How Car Autopilot Works:

Advanced Driver-Assistance Systems

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Table of Contents

What is Autopilot?

Although there are many cars on the market that offer advanced driving-assistance (ADAS) systems, such as Adaptive cruise control with lane-centering steering, Tesla is currently the only car manufacturer that has Autopilot which is the most advanced driving-assistance system on the market (Mays, 2019). The term Autopilot, coined by Tesla, refers to their semi-autonomous driving technology and it's currently the closest form to autonomous driving. It is built on a deep neural network to sense the external environment and its onboard computer quickly processes inputs within milliseconds (Tesla, 2020). There are currently no fully autonomous cars available on the market. A company owned by Google called Waymo is very close to having the necessary technology to provide self driving vehicles. Waymo is one of the companies that has begun their trial phase. To select people they have offered the experience of taking a ride in their autonomous cars through the city (Hawkins, 2019).

ADAS System

Automotive advanced driving-assistance systems involve many technologies that depend on each other. Autopilot and ADAS are systems that rely on constant machine learning, wireless connectivity, sensor and mapping data (Fehrenbacher, 2015). The main elements in any ADAS include sensors, processors, software algorithms, mapping and actuators. These elements can be grouped into three subsystems: data acquisition and processing, data fusion and decision-making, and taking action (Haydin, 2019).
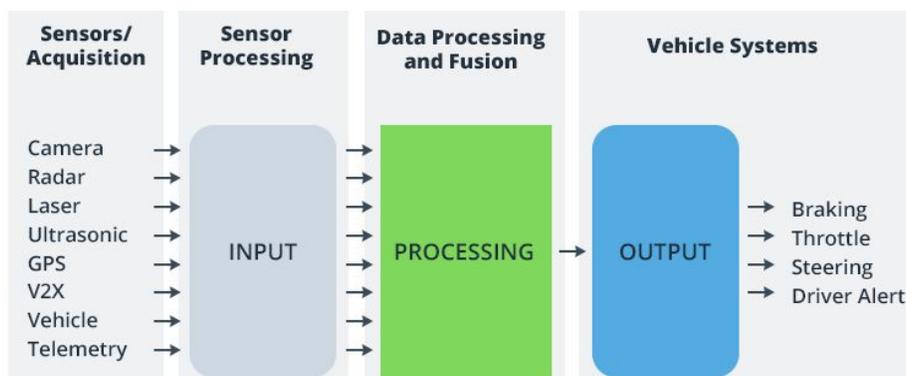
Sensors

There are multiple sensors all around the car that gather external information to help understand its external environment. Most semi-autonomous cars form and maintain an internal map of their surroundings based on a wide array of sensors ("Self-Driving Cars Explained," 2018). The most commonly used sensors in ADAS are lidar, ultrasonic and radar.

Ultrasonic

ADAS systems utilizing ultrasonic sensors have multiple sensors in the front bumper, rear bumper and side-view mirrors. The system relies on these sensors for low-speed and short-range applications: blind spot detection, self-parking and parking assistance. The sensors transmit short sound waves and they measure the travel time from the object to the receiver (Haydin, 2019).

Lidar vs. Cameras

Lidar uses its lasers to create 3D point maps of its surroundings as well as measures objects' distance by the speed of light. It has very high resolution but it is also the most expensive and is heavily avoided by Tesla. In addition, due to Lidar being light-based, it has limitations in low levels of visibility. Cornell University has proven that alternatively, cheap cameras can detect similar accuracy (Crowe, 2019).

Instead of Lidar, companies such as Tesla, use eight cameras that provide 360 degree visibility around the car and up to 250 meters in range. Tesla's mapping uses higher precision and their mapping data has 100 times the level of granularity in comparison to other navigation systems, such as Google's self-driving cars that use Lidar. Its function is to aid in automated steering and lane change applications (Fehrenbacher, 2015).

Radar

Radar sensors in a vehicle's main tasks are to detect objects at every angle such as the distance between surrounding cars and large objects in front of the car, as well as its direction and to measure speed. Radar is the lowest resolution of the three but they are increasingly useful when there is low visibility, such as driving at night, or when it is snowing or raining (Burke, 2019). In Autopilot, they are used alongside the automobile's cameras to improve detection around the vehicle.

