Sensor Technologies in Autonomous Vehicles (AVs)

SACRAMENTO STATE

WAVE

WORKFORCE FOR AUTONOMOUS VEHICLE ENGINEERING

Rohollah (Roham) Moghadam, PhD

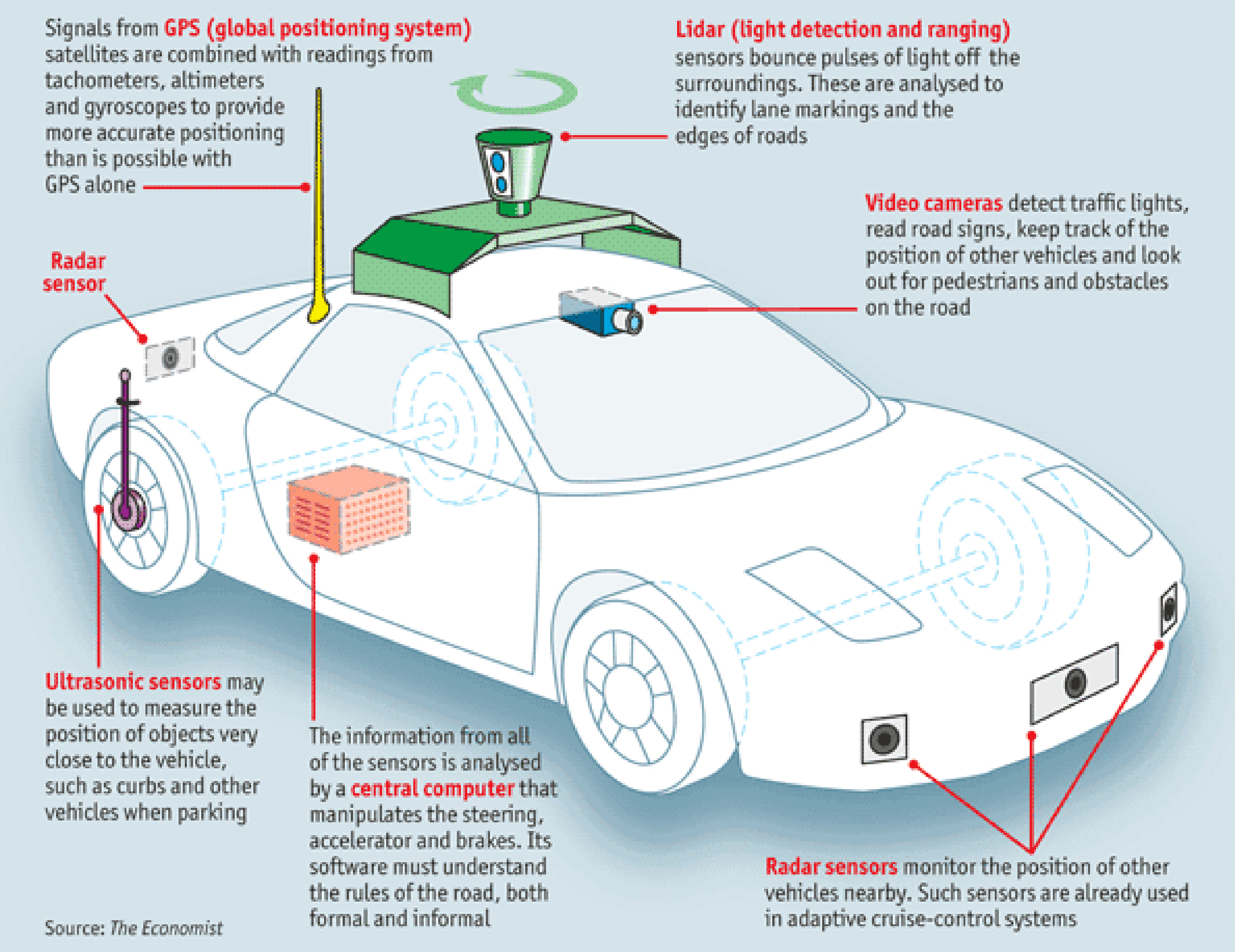
Masoud Ghodrat Abadi, PhD

MTI MINETA TRANSPORTATION INSTITUTE

Learning Objectives

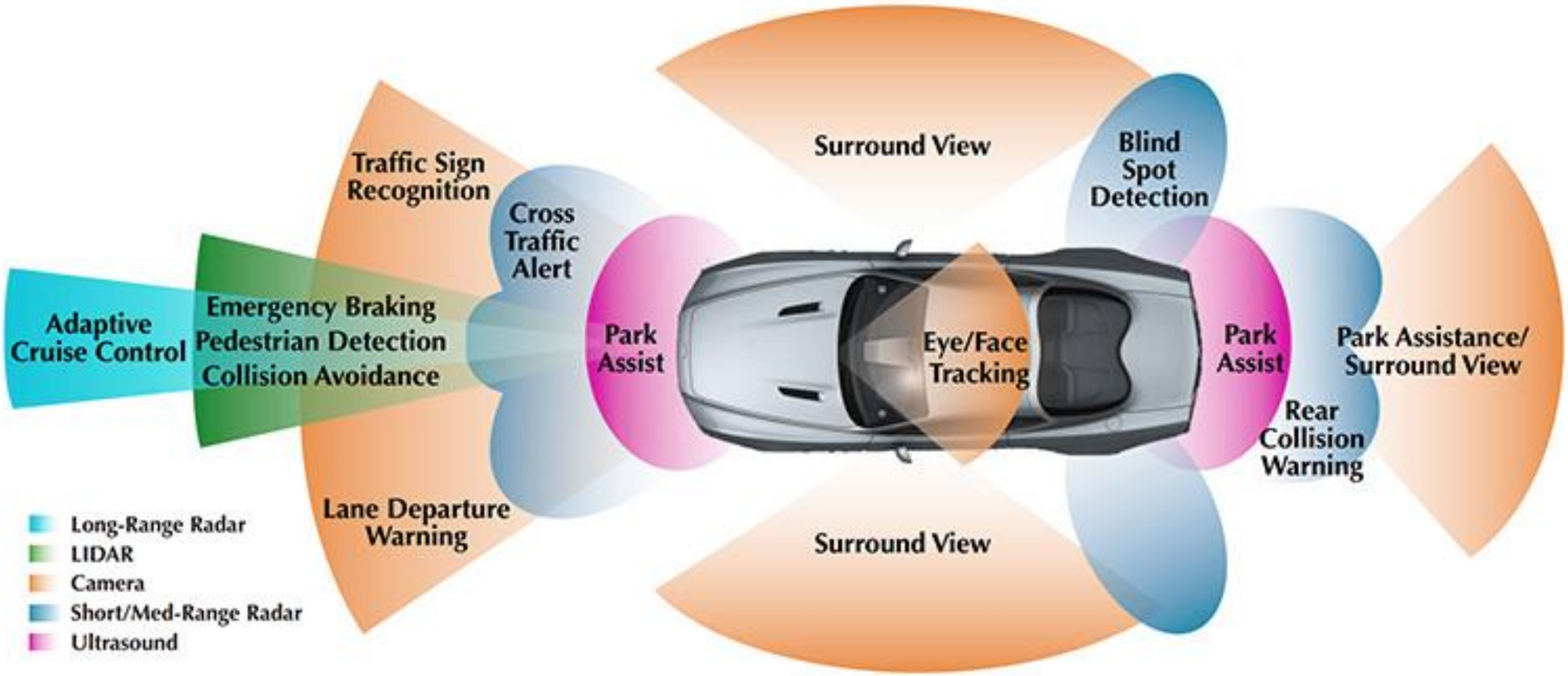
- **Identify** and describe the primary sensor technologies used in autonomous vehicles, including LiDAR, RADAR, cameras (2D, 3D, thermal), ultrasonic sensors, and GPS/GNSS.
- **Explain** the operating principles of each sensor type, including measurement mechanisms
- **Compare** sensors in terms of range and environmental sensitivity.
- **Describe key applications** of each sensor in autonomous driving, such as perception, localization, obstacle detection, and parking assistance.
- **Analyze** the limitations of individual sensors under challenging conditions (weather, lighting, occlusion, speed).
- **Understand** why sensor redundancy and sensor fusion are critical for safe and reliable autonomous vehicle operation.

Sensors in Avs:



[Debunking the Magic behind Sensors used in Self Driving Vehicles]

Autonomous Vehicle Architecture:



