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Sensors' Architecture Definition for Energy Consumption Reduction in Urban Battery Electric Vehicles

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"Passion, obsession, car addiction;
beyond the bounds of reason
Madness"

Abstract

Advanced Driver Assistance Systems (ADAS) have been one of the most active areas of studies in automotive sector in the last two decades. ADAS aim to support drivers by either providing warning to reduce risk exposures, or automating some of the control tasks to relieve the driver from manual driving of the vehicle. This work focuses on the definition of the sensors' architecture for an urban battery electric vehicle (BEV) prototype, developed in the context of MOST - Centro Nazionale per la Mobilità Sostenibile, equipped with ADAS to improve its energy efficiency.

An initial analysis is developed on the individual sensors, classifying them according to their characteristics, performances and actual ADAS use-case. After the analysis of the donor vehicle sensors' setup proposed by the OEM, the benchmarking of different commercial products is carried out to highlight their best characteristics and their fit with the requirements imposed by the energy-efficient ADAS to be developed. The sensors' chosen among the automotive-grade products are the following: Solid-State LiDAR, 4D Radar, Long-Range Radar, Short-Range Radar, Stereoscopic Camera and Monocular Camera. The final sensor kit should cover all of the ADAS functionalities to contribute to the energy management strategy, which aims to optimise comfort, battery consumption, road safety and drivability. The optimisation objective may also includes maximising battery life or, in general, a trade-off between all these objectives.

The final result is a sensor suite that meets the requirements defined maximizing the different key performance indicators (KPIs) used for benchmark, such as range, Field-of-View (FoV), cost and weather robustness. The selection of the kit and its sensors is supported by hierarchical analytical process (AHP) methodology, a mathematical decision support system in which pairwise comparisons are made between the various characteristics of individual sensors. The AHP framework allows for technically quantifying the relative importance of each sensor, by providing a methodology that incorporates qualitative and quantitative notions of performance. This methodology establishes the most exhaustive sensor among those examined in the benchmark. The analysis demonstrates that the system incorporating Radar 4D yields the highest consistency index with a value of 8%.

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Chapter 1

Introduction

1.1 Background

The recent proliferation of miniaturized autonomous driving technologies has revolutionized cities, as it has made smart cars a viable option for daily transportation. These autonomous cars effectively alleviate the burden on human drivers by performing intelligent operations, including collision avoidance, lane departure warning, and traffic sign detection. Moreover, autonomous driving technologies efficiently manage traffic flow, thus reducing congestion and contributing to advanced fuel economy by lowering emissions. [1]

With technological advancements, software-defined vehicles are presented, which are capable of operating autonomously through algorithms and decision-making processes based on situational analysis. Nowadays it is possible to introduce self-driving vehicles: these are vehicles that can move safely in an environment without, or with minimal, human intervention. They operates in three distinct phases: perception, where the system acquires data from its surroundings to analyze; reasoning, where the system processes this data to understand the best course of action; and act, where the system moves along a path with a certain level of reliability. One of the main reasons for the widespread interest in self-driving vehicles is road safety. Studies indicate that a significant portion of road accidents are caused by driver distraction. Therefore, the purpose of a self-driving vehicle is to reduce driver errors and provide support while driving. At the basis of self-driving vehicles are ADAS systems: the role of Advancend Driver Assistance Systems (ADAS) is to prevent deaths and injuries by reducing the number of car accidents and the serious impact of those that cannot be avoided. The ADAS systems introduce the notion of an autonomous driving vehicle. In particular, sensors allow the vehicle to communicate with its surroundings, transmitting information to the control units within the vehicle. This enables the generation of commands to respond to the current situation.

The Society of Automotive Engineers (SAE) International established its SAE J3016 Levels of Automated Driving [2] standards in 2014, with the aim of generating a ranking of levels of autonomous driving. The guidelines adopted by both the United Nations and the US Department of Transportation have undergone updates in 2021 and are presently viewed as the prevailing and accepted benchmark for evaluating the aptitudes and accountabilities of self-driving vehicles.

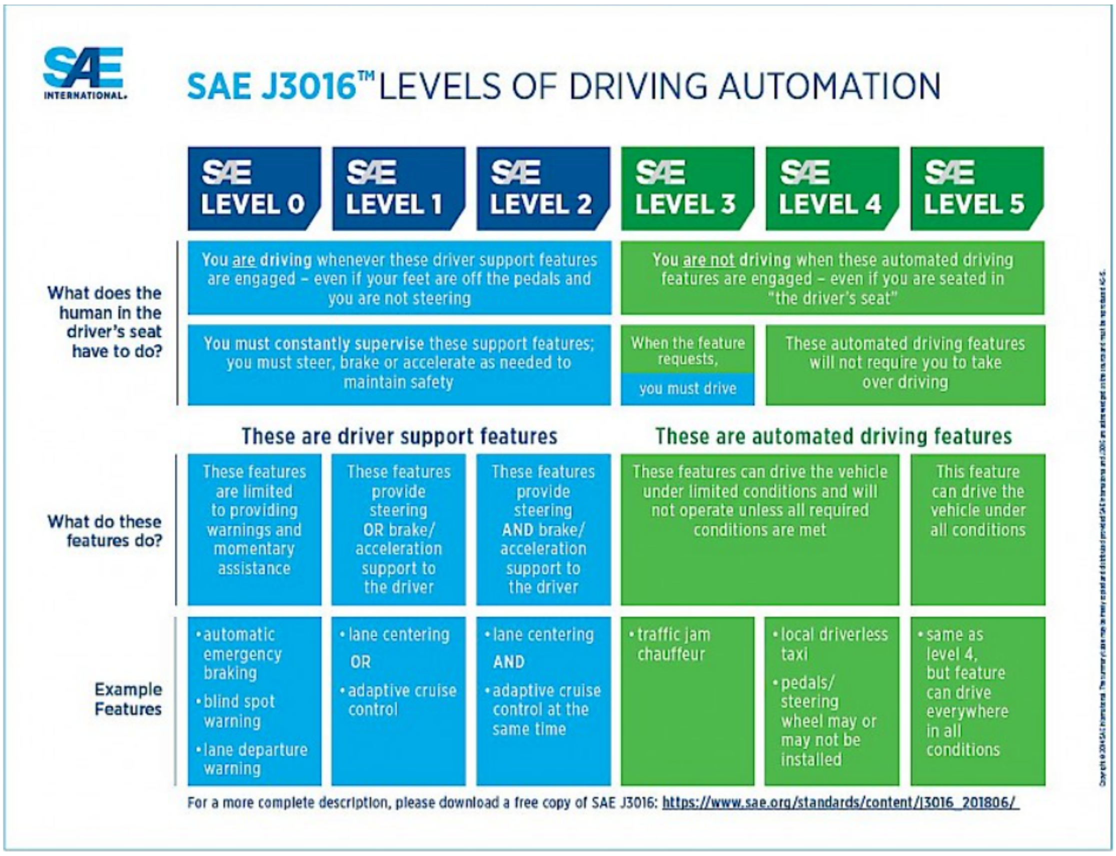


Figure 1.1: SAE Levels of Driving Automation™

Figure 1.1 report the SAE Levels of Driving Automation that consist of six different levels:

- Level 0 - No Driving Automation: At this level, the vehicle does not possess any automated driving features; however, driver assistance features may still be present. The driver is responsible for all aspects of driving, but the vehicle is equipped with a system that provides momentary driving assistance, such as warning signals or emergency safety actions. The driver is responsible for braking, steering, accelerating, etc., and must also monitor any possible warnings or safety activities.

- Level 1 - Driver Assistance: At this level, the vehicle is equipped with a system that constantly assists with acceleration, braking, and steering, while the driver remains involved and attentive. The driver still has the task of driving the vehicle and monitoring the system, which can perform steering, acceleration, and braking functions.

- Level 2 - Partial Driving Automation: Vehicles at this level are equipped with advanced driving assistance systems (ADAS) that provide continual assistance with acceleration/braking and steering. The driver remains completely attentive and involved but has the option to hand over control of combined longitudinal and lateral functions.

- Level 3 - Conditional Driving Automation: When activated, the system carries out all driving functions, but the driver must still be seated in the driver's position and ready to take control when necessary or requested.

- Level 4 - High Driving Automation: Systems in vehicles at this level are able to intervene in the event of a malfunction without necessarily involving the driver. However, the driver still retains the ability to manually take control of the vehicle.

- Level 5 - Full Driving Automation: At this level vehicles require no human intervention, not even emergency manual intervention, regardless of driving conditions or the state of the roads. Therefore, these vehicles are not equipped with pedals or a steering wheel. As a result, an individual could be on board and engage in any activity without considering the driving situation.

These cars are undergoing testing phase in several research centres around the world, and it is projected that these cars will be available in the market by 2030.

Core self-driving technology can be broadly classified into four categories

- sensing
- perception
- planning
- control

This work is focus on sensing and perception; sensing refers to the capability of the autonomous vehicle to collect real-time data from a variety of sensors (i.e., cameras, ultrasonic sonars, LiDARs, and radars) connected with self-driving cars to extract useful information from the environment. One of the most important components in a self-driving vehicle is the perception stage and fundamental element for this phase are the sensors, which are devices that measure or detect a property of the environment in which they are immersed.

There are two types of sensors:

- exteroceptive: they assess the external environment with respect to the analysed platform;
- proprioceptive: they assess the internal context of the analysed platform.

Camera is one of the most used exteroceptive sensors, which can be used by alone or, in order to simulate human vision, it can be used together with another camera placed at a specific distance, this configuration is called a stereo camera. Over the camera, there are other types of sensors that are fundamental in the field of autonomous driving to enable handling, these are LiDAR, sonar, radar, based on the concept of time-of-flight and used for measure distances to objects, and thus for obstacle detection.

Sensor fusion techniques process large amounts of information in a very similar way to the human mind. In particular, LiDARs, ultrasound sensors, radars and image recognition software are used for this purpose. These technologies have the ability to respond faster than a driver does, analysing scenes and understanding how to react to them. Sensor fusion involves data from various sources such as radar, LiDAR and cameras to construct a unified representation or visualization of the surrounding environment comprising a vehicle. This model achieves greater accuracy by taking advantage of the unique strengths of each sensor. As a result, vehicle systems can leverage the combined information obtained through sensor fusion to facilitate more sophisticated decision-making.

The automotive industry has undoubtedly come a long way from traditional vehicles to ADAS and autonomous driving technology. Traditional vehicles, also known as conventional vehicles, have been the pilasters of the automotive industry for over a century. These vehicles are primarily controlled directly by the driver, using manual controls such as steering wheels, brakes, and accelerators. The driver is responsible for all aspects of driving, including speed management, lane positioning, and decision-making.

Many car manufacturers have started integrating advanced driver-assistance systems (ADAS) into their vehicles to enhance safety and convenience. These systems, such as lane-keeping assist, adaptive cruise control, and automated emergency braking, serve as crucial building blocks towards achieving fully autonomous driving. By introducing ADAS features, drivers can experience semi-autonomous capabilities that gradually reduce their involvement in the driving process, paving the way for future advancements in autonomous vehicles. ADAS systems works by alerting the driver to danger or even taking action to avoid an accident. ADAS-equipped vehicles can sense their environment, process this information quickly and accurately in a computer system, and provide the necessary output to the driver. These vehicles have an array of advanced sensors that enhance the visual and auditory capabilities, as well as the decision-making ability, of the human driver. The ADAS system architecture consists of a suite of sensors, interfaces, and a powerful computer processor that integrates all of the data and makes real-time decisions. These sensors constantly analyze the surrounding environment and provide this information to the onboard ADAS computers for prioritization and action. Today, they are saving lives by preventing accidents that would have otherwise occurred. Eventually, these technologies will lead to fully autonomous vehicles.

With the growth of ADAS systems, the term software defined vehicle was introduced to identify a vehicle whose features and functions are enabled primarily through software, a result of the ongoing transformation of the car from a primarily hardware-based product to a software-centred electronic device on wheels. However, the ultimate goal of the automotive industry is to achieve autonomous driving, which refers to vehicles that can drive themselves without human intervention. The transition from ADAS to autonomous driving involves a gradual progression of technology and capabilities. Autonomous vehicles (AVs) rely on a combination of advanced sensors, artificial intelligence, machine learning, and connectivity to perceive the environment, make decisions, and navigate routes. The development and deployment of autonomous driving technology are driven by various factors, including the potential for improved safety, increased efficiency, reduced congestion, and enhanced accessibility. While fully autonomous vehicles are not yet common on roads worldwide, significant progress has been made in research and development. Various companies, including traditional automakers, tech giants, and startups, are investing heavily in developing autonomous driving technology and conducting extensive testing to ensure its safety and reliability.

In conclusion, the automotive industry has transitioned from traditional vehicles to ADAS and is now moving towards autonomous driving. Advanced driver-assistance systems have already made driving safer and more convenient, while autonomous driving technology aims to revolutionize transportation and reshape the way people travel.

1.2 Motivation

Sustainable mobility is an impelling issue for the worldwide scientific community and for the automotive industry. The reservoirs of hydrocarbons that are currently exploited are expected to be consumed within few decades and it is not guaranteed that new reservoirs will be found in the future. Furthermore global warming is strongly affected by ground vehicles which are included among the most important sources of pollutant gases in the atmosphere, therefore a valid way to deal with this problem is the introduction of the concept of eco-driving.

Eco-driving, for a thermal or hybrid vehicle, has been shown to be a very efficient driving technique to reduce fuel and energy consumption and CO_2 emissions into the atmosphere. ADAS can assist drivers in reducing emissions by decreasing their fuel consumption and limiting their exposure to traffic congestion and pollution. They can enhance driving behaviour and performance, leading to reduced carbon dioxide (CO_2) and nitrogen oxide (NO_x) emissions.[3] Additionally, certain ADAS can provide environmentally friendly routing choices, such as opting for the shortest or least congested route. These choices can help drivers lessen their travel time, distance, and emissions. ADAS systems can significantly impact fuel consumption and eco-driving. By improving driving efficiency and reducing fuel waste, ADAS systems can help drivers conserve fuel. For instance, adaptive cruise control (ACC) can regulate the speed and distance of the vehicle in line with traffic flow, thereby avoiding sudden acceleration and braking that consume more fuel. However, the influence of ADAS on fuel consumption varies depending on the driving style.

Furthermore, the demands for ADAS sensors for eco-driving have been quantified to evaluate fuel-saving effects. Consequently, ADAS systems can have a fundamental impact in decreasing fuel usage and encouraging eco-driving[4].

Eco-driving is a set of driving techniques that can help reduce fuel consumption and greenhouse gas emissions. Speeding, heavy acceleration, and hard braking can reduce fuel efficiency by 33%. Eco-driving techniques include driving conservatively, slowing down, and avoiding sudden acceleration and hard braking. For instance, reducing your speed by 5 to 10 mph can improve fuel economy by 7%–14% [5].

Energy management systems, which are increasingly implemented in modern vehicles such ad BEV (Battery Electric Vehicles), further enhance the efficiency of eco-driving. These systems analyze various factors such as real-time traffic conditions, terrain, and driving behavior to make intelligent decisions about energy usage. For instance, they can optimize engine performance, manage battery charging, and regulate energy flow to different vehicle components, reducing energy waste and improving fuel economy. Eco-driving refers to driving practices that aim to minimize fuel consumption and reduce carbon dioxide CO_2 emissions. Energy management in autonomous vehicles is a crucial aspect of their design and operation, it involves optimizing the energy consumption and efficiency of various systems within the vehicle. Developing intelligent control systems that can dynamically adapt energy management strategies based on real-time conditions and vehicle requirements is another approach. These systems can optimize energy consumption by considering factors such as traffic conditions, road topology, and driver behavior. The system can adjust the vehicle's speed and acceleration to minimize energy consumption during uphill driving or in heavy traffic. Driver behavior is another factor that can be considered by Intelligent Energy Management Control Systems. These systems can provide real-time feedback to the driver on their driving behavior and suggest energy-efficient driving techniques such as coasting or regenerative braking. Energy management systems are designed to monitor and control various vehicle components such as the engine, transmission, and accessories to ensure efficient operation. These systems can help reduce energy consumption by providing feedback to the driver on driving behavior and suggesting improvements. For example, they may recommend maintaining a steady speed, avoiding hard acceleration and braking.

ADAS systems, on the other hand, assist drivers in various aspects of driving and can contribute to eco-driving. For instance, features like adaptive cruise control can help maintain a consistent speed, which is more energy-efficient than frequent speed changes. Similarly, lane-keeping assist systems can help drivers stay in their lanes, reducing unnecessary lateral movements and improving energy efficiency.

Both energy management and ADAS are designed to minimise the generation of CO_2 and energy consumption. By optimizing energy usage and promoting fuel-efficient driving practices, these systems help reduce the fuel burnt and the resultant CO_2 emissions. Moreover, ADAS systems aid in this reduction by helping drivers avoid accidents and reducing traffic congestion, leading to more efficient traffic flow. In summary, energy management systems and ADAS systems are pivotal in promoting eco-driving and reduction in CO_2 emissions. These systems optimize energy usage, offer feedback and suggestions for fuel-efficient driving, and support drivers in various driving aspects resulting in reduced energy and fuel consumption and CO_2 emissions. [6]

Improving fuel efficiency plays a crucial role in global energy conservation. One approach to achieve this is by optimizing Powertrain efficiency, which involves maximizing the utilization of engine and battery power. This strategy is commonly referred to as the Optimal Energy Management Strategy.

The most important reason for using energy management strategies is related to the contribution of CO_2 reduction; fighting climate change is a priority for the EU.

Figure 1.2: EcoDriving Objectives

It has committed to a series of measurable objectives and taken several measures to reduce greenhouse gases. The EU emission target for 2030, set in the EU climate law, is at least a 55% reduction compared to 1990 levels. An upcoming package of new and revised legislation known as Fit for 55, aims to deliver the European Green Deal objectives and make Europe a climate-neutral continent by 2050. [7]

The following thesis work is part of a larger project, Spoke 2 of MOST-Centro Nazionale per la Mobilità Sostenibile, the aim of which is to create a prototype to verify the impact of adas systems on fuel consumption and eco-driving. The main step in carrying out this verification is the choice of sensors to be applied to the prototype.

However, analytical decision-making methods are used as a support tool for the selection of the sensor kit to be used on the vehicle under investigation. In particular, the method analysed is the Analytic Hierarchy Process (AHP) that is a decision-making technique used to helps individuals or groups analyze and prioritize multiple criteria and make rational decisions. The AHP method involves breaking down complex decisions into a hierarchical structure of criteria and alternatives. It allows individuals to compare and weigh the importance of different criteria and alternatives by pairwise comparisons using a subjective scale. The scale typically ranges from 1 to 9, with 1 representing equal importance and 9 representing extremely strong importance. The pairwise comparisons are then used to calculate relative weights for each criterion and alternative.

In addition to the pairwise comparisons, AHP also employs a consistency check to ensure the accuracy and reliability of the decision-making process. Consistency measures are used to determine if the pairwise comparisons are consistent with each other, and if they are not, adjustments can be made.