The Tesla model X and S with hardware 1.0 and 2.0 utilize the Bosch mid-range radar sensor (MRR). The MRR is a bi-static multimodal radar as it has four independent receive channels as well as digital beam forming (DBF) (Bosch, 2015).

Initially, the MRR is configured with an independent antennae which improves angular measurement accuracy and the radar's field of view. Once the MRR is self-calibrated, it automatically searches for reference points and uses those points to calculate "the sensor axis deviation from the dynamic driving axis" (Bosch, 2015); it is then the system software that compensates for this deviation. The radars operate in radio wavelengths by transmitting waves into pulses. Bosch stated, "the MRR sends frequency-modulated radar waves in a frequency range of 76 to 77 GHz via the transmitting antenna" (2015). In other words, the radars turn on the transmitters and propels a high-intensity burst of high-frequency radio waves. The short waves, only lasting a microsecond, are then reflected off the objects surrounding the car and return to be detected by the same device (Brain, 2020; Wood, n.d.). The relative speed and distance, between the car and the detected object, are determined on the basis of the Doppler effect.

Doppler Effect. This can be described similarly to the soundwaves of a police siren. The compressed waves are higher frequency, and higher sounding pitch, in terms of a siren when a police car is moving towards you, and vice versa. By measuring the frequency shifts of the radio waves, between the sent and received signal, allows for the calculation of speed (Wood, n.d.). More specifically within the Tesla Autopilot system, the radar signals measured by the antennae also compare its amplitudes and phases which determine the position of a given object (Bosch, 2015).

Sequentially, the MRR also generates an upward elevation beam, from an elevation antenna, to measure the height of the surrounding objects. The additional beam then classifies the objects to determine how the car will react and follow suit. In conjunction with Autopilot algorithms, this feature enables the system to cope with a multitude of traffic scenarios (Bosch, 2015).

GPS/GNSS

The navigation system in a self-driving car pulls real-time geographical data from nearby satellites to determine the speed and course the car must follow to safely reach its destination. The autonomous vehicle's system uses an inertial measurement unit (IMU) which dictates and measures orientation and velocity through factors such as accelerometers, magnetometers and gyroscopes (Rahiman, 2013). This IMU is in direct contact to the GPS receiver within the vehicle's hardware. IMU's are a key component in any autonomous systems ranging from UAVs to missiles. This component gives the self-driving vehicle the ability to measure, navigate, correct, and map its course. The data collected through the IMU must be processed through a computer to appropriately calculate the position of the autonomous vehicle. This process of IMU and a data

processing computer is called dead reckoning. It allows the self-driving vehicle to map its course and be tracked with very little use of other communication to external systems. The interaction between the vehicle's hardware and software is what allows these cars to drive autonomously. The system uses multiple techniques such as laser light, radar, odometry, and computer vision in order for the vehicle to cohesively drive without human interaction (Edelkamp, 2012).

Some advanced GPS and GNSS devices are able to communicate with the vehicle's lidar and radar to 3-D map the terrain to give mapping on a more detailed and intensive scale. In summary, the car's navigation system is linked to multiple satellites at once and is able to triangulate the position based on calculations of distance from each satellite. The system uses the satellites to determine the location and uses the IMU to determine the speed and velocity necessary for the vehicle's motion. Some advanced GNSS systems that cover a massive area have no need for IMU's since they have all the built in data necessary. Although when a car drives through a tunnel or in an underground lot they do not have a direct line of sight to the satellites so the information can become more inaccurate.