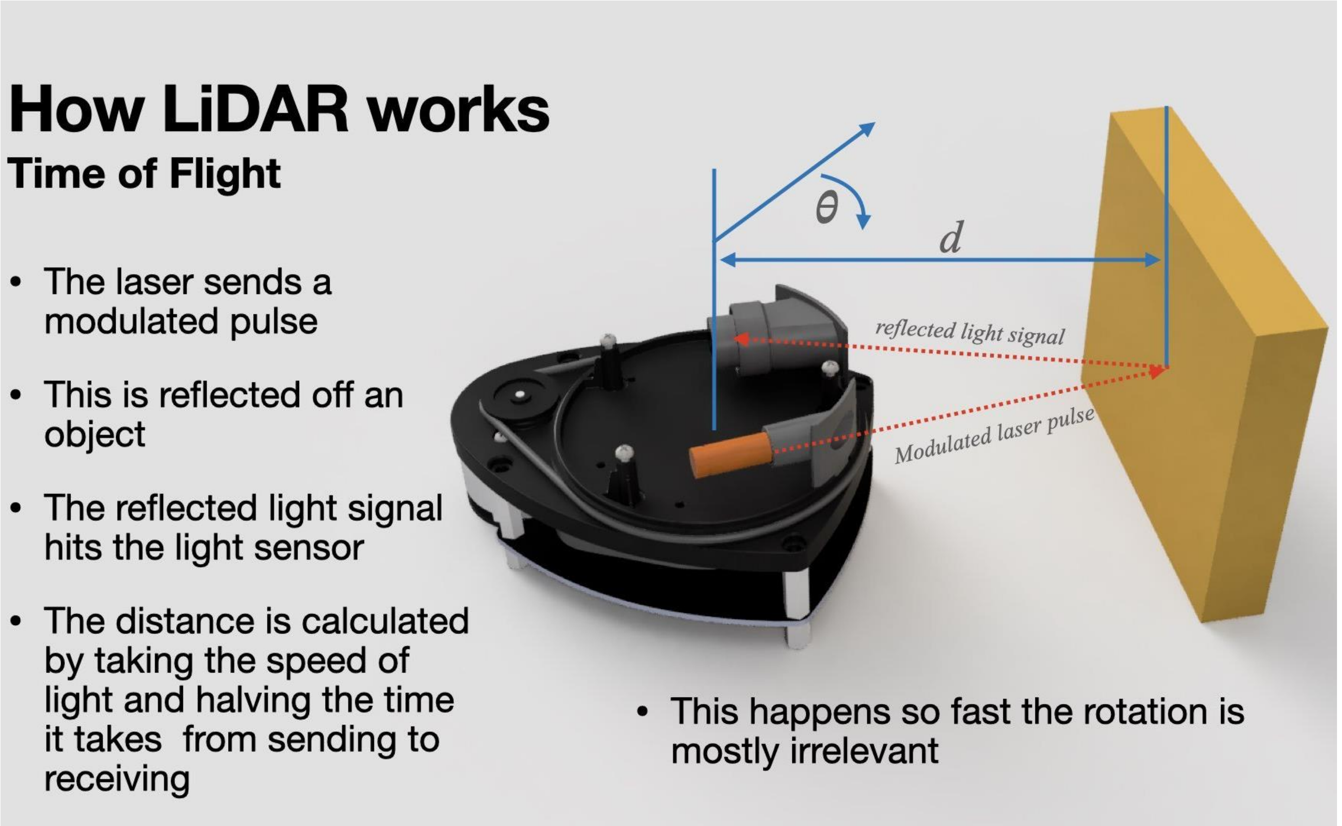
[Autonomous Vehicle Sensors and Environment]

Sensor Technologies:

- **LiDAR**: High-resolution mapping, 200–300m range
- **RADAR**: Detects speed & distance of objects, robust in adverse weather
- **Cameras**: Object & traffic sign recognition, sensitive to lighting
- **Ultrasonic Sensors**: Short-range, low-cost (e.g., parking assist)
- **GPS & IMU**: Precise positioning & backup navigation

LiDAR:

- **LiDAR (Light detection and ranging)** is an active remote sensing technology that measures distances by emitting short laser pulses and timing how long it takes for the reflected light to return to the sensor.



https://www.kevsrobots.com/resources/how_it_works/lidar.html

Key Characteristics of a LiDAR

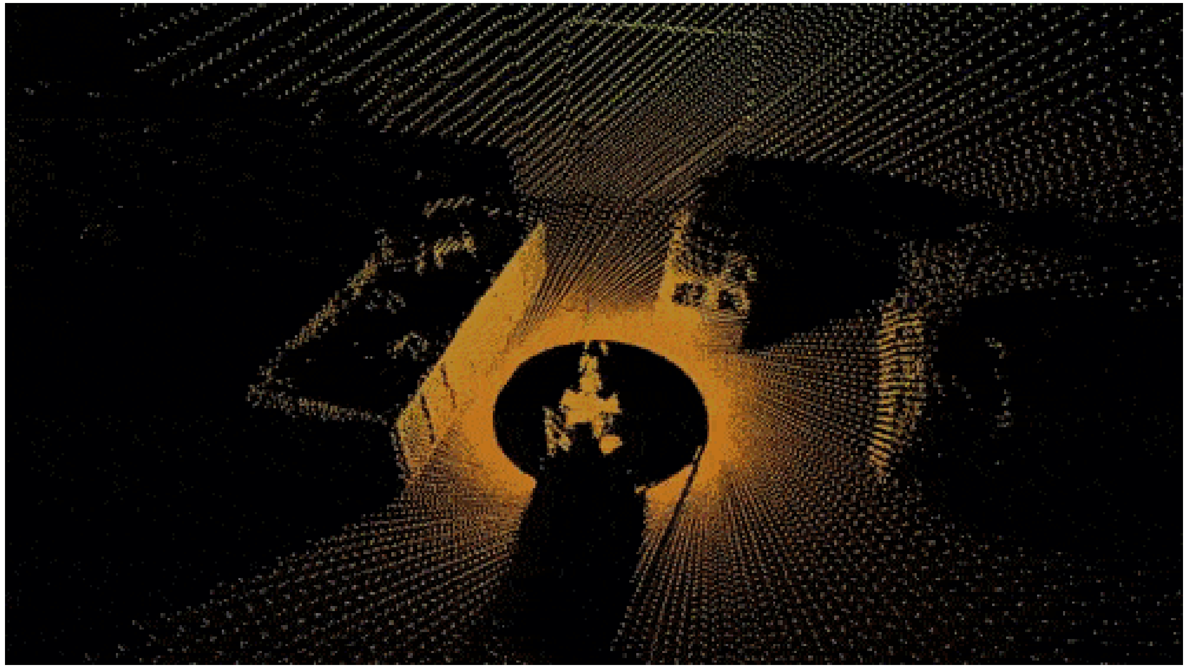
- Uses **laser pulses** to precisely measure distance and object shape
- Creates **high-resolution 3D maps** of the surrounding environment
- Provides accurate **range, angle, and elevation** information
- Operates independently of ambient lighting (day/night)