1.3 Overview of MOST – Spoke 2

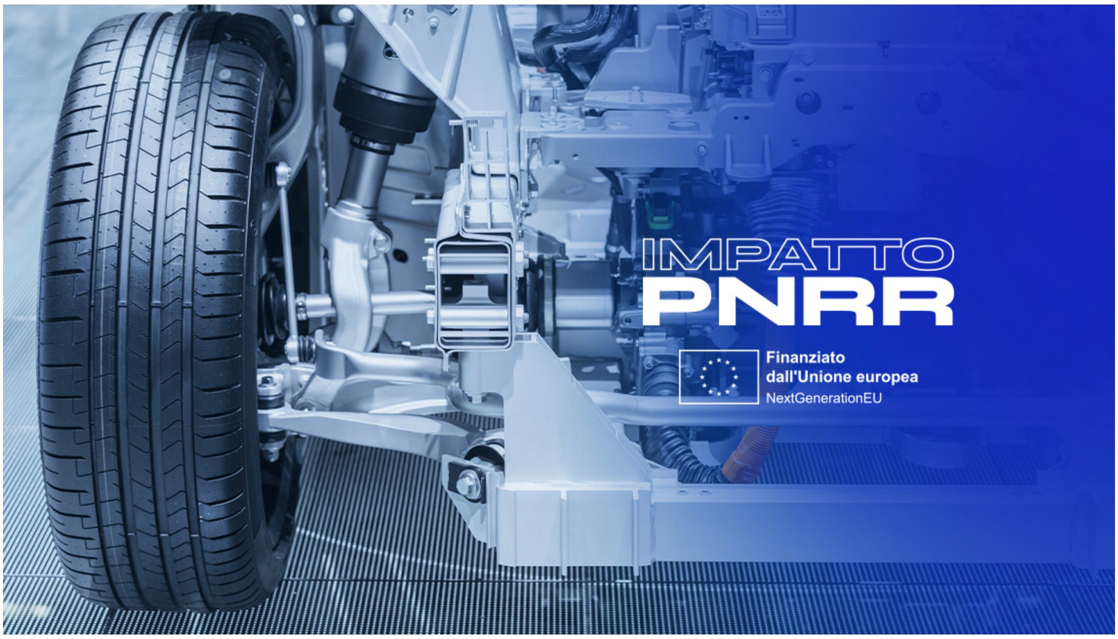


Figure 1.3: MOST Project

This thesis work was carried out through the collaboration between the Politecnico di Torino and Teoresi Group S.p.A., who are involved in the PNRR spoke 2 of MOST project, focused on industrial and green sustainability.

Teoresi Group is an international engineering services company that supports companies in creating projects with cutting-edge technologies: from electric and self-driving cars to nanotechnology applied to the medical field. With global expertise in engineering design, it focuses on developing the intelligence of machines, adding the 'brain' to devices that makes them smart. Since 1987, its goal has been one and the same: to put its wealth of talent and experience in the field of engineering design at the service of its customers, working alongside the customer from analysis to the conception of the final product, from the design idea to the prototype, from the prototype to the market with attention to the innovative aspects of each design challenge.

The PNRR (Piano Nazionale di Ripresa e Resilienza) consists of several spokes, which are interdisciplinary frameworks that focus on different areas of research and innovation. The goal of Spoke 2 of MOST is to create fresh vehicle ideas that can decrease the effect of the transportation system. The concept is that small, adaptable vehicles that are a part of data and charging networks will help to create a sustainable transport system that is environmentally, economically, and socially responsible. [8] The research will specifically explore novel designs for adaptable and secure electric cars that are light in weight, suitable for city transportation, and integrated into data and charging infrastructures. Additionally, the study will investigate the efficacy of high-efficiency hydrogen vehicles tailored for short to medium range deliveries.

Work is being carried out to achieve this goal through the development, optimisation and testing at vehicle level of:

- high-efficiency electric and hydrogen powertrains;
- innovative components and systems such as tyres, suspension, control
- vehicle integration in data and charging networks.

The primary focus will be on developing new concepts for reconfigurable and safe lightweight electric cars for urban mobility, as well as high-efficiency hydrogen vehicles for short to medium-range deliveries.

Spoke 2 of MOST (Sustainable Road Vehicle) focuses on road mobility, in particular on zero-emission electric and hydrogen vehicles, their interaction with recharging networks and data for fuel reduction, safety and reliability.

1.4 Thesis Outline

This thesis work is structured as follows:

- Chapter 2 focuses in particular on the problem of environmental perception and the operating principles of ADAS sensors.
- Chapter 3 focuses on the hardware architecture of the urban prototype and the introduction of the proposed method.
- Chapter 4 presents thesis results and achievements and a discussion on results and metrics used to evaluate the results.
- Chapter 5 is the conclusion chapter, with an overview on future works.

Chapter 2

Theoretical Background

The following chapter will address the issue of environmental perception which main functions are based on lane and road detection, traffic sign recognition, vehicle tracking, behavior analysis and scene understanding. This main topic will be divided into sections: scenario identification, object detection, and object tracking. [9] Next, this chapter will examine the operating principles of a range of ADAS sensors, including camera, LiDAR, radar, stereoscopic camera, and sonar. Additionally, the chapter will delve into select ADAS technologies, such as ACC and LKA, and mention techniques for sensor fusion, concluding the chapter.

2.1 Environmental Perception Problem

2.1.1 Scenario Identification

Environment perception is a critical function for autonomous cars since it supplies the vehicle with critical information about the driving environment, such as lane and road detection, traffic sign recognition, vehicle detection, and identification.

The process of perception in self-driving cars uses a combination of high-tech sensors and cameras, combined with state-of-the-art software to process and comprehend the environment around the vehicle, in real-time.

The principal uses of vision-based environmental perception in self-driving cars are identifying and detecting objects, estimating depth, and performing simultaneous localization and mapping (SLAM). The main visual sensors, categorised on the functioning of the camera, are: monocular, stereo, and RGB-D. The monocular camera features a singular camera, whereas the stereo camera employs multiple cameras. RGB-D is a sophisticated system that incorporates a variety of cameras capable of measuring the distance of each pixel from the camera while also capturing colourful images. [10]

The performance of environmental perception is one of the most important functions of autonomous driving. Some of the most important challenges in this phase are the need to ensure good robustness of the sensors to adverse weather conditions such as rain or snow and to ensure robustness and reliability of the perception system.

2.1.2 Object Detection

Object detection plays a crucial role in autonomous vehicles as it allows the vehicle to perceive and understand its surroundings by accurately identifying and locating objects such as pedestrians, vehicles, traffic signs, and barriers. Object detection entails two sub-tasks: localization, which determines an object's location in an image, and classification, which assigns a category such as pedestrian, vehicle, or traffic light to that object.

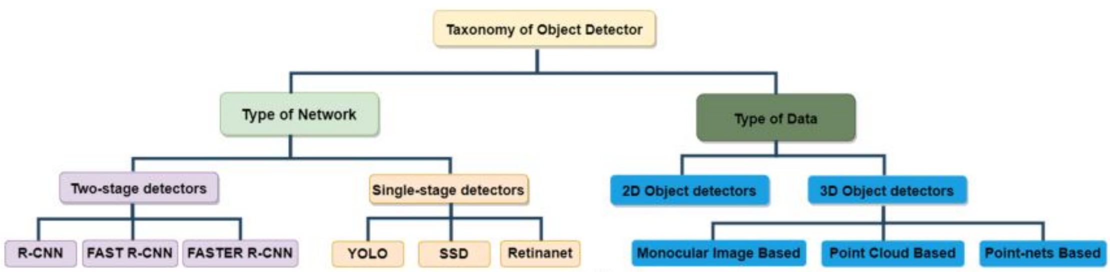


Figure 2.1: Taxonomy Of Object Detectors

Deep learning algorithms are widely used in autonomous vehicles to accurately and quickly detect objects. There are two categories of object detectors: single-stage and two-stage. Two-stage object detectors using deep learning employ a region proposal and object classification approach. During the region proposal phase, the detector suggests a set of regions of interest (ROIs) in the input image. The identified regions of interest (ROIs) have the highest probability of containing objects of interest. Next, the ROIs with the greatest potential for containing objects are selected, while the others are discarded. The two-stage detection algorithm, divides the detection process into two stages: region proposal and object classification. The stage of region proposal extracts numerous regions from the image that may hold objects, regularly referred to as regions of interest or region proposals. Single-stage object detectors implement a solitary feed-forward neural network that produces bounding boxes and simultaneously categorises objects. These detectors are faster than their two-stage counterparts, but tend to lack precision. [11]

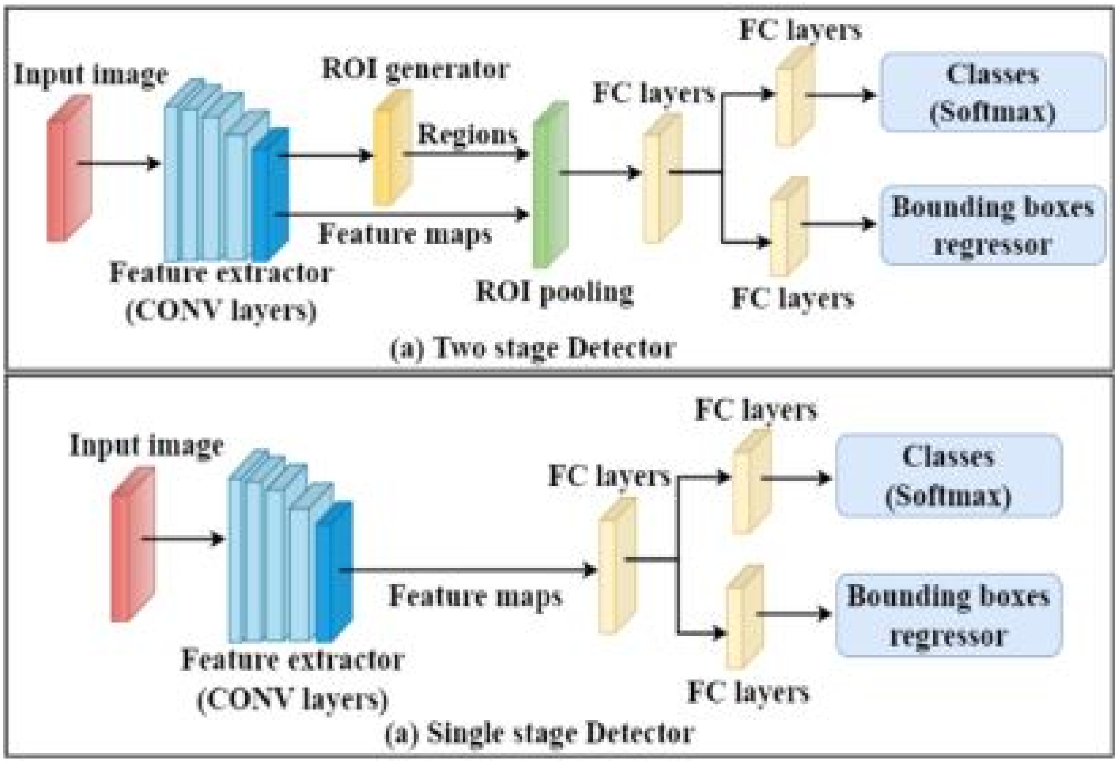


Figure 2.2: Two-stage vs Single stage object detector diagram

During the object categorisation stage, it is vital to establish if any objects exist in each considered box. Achieving this involves the creation of a classifier which accepts the candidate box as input and produces a probability value that shows whether the box contains an object or not. To ensure safe driving, it is imperative to detect, recognise and track all objects on the road and in the surrounding area for proper path planning. The object is marked by the system via a compact 3D bounding box that determines its location (x, y, z), size (width, height, depth), and orientation (α_x,α_y,α_z) concerning the 3D scenery and the vehicle's position. Lastly, the system ascertains the object's category as one of the following: vehicle, pedestrian, cyclist, or unknown. [12]

2D object detectors commonly use 2D image data for identifying objects. This sensor fusion approach includes bounding boxes with four degrees of freedom (DOF). The depth of an object is determined by analyzing data from cameras, LiDAR or radar. On the other hand, 3D object detectors utilize various techniques such as frustum pointnets and point clouds to achieve real-time object detection and produce 3D bounding boxes. Point cloud networks have the capacity to process 3D data directly. However, some networks choose to adopt 2D to 3D elevation techniques to compensate for the loss of information due to the considerable complexity and computational expenses involved. [11]

2.1.3 Object Tracking

Object tracking is the process by which an algorithm monitors the movement of an object. Its objective is to estimate or predict the positions and other relevant information for moving objects depicted in a video. The process also entails the ability to estimate or predict the position of a target object in each consecutive frame once the initial position of the target object is established. This requires determining the state of the target object in the scene based on previous information. After detection, velocity estimation should be assigned to each object. The algorithm tracks and follows the motion path of each detected object in three-dimensional space by tracing its angular velocity across image frames and its radial velocity across depth-image frames. This enables the system to distinguish between static and dynamic objects. The method generates a 3D trajectory motion for dynamic objects that will be utilised for path planning and crash prevention. Effective monitoring of the movement of other vehicles on the road is critical to autonomous driving. One crucial factor to be considered is the escalation of braking distance, which increases exponentially with vehicle acceleration. Accurate prediction of future object paths is essential for early detection, which is facilitated through Object Tracking. By combining tracking and traffic participant classification, the vehicle can adjust its speed accordingly.[13]

The Kalman filter is a valuable resource for tracking objects, as it allows for precise detection and monitoring of autonomous vehicles, predicting future positions based on velocity and past movements. Widely used in the automotive industry, Kalman filters are recursive algorithms used to determine the current state of a process via measurements taken throughout the process itself. The extended Kalman filter (EKF) is especially beneficial for monitoring dynamic states, namely the positions and velocities of objects in an automated driving situation. These objects comprise automobiles, pedestrians, bicycles, and stationary obstacles. The EKF has the capability to simulate the progression of a state that adheres to a non-linear motion model, and it is proficient in handling velocity and acceleration fluctuations.[14][15]

Tracking algorithms are more efficient than detection algorithms. They utilize data from the previous frame to forecast the object's position in the current frame and then conduct a small search around the anticipated location to precisely locate the object. Additionally, tracking algorithms offer more information, such as the movement path of a specific object, which detection algorithms cannot provide. [16][17]

2.2 Working Principles of ADAS sensors

An advanced driver assistance system (ADAS) is a set of technologies that assist drivers while driving. Automated technologies, such as sensors and cameras are used in order to detect nearby obstacles or driver distractions. The collected data is sent to the vehicle control units to develop an action to be taken in response to the current situation. The functions of ADAS can be broadly divided into two main categories: safety features and comfort features. Convenience features provide alerts and tips to advise drivers on how to approach safe driving. Safety features are designed to respond to dangerous situations. ADAS sensors can be divided into four main categories: cameras, radar, LiDAR and ultrasonic. The different sensors have advantages and disadvantages considering capacity, cost and packaging.[18]

2.2.1 Camera

Image sensors work by converting light into electronic signals that can be processed by a computer to create an image, so they are an essential component of modern vehicles. In ADAS applications, image sensors are used to capture images and provide data for various systems that make driving safer and more efficient. The two main image sensor technologies used in cars today are charge-coupled device (CCD) and complementary metal-oxide-semiconductor (CMOS). Although they both use photodiodes, their manufacturing processes and signal-reading techniques are different.

A charge-coupled device (CCD) image sensor comprises an array of capacitors, with each capacitor containing an electric charge corresponding to the pixel's light intensity. The capacitors are interconnected through a control circuit, and the final capacitor releases its charge into a charge amplifier, transferring data in a bucket-brigade fashion. On the other hand, a complementary metal oxide semiconductor (CMOS) image sensor features a photodiode and a CMOS transistor switch for each pixel, enabling separate amplification of pixel signals. The matrix of switches facilitates direct and significantly faster access to pixel signals compared to a CCD sensor. [19]

CCD vs CMOS

CMOS (Complementary Metal-Oxide-Semiconductor) sensors are generally preferred over CCD (Charge-Coupled Device) sensors for several reasons such as:

- Lower Power Consumption: CMOS sensors consume significantly less power than CCD sensors, making them more energy-efficient. This is particularly advantageous for battery-powered devices and applications where power efficiency is crucial.

- Lower Cost: CMOS sensors are less expensive to manufacture compared to CCD sensors. The manufacturing process for CMOS sensors is compatible with standard silicon production lines, resulting in cost savings.

- Faster Processing: CMOS sensors offer faster signal processing capabilities compared to CCD sensors. This makes CMOS sensors ideal for applications that require fast image acquisition and real-time processing.

- Digital Output and Flexibility: CMOS sensors provide digital output and can be controlled at the pixel level, allowing for more flexible imaging capabilities. This enables specialized imaging techniques such as partial scanning or specific control processes for different segments of the sensor.

- Wider Spectral Sensitivity: CMOS sensors can be fabricated using different semiconductor materials, allowing for sensitivity to wavelengths beyond the visible spectrum. This makes them suitable for applications that require imaging in different spectral ranges.