Computer Processors

Once the data is collected, autonomous cars require high-performance processors. All self-driving cars, and essentially all modern cars, require a computer on-board to process everything happening with the vehicle, the inputs, in real-time. They require extreme processing power, so rather than traditional CPUs, they utilize graphical processing units, or GPUs, to do their calculation. However, even the best GPUs have started to prove insufficient for the needs of the extreme data processing seen in self-driving vehicles, so companies such as Tesla have introduced a neural network accelerator chip, or NNA. These NNAs have extreme processing

power in real-time, capable of handling real-time image processing. For a perspective between

CPUs, GPUs, and NNAs, this is how many giga operations per second they can handle, or GOPS:

- *CPU: 1.5*

- *GPU: 17*

- *NNA: 2100*

 By using an NNA, vehicles must also use a neural processing unit (NPU). An NPU is a

well-partitioned circuit that comprises all the control and arithmetic logic components necessary to

execute machine learning algorithms. NPUs are designed to accelerate the performance of

common machine learning tasks such as image classification, machine translation, object

detection, and various other predictive models. NPUs may be part of a large SoC, a plurality of

NPUs may be instantiated on a single chip, or they may be part of a dedicated neural-network

accelerator.

Executing deep neural networks such as convolutional neural networks means performing

a very large amount of multiply-accumulate operations, typically in the billions and trillions of

iterations. A large number of iterations comes from the fact that for each given input (e.g., image),

a single convolution comprises iterating over every channel and then every pixel and performing a

very large number of operations. And many such convolutions are found in a single model and the

model itself must be executed on each new input (e.g., every camera frame capture).

Unlike traditional central processing units which are great at processing highly serialized

instruction streams, Machine learning workloads tend to be highly parallelizable, much like a

graphics processing unit. Moreover, unlike a GPU, NPUs can benefit from vastly simpler logic

because their workloads tend to exhibit high regularity in the computational patterns of deep

neural networks. For those reasons, many custom-designed dedicated neural processors have been developed (Neural Network, 2020).

Ultimately, it is the avoidance algorithms, predictive modeling, "smart" object discrimination and hard-coded rules that help the software follow traffic laws and navigate its route ("Self-Driving Cars," 2018). Autonomous cars are driven by various function-specific software running on electronic control units (ECUs).

Algorithms

Autonomous cars are extremely associated with the Internet of Things. The combination of machine learning, artificial intelligence and computing are the essential technologies for the car's functionality. In real time, the software algorithms use the inputs from the sensors, to incorporate environmental elements, into Advanced driver-assistance systems (ADAS). The output, provided by the algorithms are sent to the actuation system and delivers the appropriate information, such as to warn the driver of potential hazard or to give directions on how to act (Haydin, 2019). The algorithms are also classified into two categories and they differ in the ways they learn.

Unsupervised Algorithms

These algorithms try to derive value from the available data. This means that an algorithm develops a relation from the available data, in order to detect patterns. It can also divide the dataset into subgroups depending on the level of similarity between them (Ravindra, n.d.).

Supervised Algorithms

These algorithms use a training dataset to continuously learn until they are at peak confidence as their goal is to minimize the probability of error (Ravindra, n.d.). In self-driving cars, the main jobs for machine learning algorithms are rendering and predicting the changes in its

surrounding environment. These tasks are divided into four sub-tasks: object detection, object identification or recognition object classification, object localization and prediction of movement.

Machine Learning Algorithms.

Machine learning algorithms are also loosely divided into four categories: regression, decision-making, pattern recognition and clustering (Gupta, n.d.). One category of machine learning algorithms can accomplish two or more subtasks.

Regression Algorithm. Particularly good at predicting events. Regression is used for object detection, object localization, predicting movement and works by comparing variables to predict an object's movement. It is driven by 3 metrics: the shape of the regression line, type of dependent variables and the number of independent variables (Ravindra, n.d.).

Decision Making Algorithm. Used for decision making and works by using multiple models to recognize scenarios and make decisions.

Pattern Recognition Algorithm. This type algorithm is defined as a data reduction algorithm. It is used for object recognition and works by reducing the data set by finding patterns. For example, as external images are obtained through the sensors, they are to be filtered to determine the instances of an object by ruling out the irrelevant data points (Ravindra, n.d.).

Clustering Algorithm. This algorithm is specialized in discovering the structure from the data points. Clustering is used for object recognition and it uses structures in data to organize the data into groups based on commonalities.