Fully Autonomous Cruise AV Has 5 Lidar Sensors | In the Scan

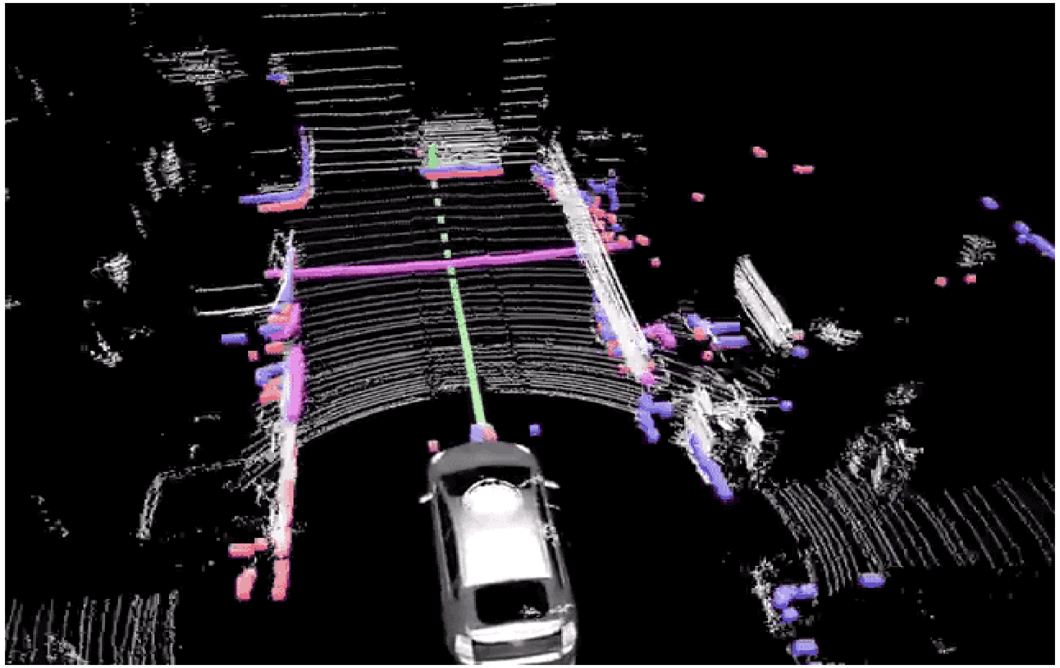
Applications of LiDAR in Avs:

- **3D environment perception:** Detection of vehicles, pedestrians, cyclists, and obstacles.
- **Localization and mapping:** High-definition map creation and LiDAR-based SLAM (Simultaneous Localization and Mapping).
- **Free-space and drivable area detection:** Identifying safe driving regions.
- **Object tracking:** Estimating object position and motion over time.
- **Support for motion planning:** Enabling safe path and trajectory planning through accurate geometry.

LiDAR in AVs:



prosthetic knowledge — Real Time 3D LIDAR Demonstration of LIDAR laser...



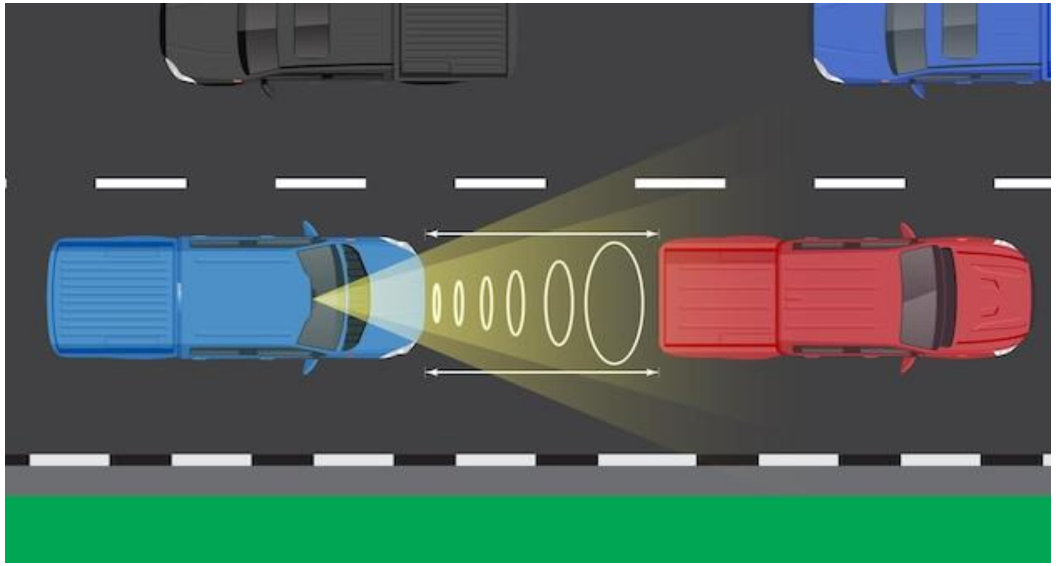
How LiDAR Is A Key Factor In Autonomous Vehicles? | by Gtssidata1 | Medium