The selection between CMOS and CCD sensors relies on the specific application and user requirements. While CCD sensors offer advantages such as higher quantum efficiency and generally lower noise, the lower power consumption, cost-effectiveness, faster processing, and flexibility of CMOS sensors have made them the preferred choice in numerous applications, including digital cameras, mobile devices, and other imaging systems.[20][21]

Pinhole Camera Model

The pinhole camera model is a simple yet fundamental concept in the field of computer vision. It describes the mathematical relationship between the coordinates of a point in three-dimensional space and its projection onto the image plane of an ideal pinhole camera. In this model, the camera aperture is represented as a single point, and no lenses are used to focus light. The model does not account for factors such as geometric distortions or blurring caused by lenses, and it provides only a first-order approximation of the mapping from a 3D scene to a 2D image. Despite its limitations, the pinhole camera model is widely used in computer vision and computer graphics as it provides a reasonable description of how a camera captures a 3D scene. [22] [23]

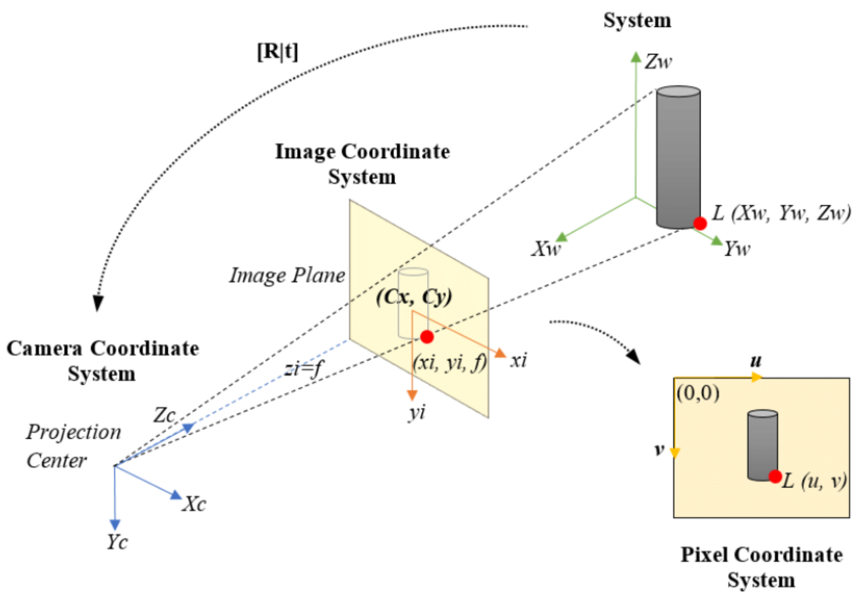


Figure 2.3: Pinhole Camera Model

Monocular Camera

One of the main sensors in the topic of perception is the camera, however it is also one of the most vulnerable in adverse weather conditions. A camera in the rain can be easily damaged by the presence of a drop of water on the emitter or lens. Image distortion compromises the immediate loss of input data and its correct processing. Even snow, could affect the camera similarly to rain especially when snowflakes touch the lens and immediately melt into an icy slush. Heavy snow may offset the intensity of the image and obscure the perimeter edges of a certain object in the image or video, causing detection error. Furthermore, the snow stuck to the road surface can cover the lane lines, preventing the sensors from reading the signal and therefore the perception problem is stopped immediately. An important aspect regarding adverse weather conditions is related to the exposure of cameras and LiDAR to strong light, the resulting image is a large shadow around the light source. High illumination can significantly reduce the visibility of a camera, and glares reflected by glossy surfaces can make exposure selection challenging. Another related issue is the reflection off reflective surfaces, which can confuse the camera and lead to false signals due to the lack of depth perception. [24]

Stereoscopic Camera

A stereoscopic camera is a specialized type of camera that utilizes multiple lenses, each with its own image sensor or film frame. By imitating human binocular vision, this camera is capable of capturing three-dimensional images, a technique called stereo photography. Stereo vision, which involves the use of two or more machine vision cameras, is a machine vision method that allows for comprehensive 3D measurements across the entire field of view. Its foundation lies in the concept of triangulation, similar to how human vision perceives 3D objects, by analyzing rays from multiple viewpoints. To determine stereo disparity, two 2D images taken from different positions are utilized, and the correlation between these images can be employed to generate a depth image. [25]

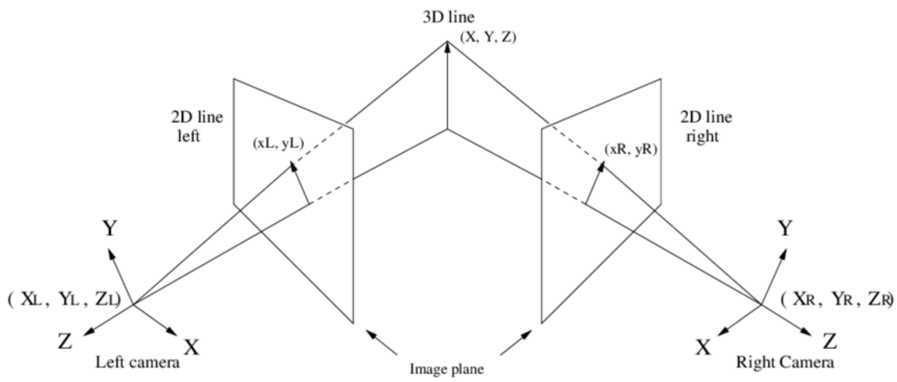


Figure 2.4: Stereoscopic Camera Triangulation

The typical distance between lenses in a stereo camera is approximately the same as the distance between human eyes, known as the intra-ocular distance, measuring around 6.35 cm. Stereo cameras have various applications such as creating stereoviews, 3D movies, and range imaging. Machine vision stereo vision is considered a passive technology as it doesn't require artificial illumination to function. However, certain stereo vision applications may benefit from artificial illumination or structured light sources, known as active stereo, to enhance visibility. Stereo vision is particularly suitable for applications with a wide field of view and outdoor usage such as automotive sector. [26] [27]

Monocular Camera vs Stereo Camera

In automotive applications, particularly in the realm of advanced driver assistance systems (ADAS), both monocular and stereoscopic cameras have proven to be useful. Monocular cameras, which are cost-effective and consume less power than alternative sensors, are an attractive option for ADAS applications. Monocular cameras excel at precisely identifying lanes, pedestrians, traffic signs, and other vehicles within the car's path. However, it is noteworthy that the monocular system demonstrates decreased reliability when assigned to calculate the environmental 3D perspective in contrast to the stereoscopic systems. Stereo cameras use two cameras to capture images and simulate human binocular vision, providing depth perception and 3D images. Stereo cameras are used to detect the lane's width and the proximity of an object on the road. Stereo cameras are capable of capturing the three-dimensional world and providing depth perception through dual-lenses. However, using stereo cameras in autonomous vehicles may encounter challenges due to the computational difficulty in finding correspondences between the two images. Monocular cameras are currently the primary computer vision solution for ADAS. Stereo cameras are computationally difficult to find correspondences between the two images, but they can improve functions such as Auto Emergency Braking (AEB) and Adaptive Cruise Control (ACC).

When considering the use of stereoscopic cameras, it is important to acknowledge several disadvantages. Firstly, active stereo systems may lose their effectiveness in direct sunlight and areas with high interference from the same external light source technology used. Stereo disparity in a camera can be found by using two 2D images taken from different positions, and the correlation between the images can be used to create a depth image. However, to find correlations, the two images need to have sufficient details and texture or non-uniformity. Thus, stereo vision is not suitable for applications with a low-textured indoor scene. Moreover,stereo vision relies solely on ambient light and is thus most suitable for outdoor usage with good lighting conditions. In low light or scenes with minimal textures, capturing stereo features becomes challenging. Furthermore, the cost of stereo cameras can be high, particularly those equipped with an infrared projector or other types of light sources for visibility enhancement. Synchronization issues between the cameras can also occur, resulting in skewing between shots. Lastly, occlusions, plain textures, and edge detection can pose difficulties for stereo cameras, leading to excessive noise and reduced precision in the resulting disparity map. [28] Currently, original equipment manufacturers (OEMs) are appraising mono and stereo cameras for diverse applications. Mono-cameras, which are more affordable and require lower computational demands, presently dominate as the primary computer vision solution for advanced driver assistance systems (ADAS). Mono-cameras demonstrate impressive performance in activities like lane identification, pedestrian detection, recognizing traffic signs, and detecting other vehicles in the car's course with high precision. Nevertheless, the monocular system's capacity to estimate a comprehensive 3D representation of the environment is slightly restricted. In contrast, stereo cameras can capture the globe in 3D, offer depth perception through dual lenses, and thus have a greater potential for developing a 3D world model. Considering these challenges, LiDAR and RADAR emerge as advantageous alternatives to cameras. Their advantage lies in their capability to excel in depth perception applications and create 3D models of the vehicle's surroundings, surmounting some of the constraints presented by camera-based systems. [29] [30]

2.2.2 LiDAR

Lidar (Light Detection and Ranging) is a remote sensing technology that leverages laser light to measure distances and construct maps of the environment. Lidar technology finds application in many fields, including autonomous vehicles. In the automotive industry, Lidar is used to enable autonomous vehicles to "see" by generating and measuring millions of data points in real-time, creating a precise map of its ever-changing environment. Lidar technology helps the vehicle sense and understand its surroundings by using laser pulses to create 3D mappings of its environment, including objects like buildings, roads, and other vehicles. It's used in combination with other sensors, such as radar and cameras, to provide a more comprehensive view of the vehicle's surroundings. Lidar technology is becoming increasingly important in the development of self-driving cars as it provides a high level of accuracy and precision in mapping the environment, which is critical for the safe and efficient operation of autonomous vehicles.[31][32]

Most LiDAR systems operate in near infra-red region of electromagnetic spectrum, i.e. around 1000 nm. LiDAR instruments can rapidly measure at a high sampling rate, (from 10 Hz in the automotive industry up to 150 kHz in aerospace missions). The resulting measurement is a densely spaced network of highly accurate points, that is called three-dimensional point cloud.

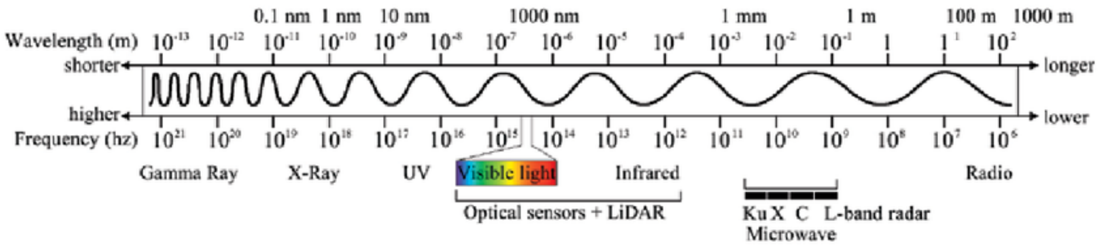


Figure 2.5: Lidar wavelength

An important distinction can be made between mechanical LiDAR and solid-state LiDAR.

Mechanical LiDAR uses a spinning mirror to sweep the laser beam, processing the returning laser pulses to produce a 3D map of the environment. It is commonly used in mapping, surveying, and robotics and provides high-resolution data. However, it may be bulkier and less dependable than other LiDAR types, such as solid-state.

Solid-State LiDAR employs a solid-state laser and photodetector for emitting and detecting laser pulses, making it a compact and reliable LiDAR sensing solution. The laser emits light pulses that bounce off objects and return to the photodetector, which calculates the elapsed time for the light to travel there and back. This information is utilised to generate a 3D map of the environment processed by the LiDAR computer. This type of LiDAR is often utilized in autonomous vehicles, robotics, and applications requiring real-time, precise environmental data.

Mechanical LiDAR

The laser emission is in the infrared spectrum, typically with a wavelength of around 905 nanometers or 1550 nanometers.

The effectiveness of Lidar systems in various applications is largely dependent on their wavelength. A Lidar system utilizes laser light to both measure distances and construct 3D maps of objects and surrounding environments. Typically, the wavelength of Lidar is situated in the near-infrared spectrum, with a range of 750 nm to 1.5 µm. At present, most high-tech Lidar systems use one of two wavelength options - 905 nm or 1550 nm. The 905 nm wavelength finds common usage in automotive Lidar systems due to its balanced features in terms of range, resolution, and cost. Some Lidar systems prefer the 1550 nm wavelength as it remains comparatively unaffected by atmospheric interference and offers a longer range. Nevertheless, the 1550 nm wavelength incurs higher expenses and necessitates greater power consumption than the 905 nm wavelength. The selection of wavelength is reliant upon the specific requirements of the application, encompassing range, resolution, cost, and atmospheric interference.

Selecting an appropriate wavelength of laser should have a comprehensive consideration of atmospheric windows, eye-safety requirements, and cost. The 850–950 nm near-infrared (NIR) and 1,550-nm [short-wave infrared (SWIR)] lasers are mostly utilized because of their popularity in industry. Either a low-price diode laser or a more powerful fiber laser at a wavelength of 850–950 nm or 1,550 nm is easily purchased from the market. The maximum power permitted by eye-safety standards for a 1,550-nm laser is higher than that of lasers in the 850–950-nm range, which means a larger range could be achieved. However, expensive indium gallium arsenide (InGaAs)-based photodiodes are required to detect laser returns at 1,550 nm. The efficiency of InGaAs-based photodiodes is lower than that of mature Si ones for NIR lasers. In addition, the atmospheric water absorption for 1,550 nm is stronger than that of 850–950 nm; therefore, lidar systems at NIR wavelengths (905 nm, for instance) are still commonplace. There are still challenges to overcome, such as the high cost of LiDAR systems and their susceptibility to adverse weather conditions. As the technology advances, LiDAR is expected to play an important role in the development of self-driving cars and transform the way people move and travel. [33] [34]

Solid State LiDAR

Solid-state LiDAR and Mechanical LiDAR are two different types of LiDAR technology. Solid-state LiDAR uses a solid-state laser and a photodetector to measure distance, and it is based on multi-beam technology that includes point cloud and 2D images. It integrates all components on a single chip, making it smaller, lighter, and more durable than traditional LiDAR systems. It typically uses a single laser beam to illuminate the scene in front of it and a time-of-flight (ToF) sensor array to capture the 3D data that is returned. Solid-state LiDAR has few to no moving parts, which makes it less expensive and more reliable than a typical scanning LiDAR sensor. However, it cannot capture 360° data like a scanning LiDAR sensor can. Solid-state LiDAR incorporates technologies like MEMS (Microelectromechanical systems) or beam steering that can manipulate laser beam to scan a much wider field of view that a typical ToF sensor. On the other hand, mechanical LiDAR uses the technology of MEMS to drive the rotating mirror and reflect the laser beam to point in different directions. It has a processor, usually an FPGA (Field Programmable Gate Arrays), that controls the motor (allows it to achieve 360-degree). However, it can only rotate at a uniform speed, which makes it unable to perform fine operations. Mechanical LiDAR has a higher cost and more moving parts that a solid-state LiDAR. In summary, solid state lidar is smaller, lighter, and more durable than a mechanical LiDAR, and it has fewer moving parts, making it less expensive and more reliable. However, it cannot capture 360° data like mechanical LiDAR can.[35]

2.2.3 Radar

Radar is an essential component of an Advanced Driver Assistance System and is proving to be a valuable sensor for enabling intelligent safety features in modern vehicles. Using electromagnetic waves, radar technology detects objects in the environment and accurately measures their distance, speed and location. Automotive radars detect the speed and distance of objects in the vehicle's vicinity. A car radar consists of a transmitter and a receiver. The transmitter sends out radio waves that collide with an object and bounce back to the receiver, which determines the distance, speed and direction of the object.

The bandwidth of automotive radar refers to the range of frequencies that a radar sensor can transmit and receive. This bandwidth is critical in determining the capabilities and performance of the radar system. In automotive applications, radar sensors operate in the microwave frequency range, typically from a few gigahertz (GHz) to around 77 GHz. The wider the bandwidth, the higher the resolution and accuracy of the radar system. A wider bandwidth allows more precise detection and measurement of objects in the radar's field of view, enabling improved object detection, distance measurement and speed estimation. A wide bandwidth is therefore essential for the reliable and efficient operation of radar-based automotive safety features such as adaptive cruise control, collision avoidance and blind spot monitoring systems.

Based on frequency, the automotive radar market is segmented into 24 GHz, 77 GHz and 79 GHz. 77 GHz radars operate in the 76-81 GHz frequency range and are used for short-range applications such as collision warning and adaptive cruise control.[35]

A Radar sensor is ideally suitable for distance (range) measurement since it is superior to optical system due to their insensitivity to poor weather condition. Radar measurement of distance is based on timing interval between transmission and reception of the radar signal. As a direct measure of time interval between transmission and reception is complicated for radar sensor, the concept of a Frequency Modulated Continuous Wave is implemented (FMCW). FMCW radar compares the frequencies of transmitted and echo waves to determine range information. According to the FMCW basic principle the distance is computed as:

$$D = \frac{c \cdot |\lambda - \lambda^{'}|}{2 \cdot \frac{df}{dt}} \tag{2.1}$$

Where $|\lambda - \lambda^{'}|$ is the change in frequency of the reflected radio signal, c is the speed of light and $\dfrac{df}{dt}$ is the rate of change of frequency.

A basic radar has the following components:

- Gunn Diode oscillator: electronic semiconductor component that generates microwave oscillation when subjected to strong electrical field. By applying a suitable voltage, frequency can be varied. Thus, they are called as voltage-controlled oscillators. Radar frequency for automotive are now in the range of 77 GHz while 24 GHz radar are used in older radar technologies.

- Driver circuit and antenna feed: printed circuit board that divides electrical power between transmitter and receiver antennas.

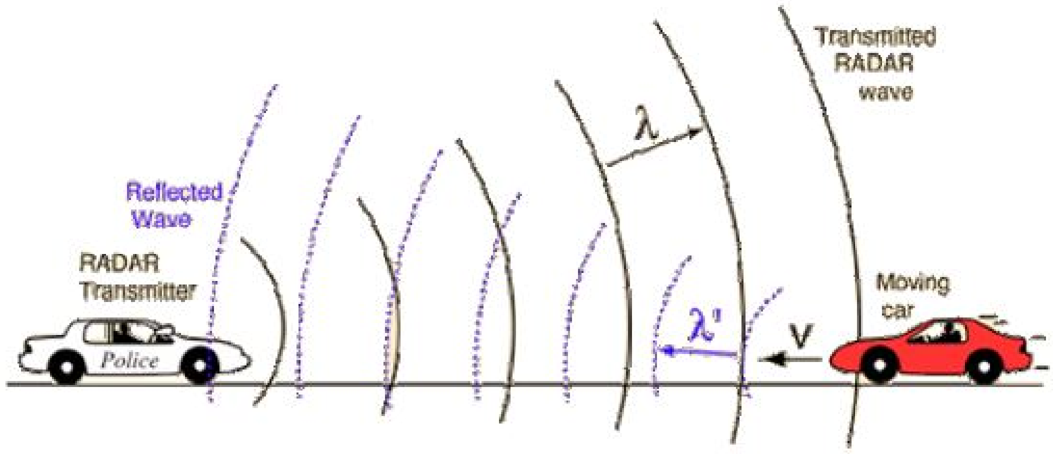


Figure 2.6: Radar Doppler

- Mixer: non linear-circuit that creates new frequency signal from two or more signals applied to it.
- Radome (radar dome): the cover apparatus with a small thickness, properly sealed along with other radar components.
- Radar antenna: usually planar antennas made of microstrip patches in embedded printed circuit boards.
- Preamplifiers: to sense echo signals at high distances.
- Lens and other electronic components: to process the signals.

A radar measurement is made of two main measurement: a Range Measurement and a Doppler Measurement. Range Measurement simply returns a signal with the same shape but delayed by the "time flight". Doppler Measurement exploits the Doppler effect, and it is the main measurement performed with a radar. It measures the target radial velocity of objects using multiple chirps. A chirp is a signal in which the frequency increases (up-chirp) or decreases (down-chirp) with time. The chirp period is short enough such that the target only moves fractions of a wavelength from chirp to chirp. At 77 Ghz, the wavelength is around 4 mm.

4D Radar

4D imaging radar technology is a highly advanced sensor system with superior resolution and range compared to conventional 3D radar systems. Its accuracy in determining the height of objects provides numerous benefits. This technology plays a vital role in enhancing Advanced Driver Assistance Systems (ADAS), especially for Level 2 and 3 functionalities, and is a pivotal enabler for achieving automation at Levels 4 and 5. While traditional radar systems excel in scanning the road horizontally and providing information on distance, direction and relative velocity (Doppler), the newer 4D imaging radar introduces a vertical dimension, enhancing its capabilities. These systems are referred to as "imaging radar," earning this label due to the richness of the data they capture. By incorporating both horizontal and vertical information, 4D imaging radar can identify multiple reflection points. When mapped in meticulous detail, these data points form an array that illustrates the sensor's aptitude for furnishing exhaustive information across both dimensions. [36] [37] These radars use mmWave sensors that operate at 76-79 GHz frequencies, to provide high resolution information about the environment.