Actuation System

The actuators convert energy into motion and they are major enablers of the ADAS system. The computer software processes all the inputs from sensors and sends instructions to the car's actuators. The actuation system facilitates interactions between the car's components and takes necessary actions based on the computed results.

It is through programmed sequencing where the actuation ADAS subsystem reacts and the results are processed into commands to control the car. Actuations have many operations such as visual, acoustic or haptic warnings to electric power steering, autonomous acceleration and autonomous braking (Haydin, 2019).

Connectivity

Connectivity allows the vehicle access to external information that can provide aid. It provides the autonomous vehicle the ability to communicate to other technologies around it. Many autonomous vehicles rely on TE connectivity which is a technology from Switzerland that creates sensor and connectivity products. It allows automotive industry leaders to more easily overcome software protocol and interface compatibility challenges (Spectrum, n.d.). V2X is constantly updating it's information in order for the vehicle to be driven without human interaction. It uses both sensor technology and radio-based communications, which allows it to interact with other things like traffic lights and other vehicles on the road. Data sensing and the transmission of data must be completely reliable because there is no room for error in this industry. Car manufactures will have to heavily increase their bandwidth in order to comprehend all of the data from these sophisticated systems (Spectrum, n.d.).

Cellular V2X

Additional inputs are also possible for ADAS, such as V2X. This connectivity relies on mobile telephony, WiFi and Bluetooth. Vehicle-to-everything connectivity in autonomous vehicles works in correlation with lane correction assistance, collision warnings, and satellite radio. V2X has a couple different wireless protocols however the most common is DSRC (direct short-range communications) and it operates using the 802.11p wireless standard (Smith, 2017). The components within V2X include vehicle-to-vehicle (V2V), vehicle-to-infrastructure (V2I), vehicle-to-pedestrian (V2P), and vehicle-to-network (V2N) and vehicle-to-grid. For example, they are able to communicate with infrastructures such as traffic lights and data centres via cellular network. As stated by McLellan, "it is where information from sensors and other sources travel via high-bandwidth, low-latency, high-reliability links, paving the way to fully autonomous driving" (2019).

Summary

Currently there have been no fully autonomous vehicles introduced to the market. The closest thing to a full autonomous car is Waymo's Self driving cars. Waymo is owned by Google and they are near the top of the industry for innovation. The car performs the functions of monitoring the road and the surroundings, as well as accelerating, decelerating, and steering (English, 2020). Waymo's veichle is also programmed to have fallback for self-driving features. The hardware is fairly consistent in most autonomous vehicles but the software is constantly being upgraded and innovated. Most of the self-driving vehicles use Advanced Driver Assistance Systems (ADAS).

The hardware consists of five main components, first one being sensors, such as radar. Radar tracks and detects the presence, speed, and direction of objects using radio wave frequencies. This allows the car to be familiar with the surrounding environment. The next is ultrasonic or more commonly Lidar, which sends very accurate 3-D depth perception to the vehicle's network. Lidar gathers data by shooting lasers and receiving reflections in order to translate the data into information. Then there are the camera vision systems which capture the surroundings in high resolution and detail. The cameras are very important to the network but in bad weather conditions the autonomous vehicle will rely more heavily on it's radar and lidar. The fourth component is connectivity, the vehicle uses these as external sources of information. This is where the network can pick up GPS/GNSS signals from satellites in order to map the proper course. These include sources such as; maps, construction updates, weather conditions, and traffic. By collecting these inputs the vehicle is able to change things like the approximate time of arrival. The last component of the hardware is having backup sensors to help aid the autonomous driving process, an example of this would be microphones in order to pick up audio from the external environment.

The software consists of four main algorithms used to filter, interpret and understand the data as well as initiate actions. The first is a regression algorithm, this allows the vehicle to detect and localize objects as well as predicting movements (English, 2020). It works by comparing a number of variables in order to predict an object's path and trajectory. The next algorithm used by the autonomous vehicle is a decision making algorithm. The technology that allows this to work is by having the vehicle be able to recognize scenarios and make the accurate decisions. The third is the pattern recognition algorithm, which is used for object recognition. It works by trying to find

patterns and commonalities that aid the driving process. This algorithm is basically the classification of data based on knowledge that is already possessed. The final algorithm is the clustering algorithm, this one is also used for object recognition. It is the only unsupervised machine learning algorithm of the four. It's purpose is to find patterns in the data in order to group them into classes of similarities or relevance.