Limitations of LiDAR

- **Weather sensitivity:** Performance degrades in **rain, fog, snow, and dust** due to laser scattering and attenuation.
- **Higher cost:** Automotive-grade LiDAR sensors remain more expensive than cameras and radar.
- **Large data volume:** Generates dense point clouds that require **high computational and memory resources.**
- Does not directly measure **object velocity.**
- **Range and reflectivity dependence:** Detection performance varies with **surface reflectivity** and object material.
- **Mechanical reliability (for spinning LiDAR):** Moving parts can reduce durability compared to solid-state sensors.

RADAR:

- **RADAR (Radio Detection and Ranging)** is an active sensing technology that uses radio waves to detect objects and measure their **range, relative velocity, and angle**.
- Distance is estimated from signal **time delay,** while velocity is obtained via the **Doppler effect**.
- Widely used in automotive systems due to its robustness and reliability.



Key Characteristics of RADAR:

- **Highly robust to adverse weather** (rain, fog, snow, dust).
- Direct measurement of **relative speed**, critical for collision avoidance.
- Longer sensing range compared to LiDAR for certain configurations.
- Lower spatial resolution than LiDAR or cameras.

Applications of RADAR in AVs

- **Object detection and tracking:** Vehicles and large obstacles at short and long ranges.
- **Adaptive cruise control:** Maintaining safe following distances.
- **Collision avoidance systems:** Forward collision warning and automatic emergency braking.
- **Sensor fusion:** Complements LiDAR and cameras to improve reliability in all conditions.

Limitations of RADAR

- **Limited spatial resolution:** Provides coarse object shape and boundary information compared to LiDAR and cameras.
- **Object classification challenges:** Difficult to distinguish object types (e.g., pedestrian vs. cyclist) without sensor fusion.
- **Multipath reflections:** Signals can reflect off buildings, guardrails, and large vehicles, causing false detections.
- **Angular accuracy limitations:** Reduced precision in lateral position estimation, especially at long ranges.
- **Reduced performance for non-metallic objects:** Some materials reflect radar signals poorly.

Cameras (2D):

- Cameras are **passive optical sensors** that capture images of the environment using visible and/or infrared light.
- **2D Cameras** capture intensity or color information of a scene projected onto a two-dimensional image plane. They provide rich **visual and semantic information** (color, texture, shape) but **do not directly measure depth**.
- Depth must be inferred using **motion, multiple views, or stereo vision**.

  Examples in AVs: Monocular RGB cameras, surround-view cameras.

Cameras (3D):

- **3D cameras** capture both visual information and **depth (distance) information** for each pixel in the scene. They generate a **depth map or point cloud**, enabling direct measurement of object geometry.
- Depth is obtained using techniques such as **stereo vision, structured light, or time-of-flight (ToF)**.
- **Examples in AVs:** Stereo camera systems, time-of-flight cameras, RGB-D sensors.

Cameras (Thermal):

- **Thermal cameras** detect **infrared (IR) radiation** emitted by objects based on their temperature, rather than reflected visible light. They produce images representing **heat signatures**, independent of ambient lighting.
- Operate effectively in **low-light and nighttime conditions**. Highly effective at detecting **warm objects** (pedestrians, animals). Performance is less affected by **shadows or glare** than visible-light cameras.

Cameras (Thermal):

- **Applications of Thermal Cameras in AVs**
  - **Nighttime pedestrian and animal detection**
  - **Safety enhancement** in low-visibility conditions
  - **Complementary sensing** for camera–radar–LiDAR fusion

Key Characteristics of Cameras:

- **High semantic resolution:** Excellent for recognizing colors, text, and object appearance.
- **Low cost and power consumption** compared to LiDAR and radar.
- Flexible placement (front, rear, side, surround-view).
- Performance depends strongly on **lighting and visibility conditions**.