MIMO radar is an advanced version of phased array radar, utilising digital receivers and distributed waveform generators across the radar aperture. The MIMO radar system uses multiple transmit antennas to send out mutually orthogonal signals. These unique waveforms can be isolated from each receive antenna by a set of matched filters. The echoes are re-linked with their source, resulting in a significantly enlarged virtual receive aperture. This enhancement strengthens the spatial resolution, Doppler resolution and dynamic range. MIMO radar has a remarkable ability to achieve low-probability-of-intercept radar characteristics, making it particularly valuable for certain applications. Each transmitting antenna independently emits a unique waveform, with no interference from other antennas. The receiving antenna captures these signals, allowing for reassignment of echo signals to the transmitter. This enables MIMO radar to efficiently detect multiple objects simultaneously, even if they are located at identical distances and speeds from the antenna.[38]

Another important aspect is related to the determination of the azimuth angle in imaging radar for several reasons. One significant application is target localization, as it allows for precise identification of a target's position in the radar point cloud. This is exceptionally vital for surveillance, target tracking, and mapping applications. Furthermore, it is imperative to estimate the azimuth angle in order to calculate the radar cross-section (RCS) of a target, which determines its reflectivity. Precise determination of the angle is necessary for thorough analysis and interpretation of radar echoes, aiding in target identification, object discrimination, and classification. The estimation of azimuth angle also holds crucial importance in the signal processing algorithms utilized in imaging radar systems. Compensating for distortions such as beamwidth effects, antenna patterns, and Doppler shifts, allows for effective signal correction, enhancement, and improvement of array point quality. By integrating azimuth angle information with range and elevation measurements, it is possible to generate comprehensive 3D representations of scenes and terrains. This approach is beneficial in areas such as remote sensing, topographic mapping, and disaster management.[39] With the improvement in the intelligence of autonomous vehicles, the demand for the amount of information provided by millimeter-wave radar is higher and higher. As a result, in recent years, the concept of high-resolution imaging radar is brought up in the field of automotive radar. The high-resolution imaging radar provides relatively dense millimeter-wave radar 4D point clouds based on the multiple-input multiple-output (MIMO) technology. The radar data not only contain the height information of the target but also provide more dense point clouds of the target. Thus, a higher level of information can be obtained to be applied to classification and semantic segmentation. Unlike the LiDAR point clouds, the radar point clouds are generated from the detector of radar signal processing procedure. Compared to the LiDAR point clouds, the point clouds of radar are relatively sparse. For automotive radar signal processing, the density of the point clouds usually relies on the resolution of the point cloud and the performance of the detector.[40]

As reported in Figure 2.7, it is possible to distinguish:

a) LiDAR point cloud;

b) Radar point cloud;

c) Top view of the LiDAR (green) and Radar (red) point cloud;

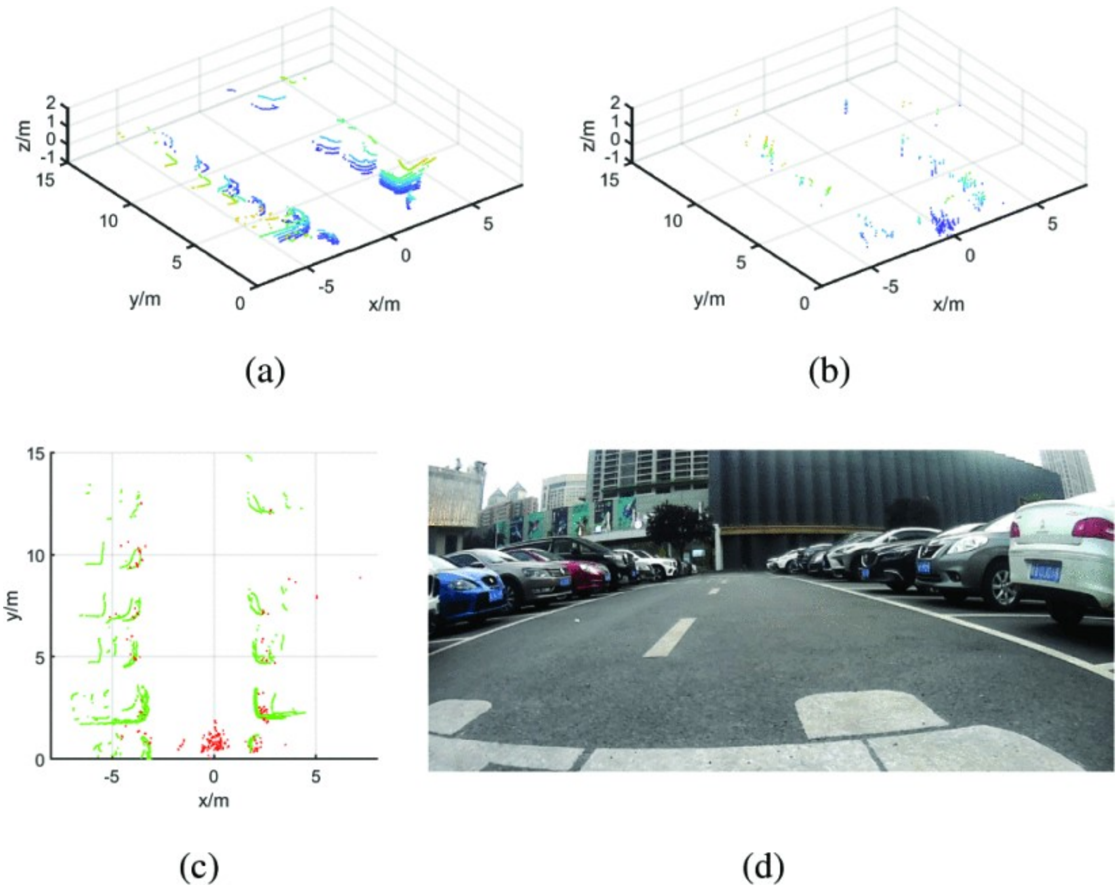


Figure 2.7: 4DRadar Point Cloud

d) Corresponding scene in the parking lot. For the same target, compared to LiDAR point clouds, radar point clouds are relatively sparse.;

A variety of signal processing tools, e.g., the fast Fourier transform (FFT), short-time Fourier transform, filtering, and beamforming, have been adopted in automotive radar to obtain target features, such as a micro-Doppler spectrum of pedestrians and a range–Doppler spectrum of the surrounding environment. Machine learning algorithms and deep neural networks have also been applied in automotive radar for target recognition and classification.

A FMCW waveform, also referred to as a chirp, is a complex sinusoid whose frequency increases linearly with time $t \in [0, T]$, i.e., $f_T(t)=f_c+(B/T)t$, where B is the signal bandwidth and f_c is the carrier frequency. FMCW radar transmit chirps

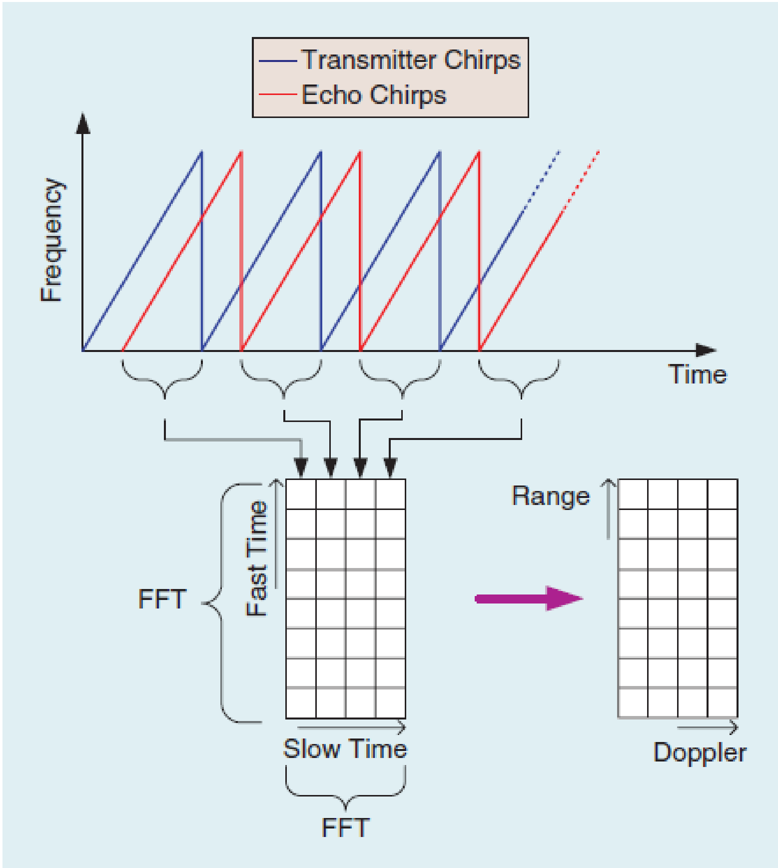


Figure 2.8: The FMCW radar chirps

in a periodic fashion, with a period referred to as the pulse repetition interval (PRI). The target eco ar the radar receiver contains a delayed and attenuated copy of the transmitted chirp. For a target at range R, moving with a radial speed of v, the delay equals $\tau = (\frac{2}{R+vt})/c$, where time t spans multiple periods and c is the speed of light. The receiver signal is mixed with the transmitted chirp, which results in a complex sinusoid known as the beat signal. The beat-signal frequency equals f_b=f_R+f_D, where f_R=$2RB/(T_c)$ is the range frequency and $f_D = (\frac{2v}{c})f_c$ is the Doppler frequency. The estimation of the beat frequency is implemented in the digital domain, after the sampling of the beat signal. In automotive scenarios, the maximum detectable range, R_{max}, is hundreds of meters. It holds that $2R_{max}/c \ll T$, and thus $f_R \ll B$. Since it typically holds that $f_D \ll f_R$, the beat frequency is much smaller than B, and therefore a low-speed analog-to-digiral converter (ADC) can be used to sample beat signal. The time during one period or chirp is usually referred to as the fast time, while the time across multiple periods or chirps is referred to as the slow time. In automotive scenarios, $f_D \ll f_R$, therefore, f_D can be taken as constant within each chirp. Thus, by applying FFTs on the sampled beat signal along the fast time, one can identify f_R based on which of the target's ranges can be obtained as $R = cf_R T/2B$. To obtain the target's Doppler frequency, a second FFT operation is subsequently carried out along the slow time. The pulse repetition frequency (PRF) is $f_{PRF} = 1/T_{PRI}$. To avoid Doppler ambiguity, it is desired that $f_{PRF} \geq 2f_D$. Thus, the maximum unambiguous detactable radial speed of FMCW radar is $v_{max} = c/(4f_c T_{PRI})$. The application of these two FFTs is equivalent to a 2D FFT to the beat signal in the fast and slow times, and the result is called the range-Doppler spectrum. Range and Doppler detection can be performed using conventional thresholding-based methods applied to the 2D range-Doppler spectrum, such as the constant false alarm rate detector or the recently proposed deep neural network network-based detector. [41]

2.3 Sensor Fusion Techniques

Sensor fusion entails integrating inputs from varied sources like Radars, LiDARs, and Cameras to construct a unified model or representation of a vehicle's surrounding environment. The resulting model achieves greater accuracy by capitalising on the varying strengths of the different sensors. The data derived from the fusion of sensors serves as a crucial input for vehicle systems, facilitating more intelligent operations and improved perception by utilising partially overlapping fields of view. In situations where numerous radar systems are monitoring the surroundings, several sensors may simultaneously detect objects. The 360-degree perception software analyses these observations to merge and overlap detection information from multiple sensors, significantly improving the accuracy and dependability of object detection in the vehicle's vicinity. This enhances the precision and trustworthiness of the environment representation.[42] Sensor fusion is crucial for several reasons, including enhanced accuracy, robustness, and extended coverage.

Various studies, combined with practical use, indicate that the use of a single sensor is insufficient to satisfy environmental awareness. Sensor fusion technology is useful for improving the reliability and accuracy of measurement and reduces the uncertainty of results. The integration of data from both LiDAR and Camera sensors, known as sensor fusion, enhances the accuracy and robustness of environmental perception. Specifically, the Camera identifies and classifies objects, whereas the LiDAR measures the precise distance of objects. By combining information from both sensors, the decision-making stage benefits from added redundancy and certainty.

There are various sensor fusion techniques used to efficiently combine data from multiple sensors, which differ in complexity, computational requirements and level of accuracy. This section examines three main categories of sensor fusion techniques: centralized fusion, decentralised fusion and distributed fusion. Centralized fusion is a method of sensor fusion that involves directing sensor data to a central processing unit or computer. The computer then combines and analyzes the information to generate an overall estimate of a system's state. For example, in a self-driving car fitted with various sensors, all sensor data is sent to a central computer, which processes the data to determine the vehicle's position, velocity, and surrounding obstacles. One common technique used in centralized fusion is the Kalman filter, which processes data from all sensors within the central processing unit to update the system's state estimate. However, centralized fusion has some drawbacks, such as the potential for data processing bottlenecks and greater susceptibility to failures in the central processing unit. Distributed fusion is an alternative to centralized fusion that addresses its limitations in terms of robustness, privacy, and low latency. The sensor fusion process is distributed across multiple nodes or processing units, each responsible for processing the data from a subset of sensors. The individual estimates generated by these nodes are then combined to produce the overall system state estimate. This method can be more scalable and resilient compared to centralized fusion, as it avoids potential bottlenecks and single points of failure associated with central processing units Hybrid fusion is a sensor fusion approach that combines advantages of both centralized and distributed fusion. In this approach, multiple levels of data fusion are employed, with some processing occurring locally at the sensor level or within sensor clusters, and higher-level fusion taking place at a central processing unit. [43]

2.4 ADAS Technologies

Driver assistance systems (DAS) were developed aiming at the development of systems that are designed to assist and improve the comfort level of the driver while driving. With the advancements in DAS technologies, the focus got shifted on to the increased level of safety of both the driver and pedestrians. Such advanced driver assistance systems (ADAS) refer to electronics, light-based, or sound-based systems that are integrated together to the development of technologies that automate, facilitate, and improve systems in the vehicles. The primary objective of ADAS technologies is to enhance factors such as safety management and stress-free automated driving for drivers. In order to facilitate these ADAS technologies, a suite of sensors is paramount. Vision sensors, LiDAR sensors, RADAR sensors, and ultrasonic sensors are examples of sensor types being implemented in a similar manner. The vision-based sensors make decisions based on the images captured. The acquired images undergo pre-processing and segmentation to detect features within them. Subsequently, these segmented images are utilized for identification and classification via several machine learning algorithms and neural networks. Additionally, this paper will explore the concept of NEXT-GEN ADAS, whereby the sensor suite is combined with advanced communication technologies, like vehicle-to-everything (V2X) communication. ADAS is a significant factor in the advancement of autonomous driving. However, several challenges are associated with ADAS technologies, including changing environmental conditions, resource-constrained systems, and security and geospatial constraints that require attention.[44]

Some of the ADAS technologies used in modern cars are illustrated in Figure 2.9. The driving assist functions are classified into two categories, longitudinal and lateral controls; in longitudinal dynamics an example is the Adaptive Cruise Control (ACC) while in lateral dynamics the Lane Keeping Assistant System (LKAS) is a fundamental function. Other ADAS technologies are represented by the following features.

2.4.1 Lane Departure Warning LDW

LDW continuously monitors the position of the vehicle on the lane markers on either side. If the vehicle comes within a certain distance of a marker, the driver is

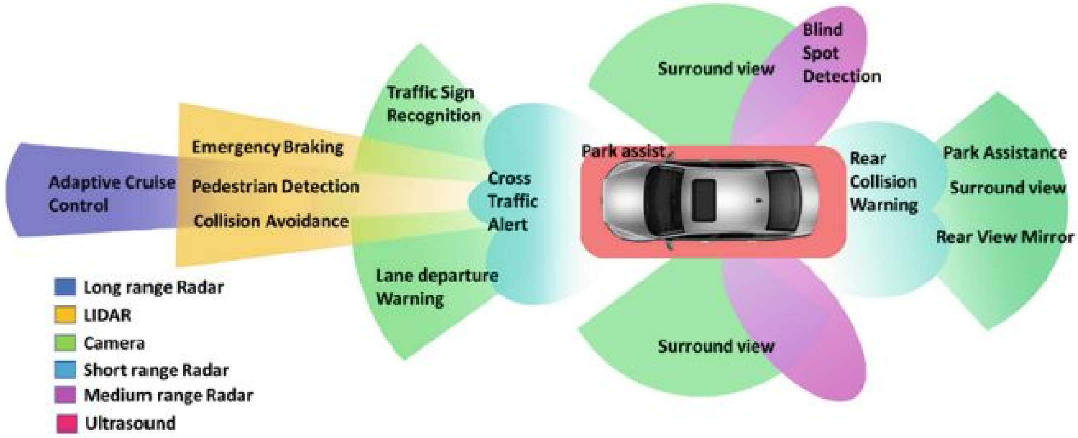


Figure 2.9: Overview of ADAS technologies

notified and a corrective measure can be undertaken. Using LDW, unintentional lane departure caused by driver's inattention, distractions, fatigue can be reduced. In lane departure warning system, a camera is mounted high up in the windshield as a part of the rear view mirror mounting block. It captures a view of the road ahead. The driver gets a warning when the vehicle deviates and approaches or reaches the lane marking. The warning may be an audible tone, or a visual alert, or vibrations in either the steering wheel or driver's seat. If the driver intentionally crossing over the lane i.e. the turn signal is on, then there is no warning. [45]

2.4.2 Lane Keep Assist LKA

Lane Keeping Assist System (LKAS), is a sophisticated driver assistance system (ADAS) that assists in keeping vehicles within their lane. If a vehicle equipped with LKAS starts to veer out of its designated lane, the system will alert the driver through visual, audible, or haptic lane departure warning (LDW) signals. Subsequently, the Lane Keep Assist system takes control, using steering and occasionally braking to guide the vehicle safely back into its lane and prevent potential fatal crashes. The Lane Keeping Assist model comprises four key elements: Estimating Lane Center, Lane Keeping Controller, Detecting Lane Departure and Applying Assist.