Finally, the actuation system facilitates the interactions based on all the computed results through the programmed sequencing. In addition to the actuators, it is the vehicle's connectivity that makes it even closer to being fully autonomous. The cellular connectivity is frequently updating information while using the sensor technology and radio-based communications. The most common V2X protocol is DSRC and it is used in many forms, such as to communicate to traffic lights via the cellular network.

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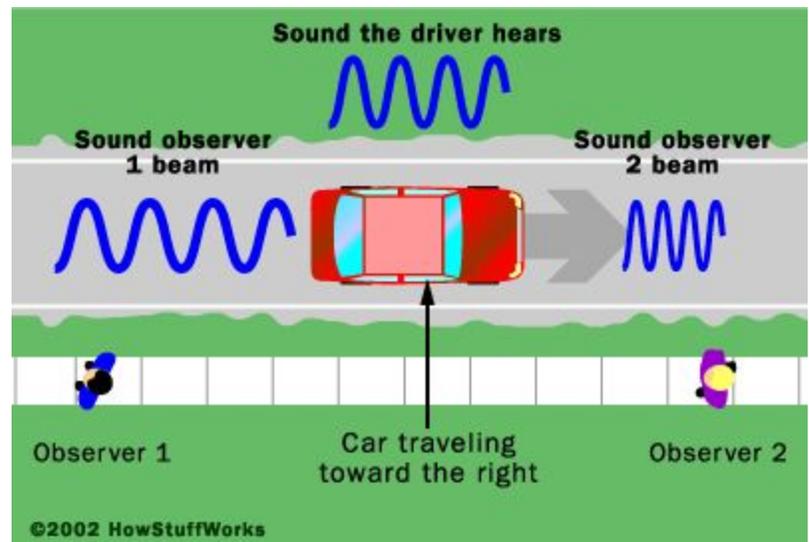
Appendix