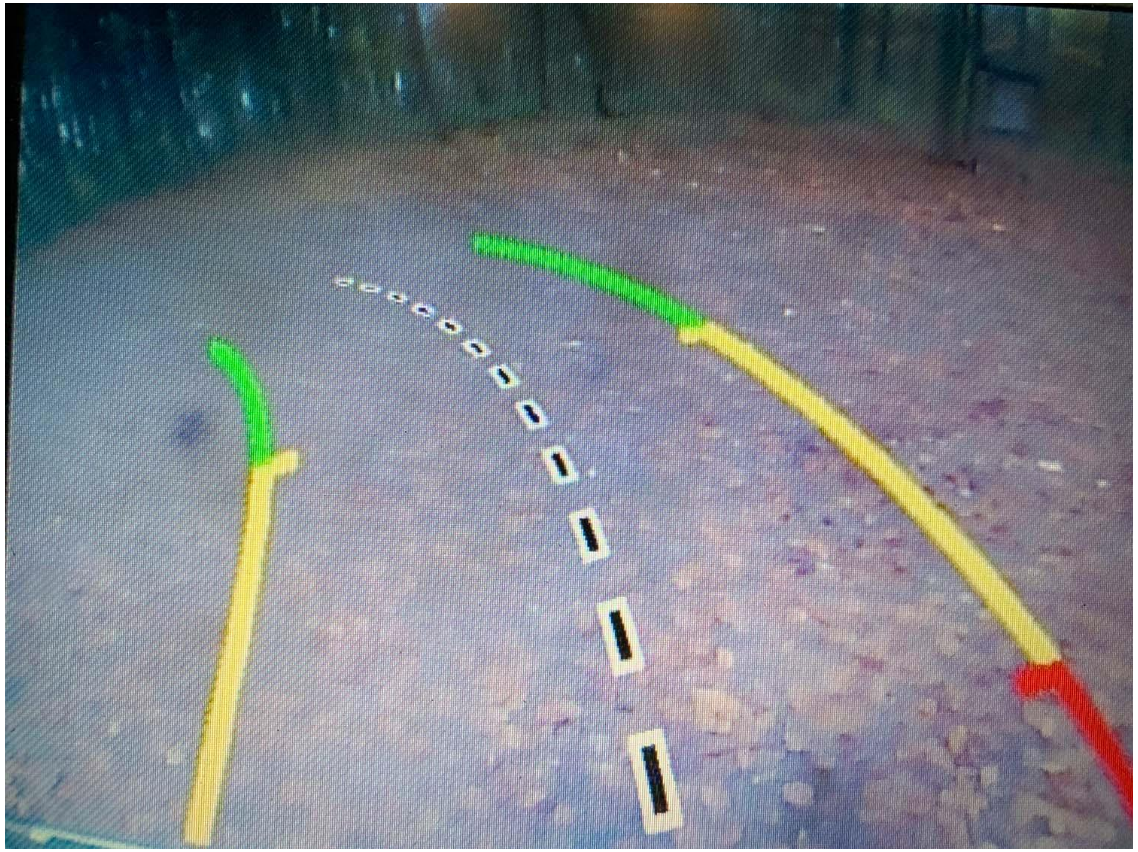
Applications of Cameras in AVs

- **Object classification:** Identifying vehicles, pedestrians, cyclists, and animals.
- **Traffic signal and sign recognition:** Reading lights, signs, and road markings.
- **Lane detection and tracking:** Supporting lane keeping and centering.
- **Scene understanding:** Semantic segmentation of the driving environment.
- **Driver monitoring (Advanced Driver Assistance Systems (ADAS)):** Monitoring driver attention and behavior.