LKA uses a combination of sensors, cameras, and algorithms to detect lane

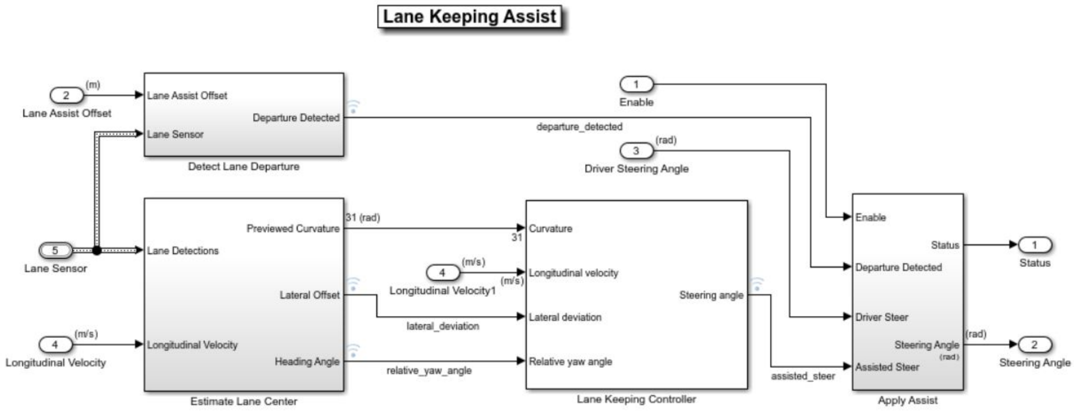


Figure 2.10: Lane Keeping Assist model

markings and provide corrective steering inputs to keep the vehicle centered in the lane. The algorithm works by detecting lane markings on the road using sensors and cameras, tracking the position of the vehicle relative to the lane markings, calculating the lateral error, and using a control algorithm to calculate the corrective steering input based on the lateral error and other factors such as the vehicle's speed and the curvature of the road. The LKA algorithm is designed to assist the driver, not replace them, and is programmed to disengage if the driver takes control of the steering wheel or if the vehicle detects a hazardous situation. There are different approaches to implementing the LKA algorithm, like Model Predictive Control to improve the performance and safety of the system. In summary, the LKA algorithm is a crucial component of ADAS that helps drivers stay in their lane while driving by detecting lane markings, tracking the position of the vehicle, calculating corrective steering inputs, and assisting the driver in staying in their lane. [46][47][48]

2.4.3 Traffic Sign Recognition TSR

Traffic Sign Recognition (TSR) is an advanced driver assistance system (ADAS) that identifies and communicates traffic sign information to drivers through the instrument panel or multimedia display. TSR systems can recognise speed limit signs, no entry signs, and stop signs. The objective of TSR is to enhance driver awareness and enable better, safer driving decisions. Traffic Sign Recognition employs sophisticated forwards-facing cameras, typically installed on or near the windscreen, close to the rear-view mirror. These cameras detect and recognise traffic signs, using software to interpret their meanings. The driver then receives this information almost instantaneously. TSR frequently utilises the same ADAS camera, responsible for tracking lane markings and alerting the vehicle's lane departure warning system.

2.4.4 Forward collision warning FCW

FCW is an Advanced Driver Assistance System (ADAS) which informs the driver of an imminent collision with an obstacle or a vehicle ahead. The aim of FCW is to decrease the number of accidents that occur due to sudden entry of unexpected obstacle or vehicle in the path without enough time to apply brakes. Radar, camera and laser technology are employed by Forward Collision Warning to monitor the road ahead. If the distance between the car and an approaching obstacle is decreasing too rapidly, FCW systems will notify the driver to apply the brakes. Audible and/or visual warnings are provided to the driver by FCW. Some models also offer haptic alerts by means of seat or steering wheel vibration.

2.4.5 Autonomous Emergency Braking AEB

Forward collision control with autonomous emergency braking alerts the driver when the speed of the vehicle can result in a collision with a vehicle or an object in front. Autonomous braking will prevent collision by applying brakes when there is a high risk of collision and the response of the driver is inadequate to avoid the collision. There are various autonomous emergency braking systems available in modern model vehicles, Low Speed AEB operates at speeds below 55 mph; it is a type of emergency braking system that automatically brings a vehicle to a halt to prevent a potential frontal collision. Highway Speed AEB, also known as highway automatic emergency braking, is a system that operates when the vehicle is travelling at speeds exceeding 55 mph, it is important to note that this system is solely meant to function when the car is on a highway or similarly-named road. Rear Automatic Emergency Braking (Rear AEB) is a system that detects obstacles during a vehicle's retrograde motion and automatically applies the brakes to prevent collisions. It is often paired with Rear Cross Traffic Alert. Pedestrian AEB systems equipped with pedestrian detection capabilities can significantly reduce the number of pedestrian accidents. The system operates using Radar, LiDAR, or Cameras to detect pedestrians in the vehicle's path. Upon detection, it sends a signal to the vehicle's brakes, enabling it to come to a halt before any collision with the pedestrian. Studies show that pedestrian AEB systems can significantly improve the safety of both pedestrians and drivers, making it an essential safety feature in modern vehicles.

2.4.6 Adaptive Cruise Control ACC

Adaptive cruise control (ACC) also known as radar cruise control is a system developed to control or adjust the speed of vehicle to maintain an optimum distance between the vehicles with the help of a radar or a laser system. In ACC, three radar sensors are needed, two short-range radars used to detect objects in the adjacent lane and one with a long range used to detect objects in-path. When the road ahead is clear, ACC automatically accelerates to the pre-set speed. Adaptive cruise control is ideal for highway speeds. ACC is a major component and precursor of fully autonomous vehicles. According to SAE, Driving Automation Level 1 driver support features provide steering or brake/acceleration to the driver while the jump to Level 2 requires features that provide both steering AND brake/acceleration to the driver. On its own, ACC is a Level 1, but when combined with another driver assist feature that steers, the vehicle reaches Level 2 on the Driving Automation scale – a step closer to fully autonomous driving. A radar sensor mounted at the front of the vehicle is used to analyse the road ahead. It does this by emitting radio waves and measuring the time they take to return to the ACC sensor (Time of Flight). With a few internal calculations, the vehicle is able to indicate the distance and speed of the car. The data from the radar distance sensors and the vehicle's speed sensors are used to adjust the speed and keep the car at a predetermined distance from those ahead.

How Does The Algorithm Work?

The longitudinal control algorithm for Adaptive Cruise Control (ACC) consists of three parts. Firstly, the speed error calculation, where the subject vehicle measures the distance to the vehicle in front of it and calculates the speed difference between the two vehicles. Secondly, the control law calculation, which is calculated based on the speed error and other factors such as the desired following distance, acceleration limits, and maximum speed. The control law determines how much the subject vehicle should accelerate or decelerate to maintain a safe following distance. Lastly, the actuator control, where the control law output is used to control the vehicle's actuators, such as the throttle and brakes, to adjust the speed of the subject vehicle. The actuators are controlled to maintain a safe following distance and avoid collisions with the vehicle in front. These three parts work together to maintain a safe following distance and adjust the speed of the subject vehicle to match the speed of the vehicle in front of it.[49][50]

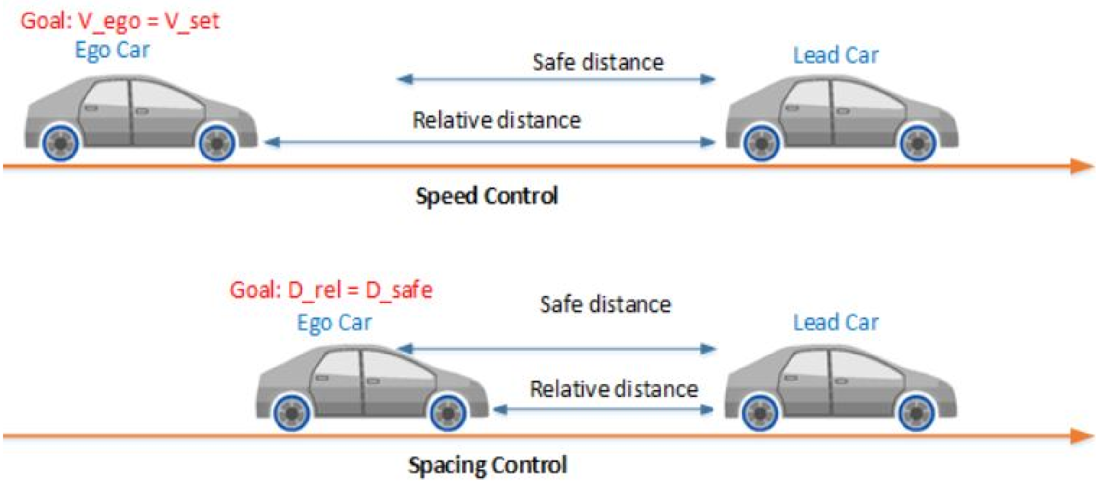


Figure 2.11: Adaptive Cruise Control model

The main component used in the ACC is the Long Range Radar (LRR), this sensor offers various advantages. Firstly, the LRR radar has the capability to detect vehicles and objects at a greater distance, granting the ACC system the ability to react quickly to potential collisions or sudden fluctuations in traffic conditions, to increase the safety of both drivers and passengers. Additionally, the extended range provided by the LRR radar allows for anticipation and response to upcoming traffic situations that may not be visible to the driver, enabling the ACC system to maintain a safe distance from the vehicle in front, even if the front end is obstructed or the leading vehicle suddenly slows down. Furthermore, the LRR radar overcomes certain limitations of shorter-range sensors, predominantly in adverse weather conditions such as heavy rain, fog, or snow, where visibility may be reduced for the driver. The LRR radar can accurately detect obstacles and make necessary adjustments to the ACC system, ensuring safe driving distances are maintained. Moreover, the employment of the LRR radar in ACC systems promotes more efficient highway driving, as it can detect traffic conditions further ahead, resulting in smoother adaptive cruise control, reduced unnecessary braking or acceleration, and enhanced fuel efficiency. Lastly, the LRR radar is skilled in detecting stationary objects, such as stalled vehicles or obstacles on the road, which effectively contributes to accident prevention by alerting the driver or autonomously applying brakes when deemed necessary. Overall, the inclusion of the Long Range Radar for Adaptive Cruise Control optimizes safety, enhances functionality, improves performance in adverse weather conditions, facilitates efficient highway driving, and aids in the detection of stationary objects, establishing it as an invaluable component for ACC systems.

2.4.7 Traffic Jam Assist TJA

Traffic Jam Assist is an advanced driver assistance system (ADAS) that assists drivers in navigating through congested traffic. It is classified as a Level 2 driver assistance system, which combines the features of Adaptive Cruise Control (ACC) and lane-centering assistance to form a traffic jam autopilot. The system utilises front-mounted radar sensors and cameras to detect traffic, lane markings, and the vehicle in front. Once a traffic jam is detected, the car's speed and steering are automatically adjusted to ensure a safe distance from the preceding vehicle. The system can come to a complete halt and then automatically recommence driving when the traffic starts moving again. The key features of Traffic Jam Assist comprise automated braking and acceleration and lane-centring assistance. The system has the capability to assist in keeping the car centered in its lane.

Additionally, it can bring the vehicle to a complete stop and then continue driving automatically once the traffic starts moving again. To alert the driver of a possible collision, the system can provide both visual and auditory warnings. Traffic Jam Assist employs an algorithm which utilizes front-mounted radar sensors and cameras to identify traffic, lane markings, and the car in front. The system utilises the provided data to regulate the speed and steering of the car to ensure a secure distance from the preceding vehicle. If required, the system can bring the car to a complete halt and then resume movement as soon as the traffic begins to flow normally. Additionally, the system emits both visual and auditory alerts to the driver when there's a potential collision detected. Traffic Jam Assist is a pivotal ADAS system in that it can help drivers make their way through heavy traffic in a more relaxed and secure manner.

2.4.8 Highway Driving Assist HDA

Highway Driving Assist is an Advanced Driver-Assistance System (ADAS) designed to aid drivers on motorways by keeping the vehicle centred in the lane while maintaining a fixed speed and distance. The system employs a front-facing radar unit, camera, GPS technology, and the navigation system's map database to provide Level 2 automation. The key capabilities of Highway Driving Assist include adaptive cruise control, which enables the system to maintain speed and distance from the car in front and lane-centring assistance. The system has the ability to maintain the car's position in its lane. GPS data and route information are used to adjust the car's speed and distance based on road conditions. In the event of a possible collision, the system offers visual and auditory warnings to the driver. The Highway Driving Assist algorithm operates by utilizing a forward-facing radar unit and camera to spot the vehicle ahead and the lane markings. The system utilises this information to adapt the speed and distance of the car in accordance with the road conditions. Additionally, the system can issue visual and auditory alerts to the driver should it detect an impending collision. In conclusion, Highway Driving Assist serves as a crucial ADAS system that contributes to a safer and less stressful driving experience on highways.

Chapter 3

System Architecture Design and Methodology

This chapter examines the hardware architecture of the road prototype and specifically discusses the selection of components based on a thorough analysis of individual requirements, both total and critical, for each sensor.

The hierarchical analytical process (AHP) is employed to support this component selection. This approach is frequently employed in automotive analyses, where several parameters need to be evaluated in order to compare different results in the same category, such as the selection of various vehicles or, as in this case, the selection of suitable sensors to be applied to the prototype in order to respond adequately to the requirements to be met.

The first section is dedicated to the requirement analysis. This thesis is focused on industrial and green sustainability, so it is necessary to define the task objectives specifically applicable to our use case based on upstream and downstream constraints and requirements in the workflow.

The second section introduces the architecture design of the hardware. While ensuring that the project requirements are met, we fully weighed the feasibility, efficiency, scalability of the system, then we choose the most suitable hardware equipment from the available resources at hand. The key parameters and workflow of the selected hardware will be emphasized.

Finally, an overview of the mathematical methodology applied to support the choices made.

3.1 Sensor Requirements

Requirement analysis is the process that includes collecting and documenting requirements, analyzing, and prioritizing them, and defining the scope and objectives of the system. It helps to ensure that the system meets the needs and expectations of its stakeholders, providing a clear understanding of what the system must do and how it should perform.

As the system is developed to realize the environmental awareness function in an ADAS system, it must be capable of accurately detecting and interpreting the surroundings of the vehicle in real-time to provide necessary information to the ADAS system, and even advanced warning to the driver in case of potential dangers.

The main function is to detect objects in front of our vehicle in the current and adjacent lanes, such as other vehicles, pedestrians, traffic lights and speed signs, etc., and to measure the relative distance between the detected objects and our vehicle. It was decided to use cameras and LiDAR to detect and analyse the vehicle's surroundings. In addition, the system had to be able to process large amounts of data in real time, have low power consumption and compact dimensions.

As the system will be installed within a vehicle and tested under real road conditions, it is crucial to ensure its robustness. The system requires an exceptional degree of precision and accuracy, consistently functioning dependably by detecting and interpreting objects within the environment, including even the most challenging weather conditions.

The first activity carried out by the team from Politecnico di Torino and Teoresi SpA has covered the new ADAS architecture definition. The donor vehicle, a Low Range 500e from Stellantis, is equipped with a suite of sensors decided by the OEM to fulfill the main requirements of ADAS regarding comfort and safety. For this reason, as showed in 3.1, the ADAS equipment of the donor car consist in the minimal sensors' suite which can guarantee Adaptive Cruise Control (ACC) and Autonomous Emergency Braking (AEB) as main features regarding the control of vehicle's longitudinal dynamics. The proposed ADAS are developed by the Tier company chosen by the OEM and are integrated to the low level controllers of the vehicle to complete the tasks the are designed for. Since the functionalities that the project proposes involve a new set of requirements especially in terms of energy management, the ADAS architecture has to be reviewed and also enhanced to guarantee their fulfillment.

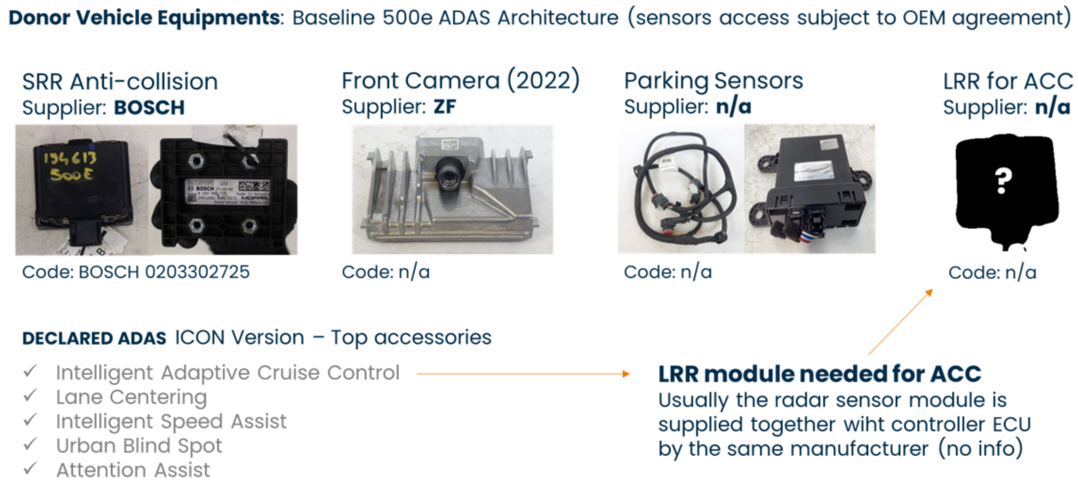


Figure 3.1: OEM Base Sensors

The starting point of the architecture definition, has been a comprehensive review of the sensors commercially available for terrestrial vehicle usage. A baseline study was conducted to build a solid understanding of the operational principles and distinctive attributes of each sensor. After comprehending the fundamental aspects of the perception system, the examination of sensor fusion and its significance in consolidating the capabilities of each sensor to achieve an output capable of overcoming individual limitations is imperative. The last phase of the preliminary study, concerns the knowledge of communication protocols, which represent the way in which sensors measurements are acquired and shared with the other systems. Starting from the previous experience of the working team, a set of system's requirements was derived and used to drive the decision-making process. The requirements have been divided in to the categories proposed in 3.2, where:

- ADAS requirements, refer to the sensors' characteristics considered as a must-have for the newly introduced sensors' suite;

- Interface requirements, refer to the sensors' interfaces needed to correctly integrate them into an embedded and highly customizable perception pipeline;
- Control requirements, refer to the target applications, which are the main ADAS which are considered as impacting on the longitudinal vehicle dynamics.

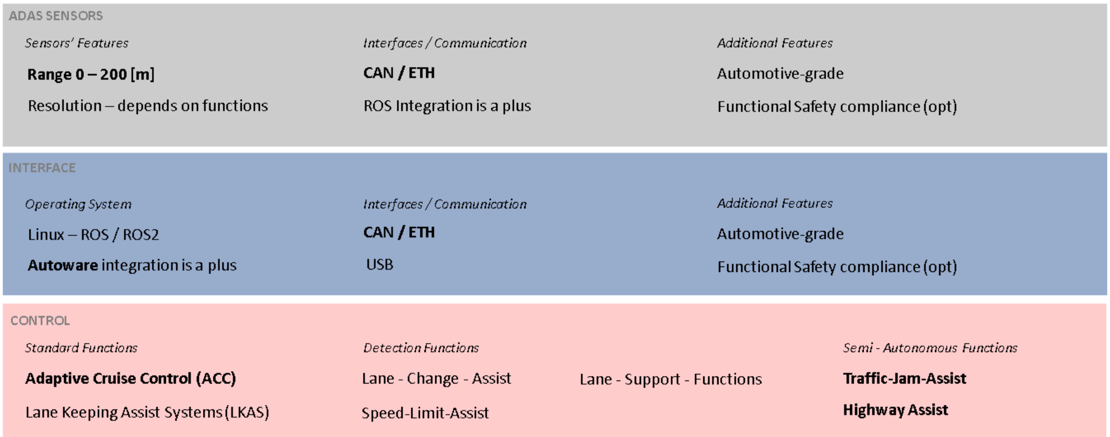


Figure 3.2: Sensor Requirements

To solve the ADAS-aided Energy Management problem, the newly designed system should be able to perceive the environment, plan the vehicle speed profile according to an energy-optimal policy and then control accordingly the longitudinal motion. The definition of the ADAS architecture is a critical task to be addressed, because providing the right amount of information to a decision making controller is fundamental for the performance of the whole pipeline.

