation.

- Standard car with forward and rear cameras
- Surround-view is the new must-have feature
- Increasing demand for ADAS will bring more cameras per car

2012 2014 2016 2018 2020e 2022e 2024e

# of Cameras

- 1 camera
- 3 cameras
- 6 cameras
- 9 cameras
- 12 cameras

Top range
Multiple forward ADAS cameras, night vision, e-mirror replacement, and driver monitoring are next to be introduced

Market average

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Tier-1s have entered the fray and trust the main positions.

All other players are well-known camera manufacturers that have diversified from either mobile or digital photography.

Competition will probably toughen in the next few years as market growth attracts more players.
THE EVOLUTION OF DRIVING

Evolution of functionalities towards full autonomy

Level 1: Driver assistance
- Automatic Cruise Control
- Advanced Emergency Breaking
- Cross Traffic Alert
- Surround View + Object Detection

Level 2: Partial automation
- Traffic Jam Assist
- Lane Assist
- Auto Parking

Level 2+: Conditional automation
- Advanced Emergency Breaking + Steering

Level 2++: High automation
- Highway Pilot

Level 3: Full automation
- City Pilot

Level 4: Auto Pilot
- Valet Parking

Level 5: Full automation
- Remote Parking
- Full automation
**THE EMERGENCE OF LIDAR**

Adoption of LiDAR in ADAS vehicles

LiDAR is penetrating the ADAS market in the F-segment. As the price decreases, it will be implemented in lower segments.

- **2020**
  - 0.1% of total vehicles
  - 70k vehicles equipped with LiDAR
  - LiDAR ASP
    - LR: $570
    - SR/MR: N/A

- **2025**
  - 2.3% of total vehicles
  - 2.4M vehicles equipped with LiDAR
  - LiDAR ASP
    - LR: $500
    - SR/MR: $122

- **2032**
  - 11% of total vehicles
  - 11M vehicles equipped with LiDAR
  - LiDAR ASP
    - LR: $380
    - SR/MR: $99
THE EMERGENCE OF LIDAR
ADAS LiDAR roadmap

Only available in Audi A8 and A7. Valeo is the only tier-1 having automotive grade at this time. The typical use case is for traffic-jam assistance.

LiDAR is introduced by more car manufacturers and now include short/mid-range LiDAR along with long-range LiDAR.

New LiDAR technologies now include MEMS, fiber laser, and SPAD array for Flash LiDAR.

New technologies are introduced in LiDAR including SiPM and FMCW

In this full automation configuration, the vehicle can perform all driving functions under all conditions. The driver may have the option to control the vehicle.

FMCW: Frequency-modulated continuous-wave
SiPM: Silicon photo multiplier
SPAD: Single photon avalanche diode
THE ADDITION OF SENSORS

Impact of adding sensors in ADAS vehicles

The multiplication of sensors in vehicles directly impacts the complexity of electronic architecture.

- More ECUs requested
- More computing power
- More software requested
- More complex E/E architecture

Ultrasound
Cameras
Long-range radar
Short-range radar
LiDAR
Consumer demand for safety and software-enabled features is increasing at an unprecedented rate.

**Evolution of E/E architecture**

- **1970s**
- **1990s**
- **2010s**

**Increase of ADAS systems and vehicle electrification**

Source: Aptiv/Modified by Yole

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THE TRANSFORMATION OF E/E ARCHITECTURE

E/E architecture evolution - Roadmap

- Today, OEMs are still using a distributed E/E architecture with roughly one ECU per function.

- Development from a distributed architecture to a centralized architecture.

- Distributed architecture
  - > 100 ECUs
  - 50-100M lines of code

- Domain centralization
  - > 30–60 ECUs

- Vehicle centralization
  - 20–45 ECUs
  - > 300M lines of code

- Super-computer
  - All domain controllers centralized into one super-computer.

- ‘One function for one ECU’ principle will evolve toward the merging of some ECUs. Limited to a few functions.

- Creation of specific domain controllers: infotainment, comfort, powertrain, sensing, safety.

- Increasing software amount
  - 200 - 300M lines of code
  - > 300M lines of code

- 2020
- 2025
- 2030-2035

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THE TRANSFORMATION OF E/E ARCHITECTURE
zfAS module from Audi – Teardown from S+C

This module has been developed to integrate data coming from radars, cameras, LiDARs and ultrasonic sensors.

Nvidia Tegra K1 SoC
- Image processing for parking
- Four cameras computed
- Driver monitoring

MobilEye EYEQ3
- Front camera image processing
- AEB for cars and pedestrians

MCU 32-bit Aurix
- Hosting different functions
- A-SIL D compliant
- Interface to the car architecture

Cyclone V SoC
- Responsible for sensor fusion
- Pre-processing ultrasonic sensors
- Internal gateway

Aptiv is the supplier of this module.

Courtesy of System Plus Consulting
MARKET FORECASTS
Overview of sensors and computing market revenue

A fast-growing market at a CAGR of 21%.

2020
$8.6B

2025
$22.4B

$3.8B
$3.5B
$0.04B
$1.3B
$9.1B
CAGR: 19%

$8.1B
CAGR: 18%

$1.7B
CAGR: 113%

$3.5B
CAGR: 22%

LiDAR
Radar
Computing ADAS
Camera module
INDUSTRY OVERVIEW

Consolidation expected in the LiDAR industry

More than 80 LiDAR companies

Limited number of OEMs

There are too many LiDAR companies compared to the number of OEMs willing to implement LiDAR. LiDAR companies must find other markets to generate cash.