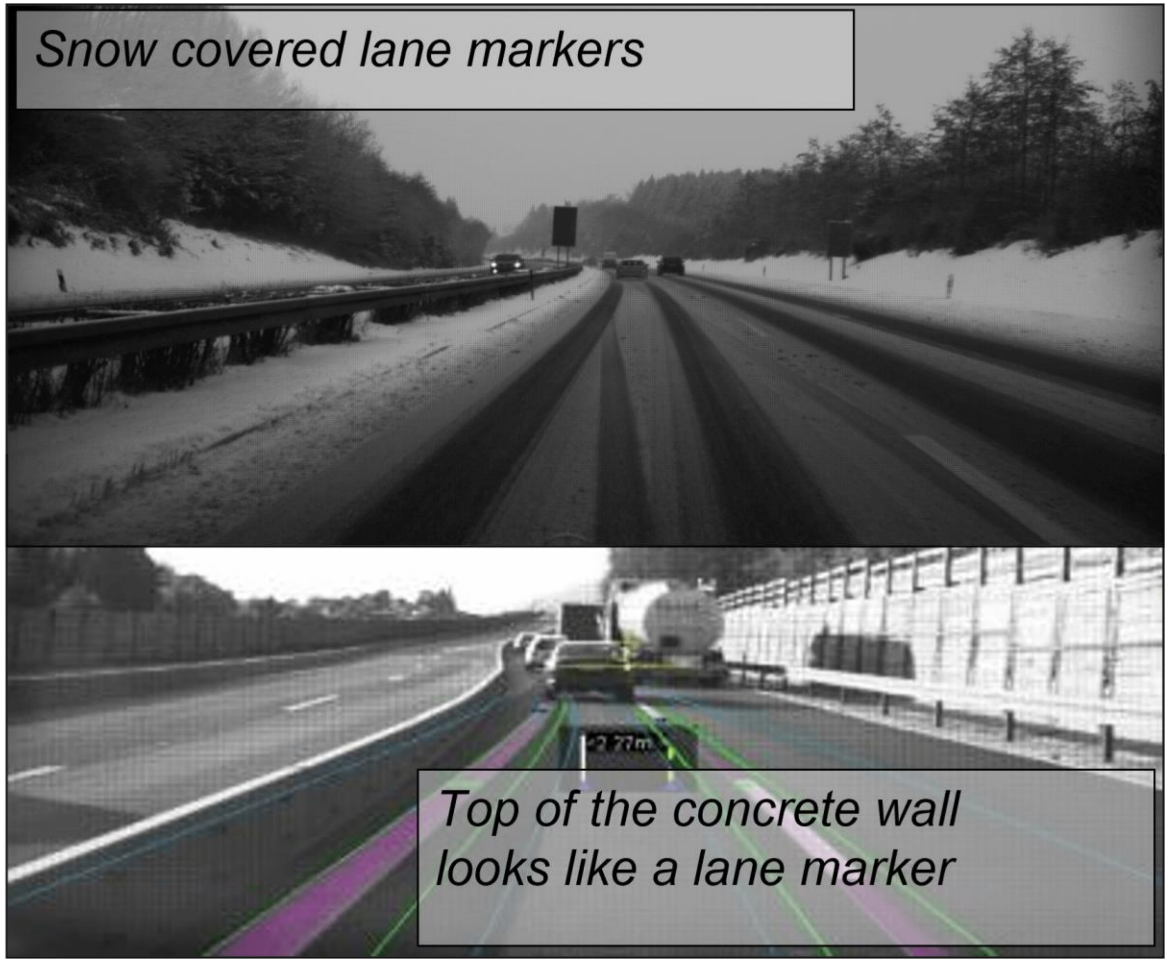
Limitations of Cameras

- Sensitive to **lighting conditions** (night, glare, shadows).
- Performance degrades in **rain, fog, and snow**.
- **No direct depth or velocity measurement** without stereo or fusion.
- Occlusion and visual clutter can reduce reliability.

Limitations of Cameras



https://www.image-engineering.de/library/blog/articles/1157-challenges-for-cameras-in-automotive-applications



Limitations of Cameras (Lighting)

https://www.image-engineering.de/library/blog/articles/1157-challenges-for-cameras-in-automotive-applications

Limitations of Cameras (Resolution)

https://www.image-engineering.de/library/blog/articles/1157-challenges-for-cameras-in-automotive-applications

Limitations of Cameras (Weather and Lighting)

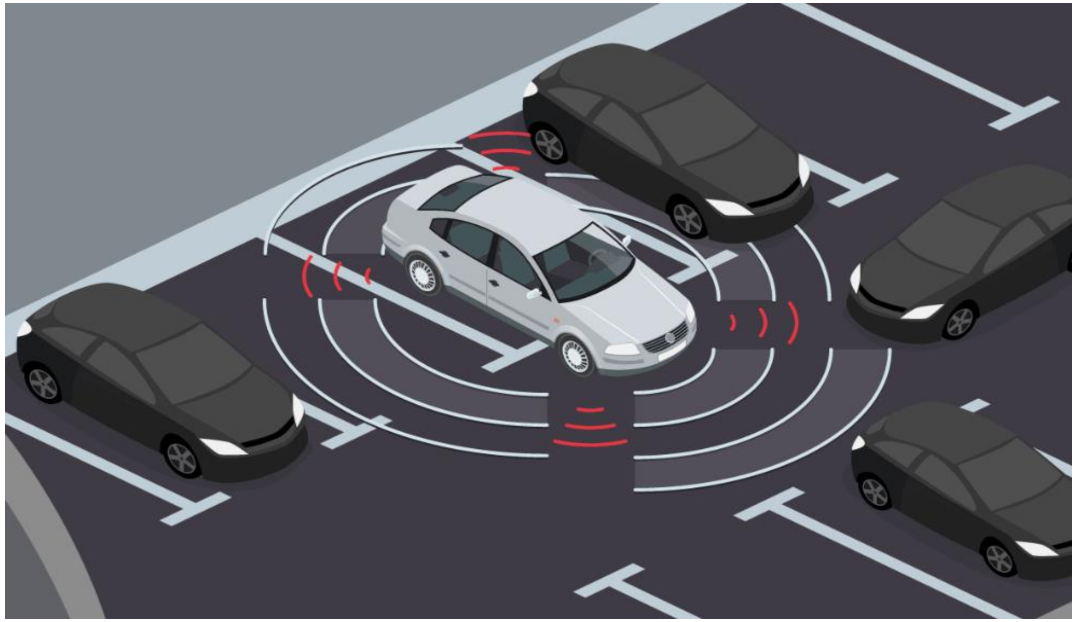
https://www.image-engineering.de/library/blog/articles/1157-challenges-for-cameras-in-automotive-applications