3.2 Hardware Architecture Design

With regard to the hardware architecture design, it is essential to define that the vehicle on which the sensor kit will be applied is an electric passenger car. The sensors present in the standard vehicle will be dismantled and the sensors defined during the study and analysis phase will be installed. In particular, LiDAR, 4D Radar, Monocular Camera, Short-Range Radar and Stereoscopic Camera sensors were chosen, suitably combined according to the solutions examined. the hardware equipment needs to be powerful in computation, efficient in power consumption, and compact in size, including the ECUs (Electronic Control Units) for central control, and the batteries for power supply during the testing phase.

3.2.1 Benchmark Solid State LiDAR

Knowing the parameters, a search was conducted that respected these characteristics, and in particular the principles of greatest relevance to solid-state lidar were defined: Field of View. We aim at a horizontal FOV of more that 100° and a vertical FOV of more that 10° to reduce the number of sensors that has to mounted on the vehicle. Resolution and number of scan lines. The sensors should have a high resolution below 0.4° and at least five scan lines to be able to detect the Lidar targets and a real-world objects. Update rate or frame rate. In order to avoid longer delays in the object detection, the sensor systems should have an update frequency or frame rate of more than 5 Hz. ROS/ROS2 support. For an easy integration into our control software stack, a Linux-based system implementation and an AD framework based on ROS2 is preferred. Robustness of sensor system. The test candidates should work well also in tougher weather conditions, and the sensor performance should not notably degrade under those conditions. Several solid-state lidar sensors were benchmarked:

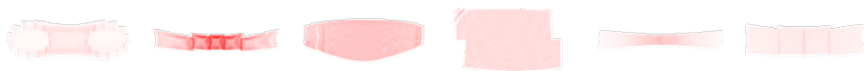
	Livox Horizon	Robosense M1	Blickfeld Cube	Blickfeld Cube Range	Velodyne Velarray H800	Innoviz Pro
Picture						
Scan pattern						
Framerate	10 Hz	10 Hz	6.3 Hz	5.7 Hz	25 Hz	16 Hz
Points per Frame	24.000	78.750	8.829	7.599	16.181	15.500
FOV	81.7° H, 25.1° V	120° H, 25° V	72° H, 30° V	18° H, 12° V	120° H, 16° V	72° H, 18.5° V
Principle	Rotating Prisms	MEMS	MEMS	MEMS	Solid State	MEMS

Figure 3.3: Benchmark SolidStateLiDAR

Some of the most important information has been reported, thanks to which we are able to cover most of the critical parameters constituting this type of sensor;

the relevant factors are points per frame, frequency and scan pattern. From these specifications it would be possible to identify the most suitable solution for the requests, but through analytical methods developed subsequently it was possible to verify the validity of the results. The methodology employed involved conducting similar research and analysis on camera sensors, long-range radar, short-range radar and stereoscopic cameras.

3.2.2 Solid State LiDAR - Robosense RS M1

RS-LiDAR-M1 is an automotive grade solid-state LiDAR, that RoboSense specially designed for massive production vehicles. It provides highly reliable 3D environment perception for vehicles to deliver safe driving. Based on RoboSense's revolutionary patented micro-electromechanical systems (MEMS) technology, M1 has much simplified structure and way less demands on components. This new revolutionary solid-state LiDAR system excels with a lot of advantages including high reliability, low cost, easy for massive production, and easy for integration into vehicle body.

The Robosense RS-M1 is an advanced LiDAR sensor revolutionizing the field of autonomous driving. This state-of-the-art sensor is equipped with cutting-edge technology, making it highly accurate and efficient. One of the main features of the RS-M1 is its exceptional long-range scanning capability,up to a range of 200 meters. This extensive coverage allows vehicles to detect and navigate through potential obstacles or hazards, ensuring a safe and smooth driving experience.

Figure 3.4: RobosenseRSM1

Additionally, the RS-M1 boasts an impressive high-resolution scanning ability, capturing precise details of the environment, including small objects and subtle variations in terrain. This level of precision enables autonomous vehicles to make informed decisions and adapt swiftly to changing circumstances. Furthermore, the RS-M1 incorporates advanced artificial intelligence algorithms, allowing real-time object recognition and classification. This feature distinguishes between different objects such as pedestrians, vehicles, and cyclists, enabling the vehicle to react accordingly and prioritize safety. With its robust features, the Robosense RS-M1 establishes itself as a game-changer in the field of autonomous driving, paving the way for a safer and more efficient future.

The vertical FOV is 25 degrees (-12.5 degrees to +12.5 degrees). The vertical resolution is 0.2 degree, and the horizontal resolution is 0.2 degree at 10 Hz frame rate typically and the range accuracy is ±5cm and the points per second are 78.750 at a frequency of 10 Hz. The LiDAR is capable of operating in temperatures ranging from –40 to +85 degrees Celsius.

3.2.3 4D Radar - Continental ARS 548 RDI

Continental offers a new type of long range radar sensor, the ARS 548 RDI, possible adaption include various industrial applications as well as premium upgrade version of the series 50X.

The ARS 548 RDI radar sensor is capable of measuring the distance, speed, and angle of objects without reflectors through live scanning. Its enhanced range resolution is achieved by utilizing Pulse Compression with New Frequency Modulation and a real-time scanning frequency of 20 times per second. The sensor enables independent measurements of distance, speed (using Doppler's principle), and angle of objects without reflectors in one measurement cycle. The device supplies concurrent detection output of object distances of up to 1500 metres, relative speed, and angles for each object in azimuth and elevation with high precision. The structure and technology of the sensor permit it to appraise the danger of collision and automatically identify any issues with the sensor and its environment, ensuring reliability and durability for a range of industrial applications, rail traffic technology, and other advanced upgrade versions. The ARS 548 RDI has been engineered to

Figure 3.5: Continental ARS 548 RDI

provide rapid and secure functionality, thus dismissing any inconsistencies between its exceptional measuring accuracy and high level of operational safety. This system contributes significantly towards improving the safety features as well as collision protection of both automobiles and industrial machinery.

3.2.4 Benchmark Stereoscopic cameras

The benchmark of products continued with the stereo camera solutions. The main parameters here are depth range, Field-of-View (FoV), resolution and baseline (referring to the distance between the two stereo camera lenses). In the following table, the stereo-cameras considered are reported with their characteristics:

The ZED products are mainly made for the robotics sector but are also well suited for automotive prototyping applications. The manufacturer provides the product with an embedded processing unit, that allows the ZED stereo cameras to capture also 3D maps of the environment and perform object detection and tracking through space. Compared to cameras, stereo cameras add depth perception, motion tracking and spatial understanding to the application, which are tasks which may also be completed from the processing hardware aside from the camera product.

	Leopard Imaging AR0144	Leopard Imaging AR0234CS	Leopard Imaging OV580	ZED 2i 60 fps	ZED X 60 fps	ZED mini 60 fps
Depth range	8 m	8 m	10 m	20 m	20 m	15 m
FOV	59°H; 36°V	121.5°H; 73.5°V	100°H; 60°V	110°H; 70°V	110°H; 80V	90°H; 60°V
Resolution	1280H; 800V	1920H; 1200V	1280H; 720V	1280H; 720V	1920H; 1200V	1280H; 720V
Baseline	7 cm	9 cm	9 cm	12 cm	12 cm	6.3 cm
Production Year	2020	2022	2020	2022	2022	2022
Cost [€]	280	370	460	460	550	370

Figure 3.6: Benchmark Stereoscopic Cameras

3.2.5 ZEDX

ZED is a 2k Stereo camera manufactured by Stereolabs, a company that specializes in producing cameras and software for 3D sensing applications, which is used for Depth Sensing and Motion Tracking. The camera uses an advanced sensing technology based on the principle of human stereo vision and can be used for depth perception, positional tracking and 3D mapping applications. It uses real time depth based visual odometry and simultaneous localization and mapping (SLAM) technology. Stereo vision cameras work on the same principle as our brain works on measuring distance using our eyes. In a stereo camera, 2 cameras are used which are generally placed a short distance apart in the same plane. 3D spatial relationships like the tilt, separation and placement are known for both the cameras. 3D stereovision algorithms are then applied on the 2 images obtained by the cameras which aligns the pixels and calculates the depth information. A depth map is then visualized from the available information.

The ZED camera can be connected to a computer via USB 2.0 without requiring an additional power source. The computer however needs to have a NVIDIA GPU and a minimum memory of 2GB.[51]

Figure 3.7: ZEDX

ZED X, the most innovative product made by Stereolabs, is an IP66-rated Global Shutter camera built for robots, powered by Neural Depth Engine 2. It features a robust aluminium casing, high-performance IMU, secure GMSL2 connection and external frame synchronisation. The ZED-X camera has been optimized for use with NVIDIA's Jetson AGX Orin supercomputer. Each Jetson module can control four ZED-X cameras, reducing cost, weight and onboard space requirements.

The camera produces crystal-clear images that quickly capture any action-filled environment, thanks to the dual 1920x1200 global shutter color sensors.

However, another important aspect is the new IMU that allows the fusion of a 16-bit triaxial accelerometer and a gyroscope with vibration resistance, very low noise and bias for remarkable motion tracking.

As camera heating induces changes in focal length and motion sensors biases, it adopts a more robust all-aluminum enclosure with thermal control to monitor temperature and compensate these drifts, allowing it to be capable of operating in temperatures ranging from –20 to +50 degrees Celsius.

3.2.6 NVIDIA Jetson AGX Orin

The NVIDIA Jetson AGX Orin is a powerful and energy-efficient system-on-module designed for AI applications in robotics, autonomous vehicles, and other edge devices. Its high performance and energy efficiency make it ideal for edge computing, where processing power and power consumption are critical factors.

It stands as one of the most sophisticated AI platforms accessible nowadays, providing exceptional energy efficiency and performance. AGX Orin is comprised of diverse processing components, namely eight ARM Cortex-A78 CPU cores, an innovative GPU architecture, and an exclusive deep learning accelerator. This amalgamation of technologies delivers unparalleled computational prowess for AI workloads, rendering it an exemplary option for various AI-fueled applications including autonomous vehicles, high-performing robots and smart urban centers.

Figure 3.8: Nvidia Jetson Orin AGX

Additionally, the AGX Orin incorporates a high-speed I/O subsystem with PCIe Gen4 and Gigabit Ethernet, facilitating the prompt and efficient transfer of data. The AGX Orin offers researchers and developers a versatile platform for experimenting and developing cutting-edge AI solutions, thanks to its extensive connectivity options and support for renowned AI frameworks like TensorFlow and PyTorch. Its exceptional performance, energy efficiency, and flexibility make it an ideal candidate for integration into various AI systems, paving the way for advancements in AI technology.

3.2.7 ROS2 environment

Self-driving cars have to take decisions based on their sensory input in real-time, providing high reliability with a strong demand in functional safety. In principle, self-driving cars are robots. However, typical robot software, in general, and the previous version of the Robot Operating System (ROS), in particular, does not always meet these requirements. With the successor ROS2 the situation has changed and it might be considered as a solution for automated and autonomous driving. Existing robotic software based on ROS was not ready for safety critical applications like self-driving cars. The second generation of Robot Operation System ROS2 provides the needed reliability and real-time performance while most of the advantages of ROS 1 are still available.

Figure 3.9: The ROS Ecosystem

ROS 2 (Robot Operating System 2) is an open-source software development kit for robotics applications. It is a set of software libraries and tools for building robot applications, from drivers and state-of-the-art algorithms to powerful developer tools. ROS 2 is designed to offer a standard set of robotics tools, libraries, and capabilities that developers need to create their applications, allowing them to spend their time on the work that is important for their business. ROS 2 is built on an abstraction layer that insulates the robotics libraries and applications from the communication technologies, which means there is no vendor lock-in. ROS 2 is designed to be modular, composable, and open-source, which allows developers to customize it for their needs. ROS 2 is ready for use across a wide array of robotics applications, from indoor to outdoor, home to automotive, underwater to space, and consumer to industrial. ROS 2 is a significant API change to ROS, which is intended to support real-time programming, a wider variety of computing environments, and more modern technology.

3.2.8 Benchmark Cameras

Figure 3.10: Camera Applications

By studying cameras, it is possible to define an initial categorization based on their application: automotive grade, robotic application, and industrial application.

- Automotive sensors: for analyzing dynamic operating conditions;
- Robotic sensors: outdoor use or mobile applications;
- Industrial sensors: enable precise sensing in industrial and personal electronics markets;

Cameras are characterized by key aspects such as Field Of View, pixel size, resolution, operation range etc. Also in this case it was also benchmarked between multiple solutions:

Based on this benchmark, the most suitable sensor for the application being examined is the NileCAM21 CUXVR GMLS2, which is then compared to version NileCAM25 CUXVR GMLS2, which is a global shutter, which is deemed more appropriate. The defining factor between the two is that NileCAM21 is a Full HD GMSL2 HDR camera with LFM and rolling shutter, highlighting a 2048 x 1280 AR0233AT CMOS image sensor. NileCAM25 features a global shutter, which is better suited to capturing images of moving objects, whereas NileCAM21 includes HDR and LFM capabilities that are beneficial for imaging in challenging lighting scenarios. Moreover, the optional IP67-rated enclosure of NileCAM25 renders it suitable for unforgiving outdoor conditions.

	Leopard Imaging AR0231	Leopard Imaging IMX390	NileCam21 CUXVR GMSL2	Sony STURD-eCam31	Continental MONO-Camera	BOSCH Multi Purpose Camera
Pixel size	3.0 µm x 3.0 µm	3.0 µm x 3.0 µm	3.0 µm x 3.0 µm	3.0 µm x 3.0 µm	3.0 µm x 3.0 µm	3.0 µm x 3.0 µm
FOV	122°H; 74°V	122°H; 74°V	111°H; 62°V	111°H; 62°V	110°H; 70V	100°H; 48°V
Resolution	1928H; 1208V	1937H; 1217V	2048H; 1280V	1937H; 1553V	1280H; 960V	2048H; 1280V
ADAS applications	ACC, LKAS, AEB	ACC, LKAS, AEB	ACC, LKAS, AEB	ACC, LKAS, AEB, Traffic Jam	ACC, LKAS, AEB, Traffic Jam	ACC, LKAS, AEB, LDW Traffic Jam
Production Year	2019	2023	2021	2021	2022	2021
Cost [€]	662	662	505	460	550	600

Figure 3.11: Benchmark Cameras

3.2.9 NileCAM25 CUXVR GMLS2

The NileCAM25 CUXVR GMLS2 is a camera kit designed for use with the NVIDIA Jetson AGX Xavier developer kit, featuring a Full HD global shutter GMSL2 colour camera and a 15-metre cable support. The camera is suitable for various applications, such as surround view systems and unmanned ground vehicles (UGV). Based on the AR0234AT CMOS image sensor, it is ideal for IP67 rated applications.

In asynchronous mode, the camera can capture Full HD footage at 65 fps and HD footage at 120 fps. The camera's interface is GMSL2 and it utilises a FAKRA connector. The sensor is included. AR0234AT CMOS image sensor has a dynamic range of 71.4 dB and is mounted on an M12 holder with an S-Mount. It provides a Field of View (FOV) of 128.2°(D), 104.6°(H), 61.6°(V) (with the lens supplied by e-con). The sensor operates at a voltage range of 5 to15V with a tolerance of +/- 5%. The operating temperature range is -30°C to 70°C, and the typical power consumption is specified. 10.681W power consumption, with the serializer board measuring 30 x 30 mm and the deserializer board measuring 75 mm x 55 mm. This product complies with RoHS regulations and was launched with a full-fledged

Figure 3.12: NileCAM25 CUXVR GMLS2

Linux camera driver for NileCAM25CUXVR, compatible with the NVIDIA Jetson AGX Xavier developer kit. The camera driver source code is readily adaptable to all NVIDIA AGX Xavier platforms. Xavier - Jetpack 4.5.1 L4T32.5.1 is the supported Jetpack & L4T version.

3.2.10 Benchmark Short Range Radars

	CONTINENTAL SRR308	CONTINENTAL SRR520	TEXAS INSTRUMENTS AWRL6432	XENSIV™ BGT60ATR24C
Detection Range	95 m	100 m	25 m	18 m
Range Accuracy	±0.2 m far ±0.5 m near	±0.22 m far ±0.5 m near	High	High
Velocity Resolution	0.33 m/s	0.35 m/s	Ultra high	High
ADAS applications	LKAS, AEB	LKAS, AEB	LKAS, AEB, Traffic Jam	LKAS, AEB
Production Year	2021	2021	2021	2022
Cost [€]	50	50	-	30

Figure 3.13: Benchmark Short Range Radars

For the choice of short-range radar, a benchmark is created, as done in the previous cases, taking four reference sensors into consideration. In particular, two products from the same company are analyzed: Continental SRR 520 and Continental SRR 308. The main differences between the two can be seen in terms of detection range and a small percentage of velocity resolution. The parameter determining the choice at this point was related to the experience had in other projects as their characteristics and cost were similar.

3.2.11 Continental SRR 520

The Continental SRR 520 is a high-performance 77GHz short-range radar sensor suitable for a range of premium backward and forward-looking applications. The compact design allows for easy integration behind painted bumpers while maintaining robustness. The SRR 520 has a modest power dissipation of 4.5 W and a supply voltage of 12V. It operates within a frequency range of 76 to 77 GHz. The SRR 520 is equipped with a range of safety features, including object detection, blind spot warning, lane change assist (Type IIIc), rear cross-traffic alert (with braking), front cross-traffic alert (with braking), rear pre-crash sensing, occupant safe exit and avoidance of lateral collisions. This versatile device is suitable for a variety of applications, such as right-turn assistance, surround view systems, and unmanned ground vehicles (UGV). Additionally, the SRR 520 is a suitable option for use in the automotive and industrial sectors.