1. 360 degree camera and sensors

2. Antennaes
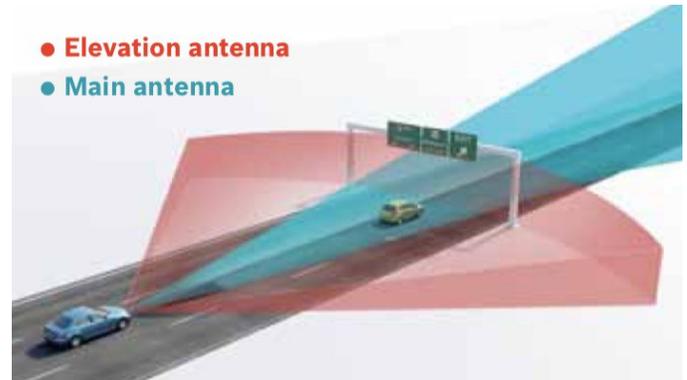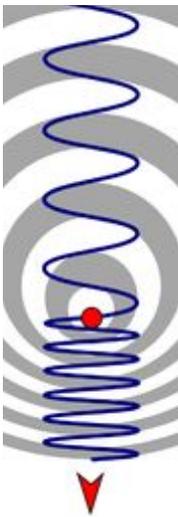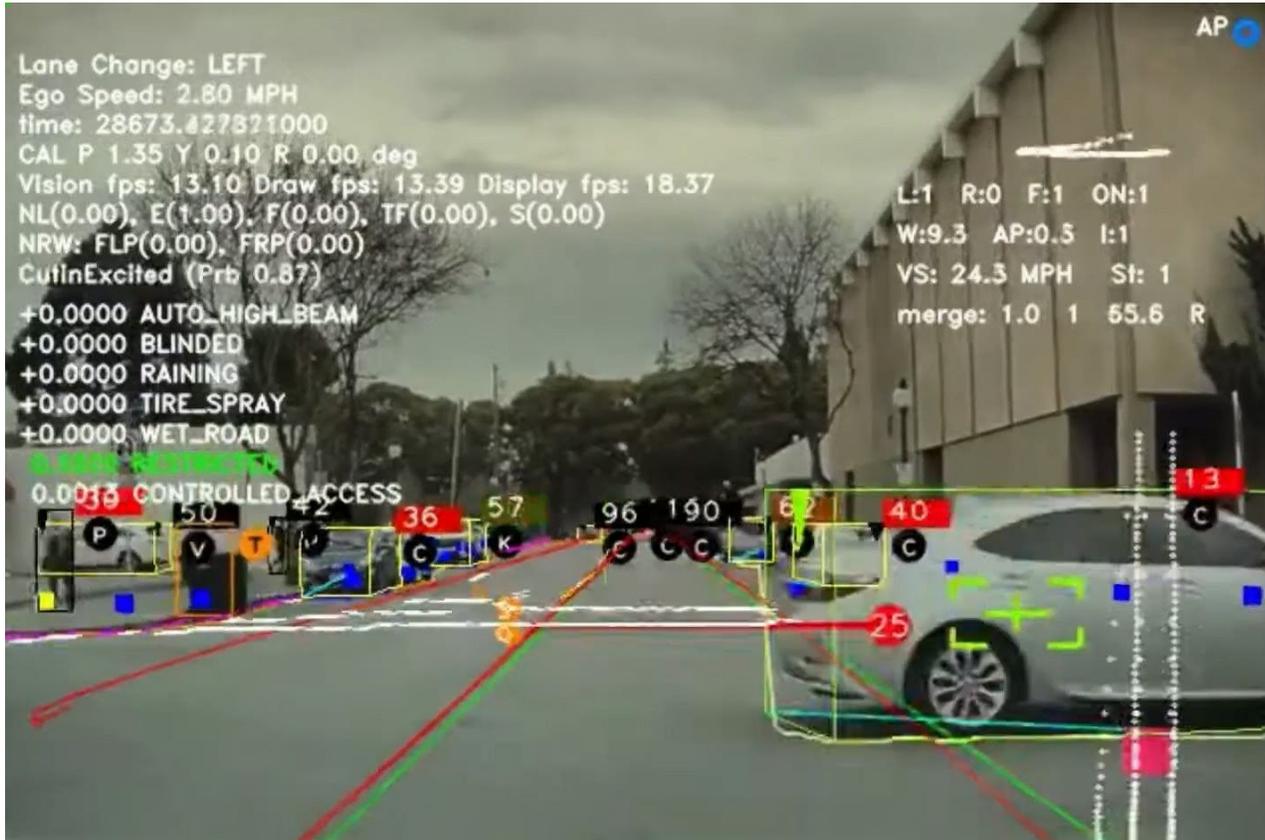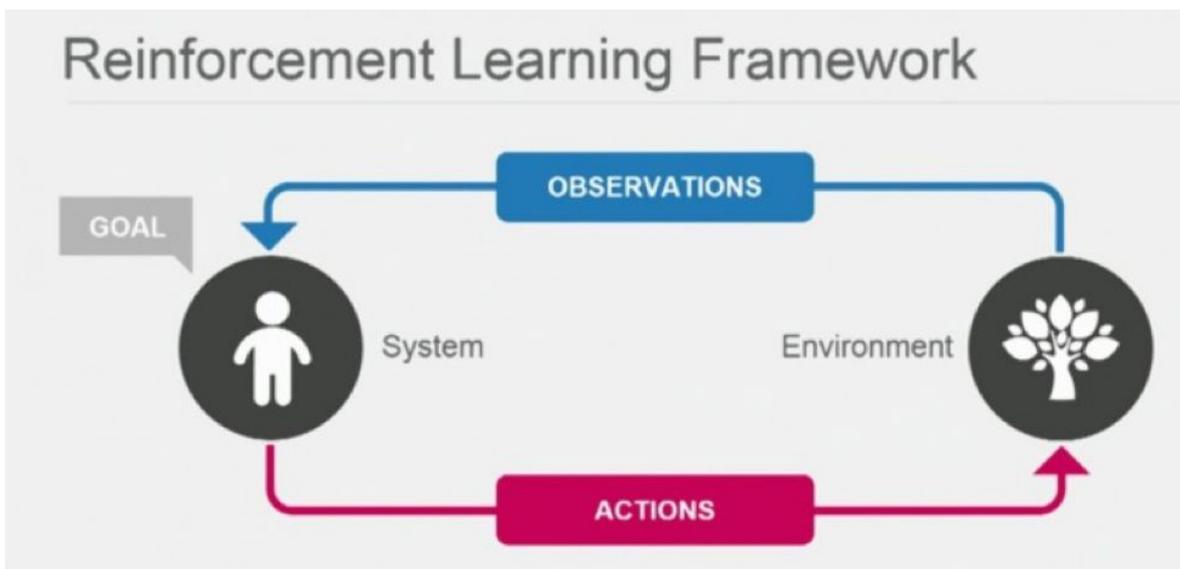