Limitations of Cameras (Number of Objects)

https://www.image-engineering.de/library/blog/articles/1157-challenges-for-cameras-in-automotive-applications

Ultrasonic Sensor

- Ultrasonic sensors measure distance using **high-frequency sound waves.**
- The sensor emits a pulse and measures **time of flight** of return.
- Distance calculated using speed of sound and return time.
- **Simpler** and **lower cost** sensor.



https://www.image-engineering.de/library/blog/articles/1157-challenges-for-cameras-in-automotive-applications

Key Characteristics of Ultrasonic Sensors:

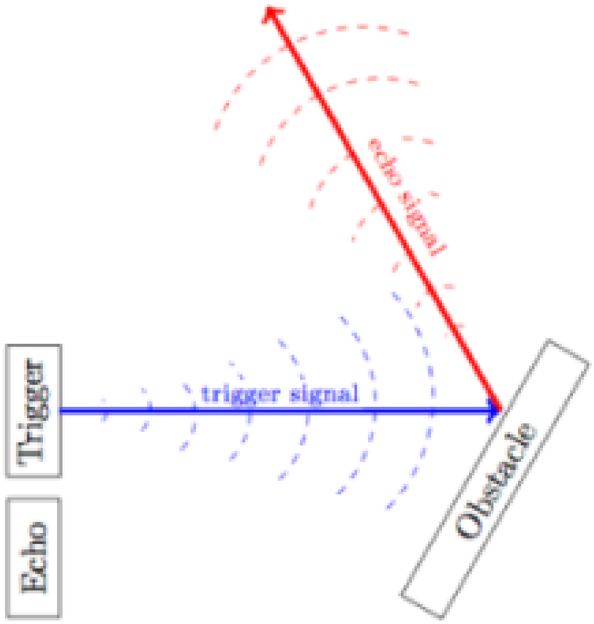
- Shorter range sensor 0.2 m – 5 m
- Moderate update rate with **minimal processing**
- Good resolution at **closer range**
- **Low complexity** sensor compared to other sensors

Applications of Ultrasonic Sensors in AVs

- **Parking assistance:** Measuring boundaries in parking
- **Blind spot detection:** Other vehicles in blind side at tighter distances
- **Collision detection:** Alerting to obstacles in the way
- **Pedestrian detection:** Subset of collision detection. High safety priority

Limitations of Ultrasonic Sensors

- Works only in **short range**
- Poor performance at **higher speeds** (Freeways)
- **Cannot classify objects** just detection and distance
- Affected by **temperature, noises, and angled surfaces**



GPS: Global Positioning System

- Data packages sent from a network of **satellites**
- Satellites send data to **receivers** (sensors on AV)
- Data includes **latitude, longitude, altitude, and speed of vehicle**
- **Accurate positioning** of 3 – 5 meters

https://www.image-engineering.de/library/blog/articles/1157-challenges-for-cameras-in-automotive-applications

Key Characteristics of GPS

- Update rate between 1Hz – 10 Hz
- **Global coverage** with network of satellites
- GPS **operates independently** from other systems
- Functions **separately** from telephone or internet connection

Applications of GPS in AVs

- **Global vehicle localization:** AV will know current position
- **Route planning & navigation:** With start/end points, a route is planned out
- **Velocity approximation:** Can be used to calculate speed from start/end point
- Network of GPS data helps with multiple AVs

Limitations of GPS

- **Signal blockage:** Dense trees, and tunnels block satellites from reaching AV
- **Not reliable for lane-to-lane level:** Can't tell what **specific lane** AV is in
- **Does not prevent collisions** with GPS alone. **Limited** physical view
- Fast and precise sensing not available with GPS compared to RADAR, LiDAR, and cameras

Supporting Sensors for Vehicle Positioning

- **Inertial Measurement Unit (IMU):** Includes accelerometers and gyroscopes, Measures vehicle acceleration and rotation, Provides short-term position and orientation estimates, Especially useful when GPS is unavailable or unreliable (tunnels, urban canyons)
- **Tachometer / Wheel Speed Sensors:** Measure wheel rotation speed, Used to estimate vehicle speed and traveled distance, Enables odometry-based positioning, Helps bridge gaps during GPS dropouts
- GPS alone is not always reliable or accurate, IMU and wheel speed sensors provide **continuous motion information,** Combined with GPS through **sensor fusion**, they improve accuracy, robustness, and reliability of vehicle positioning
- Autonomous vehicles rely on **multiple sensors working together**, not a single positioning source.

References

1. R. Siegwart, I. R. Nourbakhsh, and D. Scaramuzza, *Introduction to Autonomous Mobile Robots*, 2nd ed. Cambridge, MA, USA: MIT Press, 2011.
2. Waymo LLC, *Waymo Safety Report*, Waymo, Mountain View, CA, USA, 2017.
3. Challenges for cameras in automotive applications, https://www.image-engineering.de/library/blog/articles/1157-challenges-for-cameras-in-automotive-applications