3.3 Decision Support System AHP

This section utilises the Analytic Hierarchy Process (AHP) as a potent tool for the empirical validation of selected dimensions for evaluating and prioritising Advanced Driver Assistance Systems (ADAS) effectively. AHP is a measurement theory based on pairwise comparisons and experts' judgements to derive priority scales. The scales quantify intangibles in relative terms, facilitating systematic assessment of different criteria and alternatives linked to ADAS integration. In the first step, the decision problem is identified, which could entail selecting the most appropriate ADAS technology or prioritising criteria for ADAS integration. Next, the relative importance of each criterion is determined through pairwise comparisons, considering factors like Range, Range Accuracy, Field of View, Resolution, Cost, Weather Robustness, Urban ADAS, Highway ADAS and Innovation. Numeric scales are used to quantify judgments, and the criteria's relative weights are calculated based on these comparisons. By combining the weighted scores, decision-makers can make informed choices regarding the adoption and implementation of ADAS technologies, considering the overall criteria performance and importance. The Analytic Hierarchy Process (AHP) methodology enables a structured and methodical decision-making process, enhancing the assessment and prioritisation of ADAS alternatives for improving transport efficiency and road safety.

Numerical values are assigned on a scale of 1 to 9, using only odd values, where 1 represents equal importance, 3 represents slightly more importance, 5 represents considerably more importance, 7 represents significantly more importance, and 9 represents utmost importance. For factors of lesser importance, we apply reciprocal values in a similar manner.

This analytical hierarchical method entails developing a structure placing the objective at the highest level, attributes/criteria at the second level and alternatives at the third level. The first step involves determining the relative importance of each characteristic concerning the objective; a comparative analysis of these characteristics follows to construct the pairwise comparison matrix. After creating the matrix, the first step is normalization. Then, the criteria weights are calculated by adding up the normalized values in each row. Next, we calculate the consistency value by multiplying the criteria weights with the corresponding column values. Finally, we add up the values from each row to obtain the weighted sum value. The maximum eigenvalue is obtained by calculating the ratio of the weighted sum value to the criteria weights, which represent the eigenvalues of the matrix. We will now proceed with calculating the consistency index, which is determined by: $\frac{\lambda_{max}-n}{n-1}$.

The final step in this process is to calculate the Consistency Ratio: $\frac{C.I.}{R.I.}$ given, where the random index is the consistency index of randomly generated pairwise matrix. The consistency ratio (CR) is used to determine the value of probability. A $\frac{C.I.}{R.I.}$ value below 0.1 is important in the AHP method to ensure consistency, enhance decision quality, increase confidence, and facilitate sensitivity analysis, all of which contribute to reliable and robust decision-making.

3.3.1 Total Parameter Matrix

One crucial consideration is to evaluate the complete and essential parameters of the sensors under investigation, analysing individual sensors such as Solid State LiDAR, 4D Radar, Long Range Radar, Short Range Radar, Monocular Camera, Stereoscopic Camera, and for each of them, analysing the percentage of the total requirements met. Subsequently, we proceed to determine the extent to which the critical requirements, specifically the parameters that are essential to be addressed, have been fulfilled.

Total Requirements considered for each sensor are respectively:

- Solid State LiDAR: Price, Detection Range, Weather Affection, Frame Rate, Resolution, Scan Pattern, Points Per Frame, Field Of View;
- Camera: Price, Range, Weather Affections, Field Of View, Adas Application, Resolution, Range Accuracy;
- Radar Long Range: Price, Distance Range, Weather Affections, Speed Resolution, Adas Application, Velocity Resolution;
- Radar Short Range: Price, Distance Range, Weather Affections, Speed Resolution, Adas Application, Velocity Resolution;
- 4D Radar: Price, Distance Range, Weather Affections, Speed Resolution, Adas Application, Velocity Resolution;
- Stereoscopic Camera: Price, Range, Weather Affections, Field Of View, Adas Application, Resolution, Range Accuracy, Baseline;

3.3.2 Critical Parameter Matrix

The critical requirements considered in the sensors examined are those factors that must necessarily be satisfied to cover the design specifications defined by the OEM. In particular, the following requirements are considered critical:

- Solid State LiDAR: Price, Detection Range, Resolution;
- Camera: Price, Range, Field Of View, Resolution;

- Radar Long Range: Price, Distance Range, Speed Resolution;
- Radar Short Range: Price, Distance Range, Speed Resolution;
- 4D Radar: Price, Distance Range, Speed Resolution;
- Stereoscopic Camera: Price, Range, Field Of View;

Chapter 4

Results and Discussion

This chapter illustrates the results obtained following the application of the hierarchical analytical mathematical process. The matrices shown relate to the components chosen for the three final kits considered, which are themselves analysed in a further section. For each sensor category, the analysis is carried out by examining several alternatives, e.g. the six solid-state LiDARs reported in the benchmark and the seven cameras considered in the initial stages are compared. Similarly for 4D radar, short-range radar and stereoscopic cameras. In the second section, the three final kits obtained are shown with the corresponding bills of materials in which the number of elements of the eventual component to be redundant is listed. The last section deals with the metrics used to arrive at the results and their discussion.

4.1 Introduction to Results

In the analysis for the selection of the sensor kit to be applied to the MOST prototype urban vehicle under study, three kits are considered, as illustrated below, with the following results:

The table displays the sensors that were used in the sensor architecture solutions applied in the urban prototype. It also provides the total cost information, which encompasses the redundant components, percentage of total requirements met, and percentage of critical requirements satisfied. The selection of the kit and its sensors

	Solid State Lidar / Radar 4D	Stereo Camera	Radar Short Range	Camera	Costs [€]	REQUIREMENTS [%]	CRITICAL REQUIREMENTS [%]
Kit 1	Continental ARS 548 RDI	ZED X	Continental SRR 520	NILecam25 CUXVR GMLS2	5100	92	92
Kit 2	Robosense RS M1	ZED X	Continental SRR 520	NILecam25 CUXVR GMLS2	6100	92	92
Kit 3	Continental ARS 548 RDI	-	Continental SRR 520	NILecam25 CUXVR GMLS2	6070	90	89

Figure 4.1: Kit Percentage Requirements

is supported by hierarchical analytical process, therefore the matrices obtained are reported and at the end of these the bills of materials of the selected kits are illustrated.

4.2 AHP Solid State LiDAR

The resulting matrix from the AHP analysis is presented for the sensor deemed most suitable for the application at hand. Specifically, is reported the AHP analysis of the Robosense RS M1 Solid State LiDAR.

	Range	Range Accuracy	Field Of View	Resolution	Cost	Weather Robustness	Urban ADAS	Highway ADAS	Innovation
Range	1	1	5	3	7	5	5	3	9
Range Accuracy	1	1	7	3	7	3	5	3	9
Field Of View	1/5	1/7	1	1/5	3	1/5	1/3	1/3	1
Resolution	1/3	1/3	5	1	3	1	5	3	5
Cost	1/7	1/7	1/3	1/3	1	1/5	1	1/3	1/3
Weather Robustness	1/5	1/3	5	1	5	1	3	1	3
Urban ADAS	1/5	1/5	3	1/5	1	1/3	1	1/3	5
Highway ADAS	1/3	1/3	3	1/3	3	1	3	1	5
Innovation	1/9	1/9	1	1/5	3	1/3	1/5	1/5	1

Figure 4.2: AHP Solid State LiDAR

The matrix shows different colours to indicate the different working areas: the

Feature	Percentage
Range	26,3%
Range Accuracy	25,2%
Resolution	13,6%
Weather Robustness	10,5%
Highway ADAS	9,3%
Urban ADAS	5,5%
FoV	3,6%
Innovation	3,2%
Cost	2,8%

Table 4.1: AHP Solid State LiDAR

area where the parameters relating to pairwise comparisons are defined is shown in blue, the unit values due to the relationship between similar characteristics are shown on the main diagonal and finally the reciprocal values to those calculated in the first part are shown in the part below. Paired comparisons are evaluated row by row, i.e. range is compared to range, range to range accuracy, range to field of view, etc. In the pairwise comparison, the relationship between range and range accuracy is unity. Their importance is considered equal because, being a mathematical analysis obtained from subjective evaluations, in the actual application the two parameters are equally fundamental in fulfilling the requirements defined in the primary stages.The assessment demonstrates that range holds a considerably more significant value than Field of View (FoV). This last feature is supported by other factors, such as camera and stereoscopic camera. Resolution is more crucial than FoV when compared to range because it is essential to differentiate the objects within the produced point cloud. The cost parameter is of less importance in this context as the chosen product has a competitive economic value in the market for the analysed sensor category. We proceed to evaluate the weather robustness which is considerably significant in LiDARs. LiDARs prove highly vulnerable to adverse weather conditions including rain, fog and even lightning, meaning that the range proves significantly more pertinent in the pairwise analysis. The next comparisons focuses on functionalities rather than characteristics. Specifically, it establishes the significance of range feature in relation to ADAS functionalities in urban and highway settings. Moreover, this study considers the importance of characteristics concerning the level of component innovation. In this context, the range parameter has been given maximum weightage with regards to the innovation parameter. This is because the range has already been tested on prior models and is necessary to satisfy ADAS technologies like Adaptive Cruise Control, which represents the first level of Driving Automation. Similarly, the subsequent features on the y-axis are analysed. The result obtained indicates a hierarchical importance such:

In particular, significant values of $\frac{C.I.}{R.I.}$ equal to 9%, maximum eigenvalue equal to 10,02 and consistency index equal to 0,127 are obtained.

LiDAR i	LiDAR j	Baseline 200m		Ranking		Value
Robosense RS M1	Hesai AT 128	200	200	A	1	1
Robosense RS M1	Blickfeld Cube 1	200	250	B	0,8	5
Robosense RS M1	Velodyne Velarray	200	200	A	1	1
Robosense RS M1	LivoxHorizon	200	260	B	0,77	5
Robosense RS M1	Innoviz PRO	200	135	A	1,48	7
Hesai AT 128	Blickfeld Cube 1	200	250	B	0,8	5
Hesai AT 128	Velodyne Velarray	200	200	A	1	1
Hesai AT 128	LivoxHorizon	200	260	B	0,77	5
Hesai AT 128	Innoviz PRO	200	135	A	1,48	7
Blickfeld Cube 1	Velodyne Velarray	250	200	A	1,25	5
Blickfeld Cube 1	LivoxHorizon	250	260	B	0,96	1
Blickfeld Cube 1	Innoviz PRO	250	200	A	1,85	9
Velodyne Velarray	LivoxHorizon	250	260	B	0,77	5
Velodyne Velarray	Innoviz PRO	250	135	A	1,48	7
LivoxHorizon	Innoviz PRO	260	135	A	1,93	9

Table 4.2: Second Level Solid State LiDAR - Range

The second step in AHP analysis necessitates making comparisons between the competing components in pairs by assessing and weighing numerical values for each characteristic listed in the data sheet. For example, when assessing the range parameter of the Solid State Lidar, a comparison would be made between the ranges of the Robosense RS M1 and the Hesai AT 128. This would determine which device provides a superior range and by what margin it deviates from the minimum requirements set during the initial phase to meet specific requirements. Further comparisons would be carried out between the Robosense RS M1 and the Blickfeld Cube 1, with each component compared to the others in turn. Subsequently, the importance of each component is determined by assigning weights between 1 and 9 for greater significance or between 1 and 1/9 for lesser importance, using the same method as in the preceding analysis stage. New AHP matrices are produced according to specific characteristics (e.g. range, field of view, resolution). These characteristics are used to determine the hierarchical order of importance of the sensors in relation to those technical features.

The table 4.2 give the following hierarchy:

Sensor	Percentage
Blickfeld Cube 1	35,1%
LivoxHorizon	15,1%
Robosense RS M1	9,2%
Hesai AT 128	9,2%
Velodyne Velarray	9,2%
Innoviz PRO	2,3%

Table 4.3: LiDAR's Range Hierarchy - Range

The values obtained within the hierarchical scale are useful to define which sensor has the highest performance on the specific requirement. We proceed with the similar calculation for all characteristics and report the results within a matrix, which is used to calculate the overall priority. A table is created next, with sensors displayed on the x-axis and characteristics plotted on the y-axis. The values from each column are obtained by multiplying the corresponding general priorities and local priorities and then combined. Finally, the sensor with the best performance can be identified.

The same analyzes carried out for the range are reported, but for features such as: range accuracy, Field Of View, Resolution and Cost.

4.3 AHP 4D Radar

In the 4D radar matrix, one notices a different assortment of assigned weights, in particular more emphasis is placed on weather robustness. Radar seems to be more resilient in weather conditions: the detection range of the configuration of a linear frequency-modulated 77 GHz and 1550 nm continuous-wavelaser could reach 260 m in heavy fog, 460 m in mild fog and over 600 m in heavy rain with SNR (signal-to-noise ratio) threshold at 20 dB. Studies have also been conducted on the radar's signal attenuation in snowfall.

	Range	Range Accuracy	Field Of View	Resolution	Cost	Weather Robustness	Urban ADAS	Highway ADAS	Innovation
Range	1	1	7	3	5	3	9	9	9
Range Accuracy	1	1	7	3	3	3	9	9	9
Field Of View	1/7	1/7	1	1/3	1/3	1/3	3	3	3
Resolution	1/3	1/3	3	1	3	1	7	7	5
Cost	1/5	1/3	3	1/3	1	1/5	3	3	1
Weather Robustness	1/3	1/3	3	1	5	1	5	5	5
Urban ADAS	1/9	1/9	1/3	1/7	1/3	1/5	1	1	3
Highway ADAS	1/9	1/9	1/3	1/7	1/3	1/5	1	1	3
Innovation	1/9	1/9	1/3	1/5	1	1/5	1/3	1/3	1

Figure 4.3: AHP 4D Radar

A higher snow rate yields larger attenuation as expected, and wet snow shows higher attenuation because of the higher water absorption and larger snowflakes. Considering a snowfall with 10 mm/h already has quite low visibility (< 0.1 km) it is possible to estimate that the specific attenuation for a 77 GHz radar in a 10 mm/h snow is about 6 dB/km, which is seemingly acceptable given the rain data. [24] Radars even manage to penetrate small surfaces such as thin layers of paint, from which they might be covered by design choices during vehicle assembly.

In particular, the hierarchical scale obtained in this case is:

Values of $\frac{C.I.}{R.I.}$ equal to 8%, maximum eigenvalue equal to 9,88 and consistency index equal to 0,11 are obtained. In this study, the key considerations are the weather resistance and cost parameters of the sensor technology. In terms of cost,

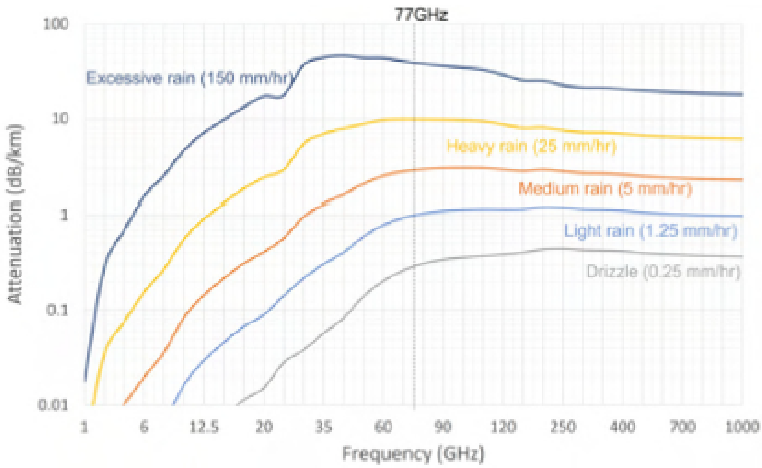


Figure 4.4: Radars' Attenuation vs. frequency in different rain rates

Feature	Percentage
Range	27,6%
Range Accuracy	26,5%
Weather Robustness	13,2%
Resolution	13,2%
Cost	6,3%
FoV	5,0%
Urban ADAS	2,9%
Highway ADAS	2,9%
Innovation	2,4%

Table 4.4: AHP 4D Radar

it is significantly higher than traditional long-range radar, but the benefits justify this cost. Additionally, in the chosen sensor kit for this application, the cost does not have a significant impact compared to the adoption of alternatives such as solid-state LiDAR.

4.4 AHP Short Range Radar

When studying the Continental SRR 520 short-range radar, it becomes evident that the resolution is the crucial parameter, as it requires exceptional accuracy in short distances, for instance, during busy traffic situations or in confined spaces. In fact, their use is fundamental in the case of ACC technology, which requires one long-range radar and at least two short-range radars, the latter being essential for detecting objects in an adjacent lane.

	Range	Range Accuracy	Field Of View	Resolution	Cost	Weather Robustness	Urban ADAS	Highway ADAS	Innovation
Range	1	1/3	1	1/5	7	1/5	5	1/3	3
Range Accuracy	3	1	3	1	7	1	7	1	7
Field Of View	1	1/3	1	1/7	5	1/5	3	1/3	3
Resolution	5	1	7	1	9	1	7	3	7
Cost	1/7	1/7	1/5	1/9	1	1/9	1/5	1/5	1/3
Weather Robustness	5	1	5	1	9	1	5	3	3
Urban ADAS	1/5	1/7	1/3	1/7	5	1/5	1	1/3	3
Highway ADAS	3	1	3	1/3	5	1/3	3	1	5
Innovation	1/3	1/7	1/3	1/7	3	1/3	1/3	1/5	1

Figure 4.5: AHP Short Range Radar

Millimeter-wave radars are immune to adverse weather conditions, such as scene illumination and airborne obscurants, which can disrupt visible spectrum sensors. They are not impacted by fog, rain, and snow, as their wavelength is significantly larger than the tiny airborne particles that cause these weather conditions. Furthermore, radars do not depend on optical lenses and can be integrated into plastic housings, thus enhancing their resilience to water and dust ingress. Although radar measurements still possess inherent artifacts, they exhibit greater resistance to weather conditions when compared to other sensors.

In this context $\frac{C.I.}{R.I.}$ has a value of 9%, maximum eigenvalue is 10,1 and Consistency index is 0,137.

Feature	Percentage
Resolution	24,5%
Weather Robustness	21,4%
Range Accuracy	18,4%
Highway ADAS	12,4%
Range	7,6%
FoV	6,3%
Urban ADAS	4,4%
Innovation	3,3%
Cost	1,7%

Table 4.5: AHP Short Range Radar

4.5 AHP Camera

	Range	Range Accuracy	Field Of View	Resolution	Cost	Weather Robustness	Urban ADAS	Highway ADAS	Innovation
Range	1	1	1/3	1/3	7	1/3	1	1/3	3
Range Accuracy	1	1	1/7	1	7	1/3	3	1	3
Field Of View	1/3	1/7	1	3	9	1	5	3	5
Resolution	3	1	5	1	5	1/3	3	1	5
Cost	1/7	1/9	1/3	1/5	1	1/9	1/5	1/7	1/5
Weather Robustness	3	3	7	3	9	1	7	3	3
Urban ADAS	1	1/3	5	1/3	5	1/7	1	1/3	3
Highway ADAS	3	1	3	1	7	1/3	3	1	3
Innovation	1/3	1/3	3	1/5	5	1/3	1/3	1/3	1

Figure 4.6: AHP Camera

Upon analysis of the camera, it is evident that the essential factor is its field of view, which makes it possible to see what is around the vehicle and to obtain information on the presence of pedestrians, cyclists or obstacles on the road. The LKAS function is supported by this sensor and recognises the distance between the vehicle and the road line to alert the driver of any potential crossing. The second parameter considered with greater relevance in this analysis is related to

Feature	Percentage
FoV	26,2%
Weather Robustness	23,3%
Resolution	11,6%
Highway ADAS	11,2%
Range Accuracy	9,1%
Range	7,3%
Urban ADAS	5,5%
Innovation	4,2%
Cost	1,6%

Table 4.6: AHP Camera

weather robustness, thanks to the IP67 classification which allows it to be protected from the ingress of dust and is also impervious to water, therefore it can be used under adverse weather conditions without compromising its functioning. The relevant parameters obtained in this context are: $\frac{C.I.}{R.I.}$ has a value of 8%, maximum eigenvalue is 9,9 and Consistency index is 0,118.