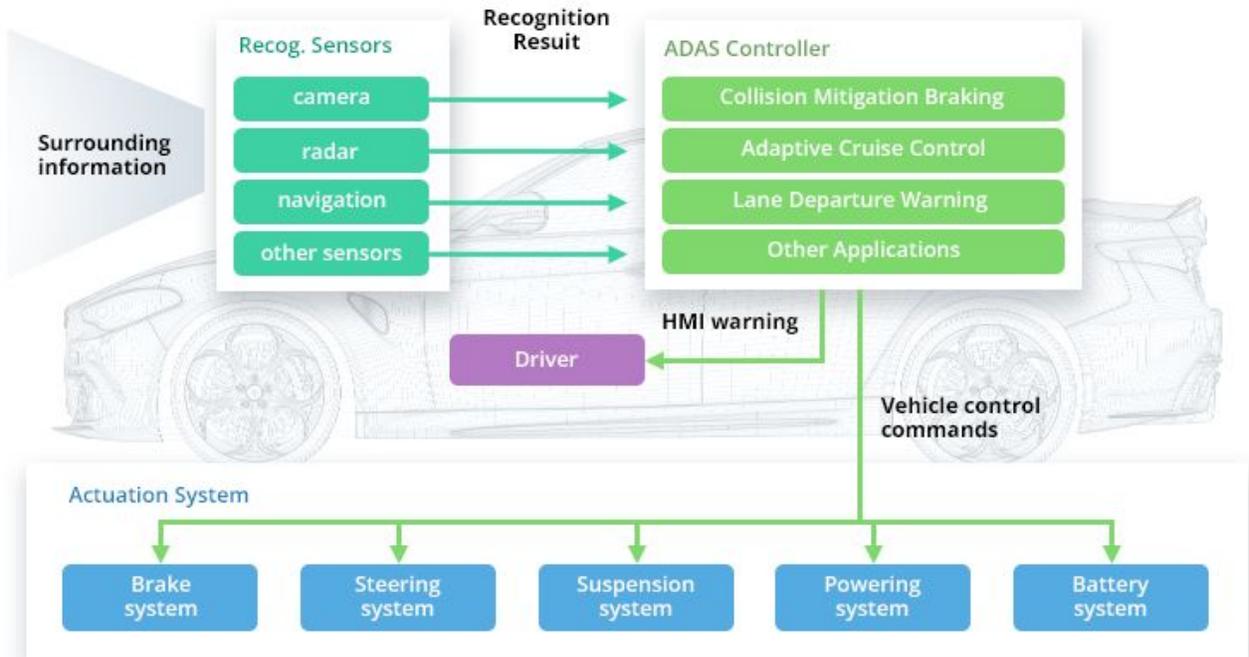

3. Doppler effect

4. Doppler effect around car

5. Tesla Autopilot Scan: What it sees

6. The Cycle of Machine Learning

7. ADAS System