Oryx went bankrupt in 2019 and Aurora acquired Blackmore the same year. Aurora recently acquired Uber ATG. Other LiDAR companies are expected to follow the same path.
Robotic vehicles will primarily use industrial grade technology.

5th generation Waymo sensor suite

**Lidars**
- Short-/mid range x4
- Long range x1

**Radars**
- 360° view x6

**Cameras:**
- 360° view x29
For ADAS equipment, cost is the primary driver and reliability the barrier to entry. « Good enough » performance has nevertheless to be achieved.

"Lidars have been instrumental in putting fully self-driving cars on public roads"
LOGISTICS: THE FLOW OF THINGS

Logistics: Toward full automation

The size of moving objects in the logistic chain varies tremendously, from human hand to huge ships.

Need of sensors: cameras, radars, LiDARs

• Each step of the logistic chain is changing to automated vehicles.
• It is a major shift in business model for system suppliers.
LOGISTICS: MANY PLAYERS ALREADY INVOLVED

Industry

AGV

Trucks

Small AGV

Large AGV

FedEx

marble®

NURO

Postmates

Last mile delivery

STARSHIP

boxbot

Edge AI | Webinar | www.yole.fr | ©2020
As more and more sensors are used for ADAS, computing will become critical. Data processing and computing power will become differentiating parameters.
There is no perfect 3D sensing technology.

**Camera**: provide high resolution images but lack of native depth information and depend on light conditions.

**Radar**: measure velocity with great precision but have trouble to detect static objects and to measure the position of objects due to low resolution.

**LiDAR**: only sensor to provide native 3D data but high performances LiDAR are very expensive.
SENSOR FUSION

The parallax issue

Calibration will be crucial to combine different perspectives.

When sensors are positioned apart from each other, they will have a different perspective on the vehicle’s environment (parallax) which may lead to a situation in which one sensor can perceive an object, while it is occluded for the other sensor.

Courtesy of Outsight
Gathering all the sensors in one place is not possible in ADAS vehicles. All the sensors are aligned and closed one to the others. The parallax issue is limited, and fusion of data is easier.

In most of the times, it is difficult to integrate more than two sensors in a place due to several constraints.
Sensor fusion uses sophisticated computer vision and deep-learning-based algorithms. Complex use-case scenarios expected of driverless cars can be understood.

**Localization**
- GPS + IMU + Wheel sensors: Global position + vehicle state information

**Perception and Computing**
- Mono cameras: Image
- RADAR: Point data, Relative velocity, Occuancy grid map generator, 3D object Region of Interest
- Lidar: Point cloud data
- Stereo cameras: Left & right image, Vehicle state estimator, Vehicle state information
- Object detector

**Sensor fusion engine**
- Dedicated hardware & software

**Path Planner**
- Object detector
- Lane detector
- Traffic sign detector

**Motion Planner**
- 2D object detection

**Actuation**
- Vehicle control
  - Longitudinal control
  - Accelerator control
  - Brake control
  - Lateral control
  - Steering control

**Environmental map**
SENSOR FUSION

From image processing to fusion platform

- Amount of data processed
- Performance
- Consumption

Frame processing + other sensors
Fusion platform

Frame processing
Vision processor

Image processing
Computer vision
AI algorithms

Sensing Processing Unit – ISP stacked with CIS

Vision processor from MobilEye

Standalone ISP from Altek

Price per unit

> $1000
$100
$10
< $1

Algorithm complexity
SENSOR FUSION

Toward accelerators in automotive

Accelerators allow OEMs to implement their own neural networks

Ambarella CV2 series
In production for 2021

Mobileye
An Intel Company

In production for 2021

Texas Instruments

In production for 2021

Ambarella

Accelerator embedded in SoC

In production for 2021

Edge AI | Webinar | www.yole.fr | ©2020
Data fusion for automated driving enables more functionalities

**2020**
- Lane Keeping Assist
- ACC with Stop & Go
- Blind Spot Monitoring
- Parking Assist
- High Beam Assist
- Traffic Sign Recognition

Distributed or domain centralized E/E architecture

**2030**
- Lane Keeping Assist
- ACC with Stop & Go
- Blind Spot Monitoring
- Parking Assist
- High Beam Assist
- Traffic Sign Recognition
- AEB
- Parking valet
- Traffic Jam Pilot
- Highway Pilot
- And more functions

Domain or vehicle centralized E/E architecture

Data fusion
SENSOR FUSION
Add chips to add functionalities

Source: BMW
SENSOR FUSION

From sensors to fusion in automotive – Overview of players

- **Sensor**: FLIR, Sony, Panasonic, Velodyne, Lidar, Radar
- **Module**: Continental, Continental, Continental
- **Signal processing**: Sony, pixelworks, Toshiba
- **Analysis**: Socionext, Microchip, Texas Instruments
- **Fusion**: Toshiba, Xilinx, NXP, Infineon, Ambarella, Kalray, Ib茅c, Continental

**Players**
- **Cameras**: FLIR, Sony, Panasonic, Velodyne, Lidar, Radar
- **Lidar**: Continental, Continental, Continental
- **Radar**: Continental

**Analysis**
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Thank you for your attention

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