4.6 AHP Stereoscopic Camera

	Range	Range Accuracy	Field Of View	Resolution	Cost	Weather Robustness	Urban ADAS	Highway ADAS	Innovation
Range	1	1	1	1/5	5	1/5	5	1/3	3
Range Accuracy	1	1	3	3	9	1	7	1	7
Field Of View	1	1/3	1	1/3	3	1/3	5	1/3	3
Resolution	5	1/3	3	1	7	1	5	1	5
Cost	1/5	1/9	1/3	1/7	1	1/7	1	1/7	1/3
Weather Robustness	5	1	3	1	7	1	9	1	3
Urban ADAS	1/5	1/7	1/5	1/5	1	1/9	1	1/5	3
Highway ADAS	3	1	3	1	7	1	5	1	3
Innovation	1/3	1/7	1/3	1/5	3	1/3	1/3	1/3	1

Figure 4.7: AHP Stereoscopic Camera

Feature	Percentage
Range Accuracy	21,2%
Weather Robustness	19,2%
Resolution	17,3%
Highway ADAS	16,7%
Range	9%
FoV	7,5%
Innovation	3,8%
Urban ADAS	3,3%
Cost	2,1%

Table 4.7: AHP Steroscopic Camera

Stereoscopic cameras can enhance the overall perception of a vehicle's environment by providing accurate depth perception, a wider field of view, and the ability to capture rich visual information. They effectively complement monocular systems, so they are used to assist them. Stereoscopic cameras are robust to occlusions and obstacles such as rain, fog, or dust, making them more reliable in adverse environmental conditions. This robustness enhances the overall performance of ADAS systems, especially in challenging weather and lighting conditions. The analysis yields a hierarchical ranking that prioritises range accuracy and weather resilience. Range accuracy ensures precise data collection, while weather resilience is guaranteed by the IP66 classification. Stereovision technique is pivotal in object distance estimation algorithms that use the computed depth map and artificial intelligence algorithms. In conclusion, the parameters obtained in the analysis are: $\frac{C.I.}{R.I.}$ has a value of 9%, maximum eigenvalue is 10,03 and Consistency index is 0,129.

4.7 Evaluation Kits

4D radar systems offer improved resolution compared to previous versions of radar and match LiDAR systems in terms of performance. They have the ability to accurately determine an object's position in terms of range, azimuth, elevation and relative speed, providing comprehensive information regardless of weather or

	Range	Range Accuracy	Field Of View	Resolution	Cost	Weather Robustness	Urban ADAS	Highway ADAS	Innovation
Range	1	1	5	3	7	1	5	5	7
Range Accuracy	1	1	7	3	7	1/3	5	5	9
Field Of View	1/5	1/7	1	1/3	3	1/5	3	1	1
Resolution	1/3	1/3	3	1	5	1/3	5	3	5
Cost	1/7	1/7	1/3	1/5	1	1/5	1	1/3	1/3
Weather Robustness	1	3	5	3	5	1	7	7	9
Urban ADAS	1/5	1/5	1/3	1/5	1	1/7	1	1	3
Highway ADAS	1/5	1/5	1	1/3	3	1/7	1	1	3
Innovation	1/7	1/9	1	1/5	3	1/9	1/3	1/3	1

Figure 4.8: AHP Kit 1

environmental conditions. This versatility makes 4D radar highly advantageous for a wide range of applications, particularly in situations where LiDAR may be restricted by adverse weather.

Feature	Percentage
Weather Robustness	26,8%
Range	21,5%
Range accuracy	20,9%
Resolution	11,4%
FoV	5,1%
Highway ADAS	4,8%
Urban ADAS	3,7%
Innovation	3,1%
Cost	2,6%

Table 4.8: AHP Solution 1

This analysis is focused on enhancing weather robustness, immunity to rain, snow, fog, lightning etc. is ensured by the adoption of a 4D radar instead of a solid state LiDAR. This sensor guarantees information similar to that provided by the use of a solid-state LiDAR. Solid State LiDAR creates point clouds using laser or LED light, resulting in high-density and high-quality point clouds suitable for detailed mapping of smaller objects. On the other hand, 4D Radar uses radio waves and can provide more point cloud data compared to traditional radar, but its point cloud is still much sparser than that of LiDAR and has limitations on target size due to its longer wavelength. The following results were obtained: $\frac{C.I.}{R.I.}$ has a value of 8%, maximum eigenvalue is 9,91 and Consistency index is 0,115.

4.7.1 Solution 1

In this solution, four components were considered: 4D radar, stereoscopic camera, short-range radar and a single camera/smart camera. 4D radar boasts a significantly superior angular resolution in comparison to solid-state LiDAR, offering more accurate insights on the location of an object based on its range, azimuth, elevation and relative speed. The enhanced resolution enhances object detection and tracking capabilities. One notable advantage of using 4D radar, is its superior performance in adverse weather conditions, such as rain, fog, and snow, as opposed to LiDAR. The weather resistance of autonomous vehicles, operating in diverse environmental conditions, provides a significant advantage by ensuring reliable perception capabilities, irrespective of weather challenges.

However, it is also necessary to consider a stereoscopic camera for depth estimation and a short-range radar for high accuracy over short distances, to meet application requirements related to adaptive cruise control. The mono camera/smart camera provides information about what the vehicle encounters on its path, i.e. images are captured, so an appropriate update rate is required to be able to intervene in time. Cameras form an indispensable component of autonomous vehicles' active safety system, as they can spot probable dangers that other sensors may neglect. The system is able to recognise road signs and track lane markings, as well as detect traffic lights and other vehicles on the road, which positively impacts overall safety. Early warning systems based on cameras can alert drivers promptly, allowing them to correct their driving before accidents occur. When the system detects that the vehicle is drifting out of its lane, for example, it is capable of warning the driver or even of applying the brakes or steering the vehicle back into its lane. When radar and cameras combine, they can monitor pedestrians and

Solution 1: Kit composed by 4D Radar, SR Radars and mono/stereo camera redundancy

SENSOR	Type	Max Range	Range Accuracy	FoV	Resolution	Cost	Quantity
CONTINENTAL ARS 548 RDI	Radar 4D	300 m	±0.15 m	±60°	0.10 m/s	4000 €	1
ZED X / Leopard AR0234CS	Smart Stereo / Stereocamera	20 m / 8 m	-	110°H/80°V 121.5°H/73.5°V	1920Hx1200V	550 € / 370 €	1
CONTINENTAL SRR520	Radar SRR	100 m	±0.22 m ±0.5 m	±90°	0.35 m/s	50 €	3
NileCam25 CUOAGX GMLS2 / CONTINENTAL MFC527	Monocamera / Smart Mono	-	-	104.6°H/61.6°V 110°H/70°V	1920Hx1200V 1280Hx960V	505 € / 550 €	1

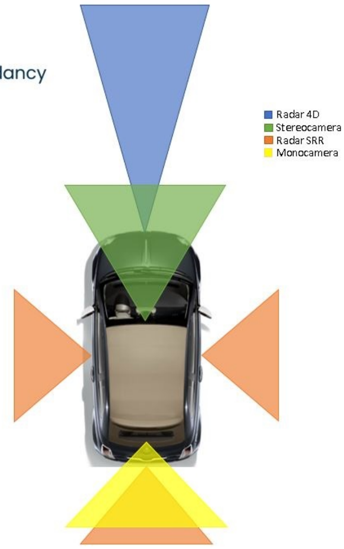


Figure 4.9: Kit solution 1

cyclists by predicting their travel routes. Should a collision be likely, an alarm will sound, and the brakes will be applied automatically, helping to prevent accidents.

4.7.2 Solution 2

In this solution are considered a solid-state LiDAR instead of the 4D radar, in this way, it is possible to test the prototype with the same performance, but guaranteed by two different sensors, and to verify its efficiency in both cases.

Solid-state LiDAR sensors provide a wider field of view for autonomous vehicles than 4d Radars. Nevertheless, these sensors may encounter limitations in severe weather conditions such as heavy rain, snow, and fog, which can have an impact on their performance to some degree. In contrast, 4D radar systems offer intricate insight into the 3D placement and speed of objects, similar to the capability of LiDAR systems. However, due to restricted point cloud concentration and quality constraints, they cannot replace LiDAR over long distances, especially for high-level autonomous driving requirements.

Solution 2: Kit composed by 3D LiDAR, SR Radars and mono/stereo camera redundancy

SENSOR	Type	Max Range	Range Accuracy	FoV	Resolution	Cost	Quantity
ROBOSENSE M1	Solid State LiDAR	200 m	-	120°H 25.1°V	0.2°H 0.2 °V	5000 €	1
ZED X	Smart Stereocamera	20 m	-	110°H/80°V	1920Hx1200V	550 €	1
CONTINENTAL SRR520	Radar SRR	100 m	±0.22 m ±0.5 m	±90°	0.35 m/s	50 €	3
NileCam25 CUOAGX GMLS2	Monocamera	-	-	104.6°H/61.6°V	1920Hx1200V	505 €	1

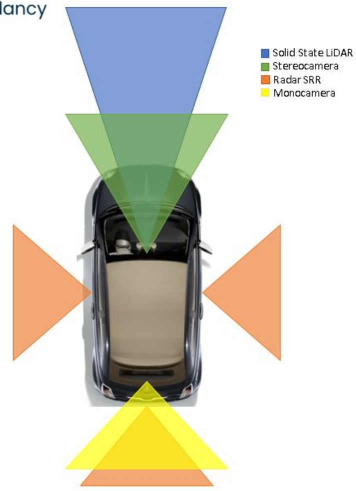


Figure 4.10: Kit solution 2

4.7.3 Solution 3

In the last solution considered, the same sensor kit chosen in solution 1 is used, the stereoscopic camera is removed in order to evaluate the performance of the kit without the depth information provided by the camera, but using the information obtained by the 4D radar. However, with the use of 4 cameras, the entire field of view that the stereoscopic camera would have had, is available.

Solution 3: Kit composed by 4D Radar, SR Radars and combination of mono cameras

SENSOR	Type	Max Range	Range Accuracy	FoV	Resolution	Cost	Quantity
CONTINENTAL ARS 548 RDI	Radar 4D	300 m	±0.15 m	±60°	0.10 m/s	4000 €	1
CONTINENTAL SRR520	Radar SRR	100 m	±0.22 m ±0.5 m	±90°	0.35 m/s	50 €	3
NileCam25 CUOAGX GMLS2	Monocamera	-	-	104.6°H/61.6°V	1920Hx1200V	505 €	4

Figure 4.11: Kit solution 3

This type of approach allows us to have a complete view even in a scenario in which the vehicle must make a curve and we can also have greater control over the information captured by the three cameras: the images can be manipulated to obtain a single panoramic image, or we can consider the information coming from only one of the three cameras according to need.

4.8 AHP Global Results

Solid State LiDAR						
	Robosense RS M1	Hesai AT128	Blickfeld Cube-1	Velodyne Velarray	Livox Horizon	Innoviz Pro
Consistency check	9	9	10	9	9	10

Camera							
	NILeCam25 CUOAGX GMLS2	Continental Mono Camera	Bosch MultiCamera	Sony STURDeCAM 31	Chameleon3 USB3	Grasshoper3 USB3	Leopard Imaging IMX390
Consistency check	8	10	9	10	9	10	9

Stereoscopic Camera			
	ZED X	ZED 2i	LeopardImaging AR0234CS
Consistency check	9	10	9

4D Radar			
	Aptiv FLR4+	Continental ARS 548	Aptiv FLR7
Consistency check	9	8	9

Radar Short Range				
	Continental SRR 308	Continental SRR 520	Texas Instruments AWRL6432	XENSIV BGT60ATR24C
Consistency check	10	9	10	10

Kit			
	Solution 1	Solution 2	Solution 3
Consistency check	8	8	9

Figure 4.12: AHP Global Results

Figure 4.12 shows the overall results collected at the end of the AHP analyses conducted. It can be seen that the components selected in the kits are those which presented a lower consistency check, i.e. a higher reliability index of the result. In some cases, components in the same category may obtain equal values through the mathematical method, such as with solid-state LiDAR. In such instances, selection of the sensor is based on evaluations of other factors, including the percentage of satisfied parameters, both total and critical, and prior experience in similar projects.

4.8.1 Sensors' Global Priority

Below are the final AHP analysis matrices, giving a clear view of the best performing component according to the requirements analysed. Some of the components selected within the kits are the best performers, while in other cases the analysis shows a higher performance of another sensor, however, due to a non-disclosure agreement (NDA), some parameters are taken into account that are not reported in the document. In particular, the values obtained are:

	Global Priority Solid State LiDAR					
	Robosense RS M1	Hesai AT 128	Blickfeld Cube 1	Velodyne Velarray	Livox Horizon	Innoviz Pro
Range	0,0257	0,0257	0,0983	0,0257	0,0983	0,0064
Range Accuracy	0,0352	0,1249	0,0087	0,0352	0,0087	0,0352
FoV	0,0124	0,0124	0,0045	0,0031	0,0029	0,0011
Resolution	0,0169	0,0247	0,0081	0,0097	0,0546	0,0244
Cost	0,0009	0,0019	0,0010	0,0125	0,0063	0,0062
Weather Robustness	0,0108	0,099	0,0104	0,0104	0,0104	0,0109
Urban ADAS	0,0269	0,0206	0,0025	0,0024	0,0025	0,0025
Highway ADAS	0,0081	0,0063	0,0075	0,0075	0,0076	0,0077
Innovation	0,0009	0,0011	0,0089	0,0009	0,0011	0,0014
	0,1138	0,2091	0,1419	0,1075	0,1921	0,0958

Table 4.9: Global Priority Solid State LiDAR

	Global Priority Camera					
	NILeCam25	Continental MonoCam	Bosch MultiCam	STURDeCAM31	Chameleon3	Leopard IMX390
Range	0,0068	0,0065	0,0058	0,0058	0,0057	0,0057
Range Accuracy	0,0272	0,0407	0,0369	0,0367	0,0333	0,0329
FoV	0,0229	0,0041	0,0007	0,0021	0,0042	0,0155
Resolution	0,0456	0,0054	0,0437	0,0782	0,0059	0,0609
Cost	0,0012	0,0024	0,0036	0,0011	0,0007	0,0018
Weather Robustness	0,0603	0,0498	0,0431	0,0412	0,043	0,0211
Urban ADAS	0,0053	0,0052	0,0041	0,0049	0,0056	0,0045
Highway ADAS	0,0178	0,0178	0,0162	0,0168	0,0157	0,0166
Innovation	0,0026	0,0021	0,0021	0,0024	0,0023	0,0022
	0,1691	0,1341	0,1562	0,1894	0,0778	0,1614

Table 4.10: Global Priority Camera

From table 4.10 it should be noted that the Sony STURDeCam31 achieves the highest global priority value, but for this particular application, the NileCAM25 CUXVR GMLS2 is chosen for its compatibility with the application environment: global shutter cameras can be used to accurately capture fast-moving objects in traffic management contexts.

	Global Priority 4D Radar		
	Aptiv FLR4+	Continental ARS 548 RDI	Aptiv FLR7
Range	0,0766	0,0789	0,0841
Range Accuracy	0,0661	0,0641	0,0621
FoV	0,0223	0,0026	0,0022
Resolution	0,0165	0,0175	0,0171
Cost	0,0489	0,044	0,0044
Weather Robustness	0,0161	0,0165	0,0151
Urban ADAS	0,0011	0,0009	0,0011
Highway ADAS	0,0008	0,0007	0,0009
Innovation	0,0009	0,0007	0,0009
	0,1852	0,1867	0,1879

Table 4.11: Global Priority 4D Radar

	Global Priority Short Range Radar			
	Continental SRR 520	Continental SRR 308	Texas Instruments AWRL6432	XENSIV BGT60ATR24C
Range	0,0341	0,0341	0,0079	0,0031
Range Accuracy	0,0132	0,0132	0,0324	0,0141
FoV	0,0031	0,0031	0,0271	0,0271
Resolution	0,0625	0,0615	0,0697	0,0607
Cost	0,0004	0,0004	0,0003	0,0004
Weather Robustness	0,0468	0,0447	0,0441	0,0484
Urban ADAS	0,0023	0,0019	0,0018	0,0018
Highway ADAS	0,0129	0,0119	0,0103	0,0105
Innovation	0,0014	0,0011	0,0011	0,0008
	0,1766	0,1717	0,1946	0,1512

Table 4.12: Global Priority Short Range Radar

	Global Priority Stereoscopic Camera		
	ZED X	ZED 2i	LeopardImg AR0234CS
Range	0,0317	0,0317	0,0045
Range Accuracy	0,0479	0,0664	0,0492
FoV	0,0315	0,0005	0,0382
Resolution	0,0749	0,0084	0,0749
Cost	0,0014	0,0036	0,0149
Weather Robustness	0,0396	0,0398	0,0406
Urban ADAS	0,0017	0,0015	0,0022
Highway ADAS	0,0344	0,0199	0,0221
Innovation	0,0014	0,0013	0,0013
	0,2647	0,1733	0,2481

Table 4.13: Global Priority Stereoscopic Camera

4.9 Results and Discussion

The analysis of the requirements and hierarchical analytical model results enable us to evaluate the selected sensor kit that most comprehensively meets the design phase specifications for fulfilling ADAS technologies such as ACC and LKAS, necessary to obtain a reduction in terms of energy consumption of the prototype. By analysing all of the requirements, we can determine the percentage of features that the sensor covers, without providing excessive detail about the extent of the coverage. Specifically, we examine the degree to which the critical requirements - those essential to the device's functions - are satisfied as a percentage of the total values. Using the AHP method, we examine each individual component in depth to identify suitable sensors for developing the prototype. We perform pairwise comparisons based on technical specifications for each component and determine the most effective category for each one. From the values obtained with the two analyses, a graphic representation is conducted, known as a spider plot:

Spider plots, also known as radar charts, are used for representing multidimensional data in a two-dimensional chart. They are often used when there is a need to display data across several unique dimensions, typically ranging from zero to a maximum value. Each graph shows the coverage area of the main criteria to be met, they are particularly valuable to compare the features and performance of

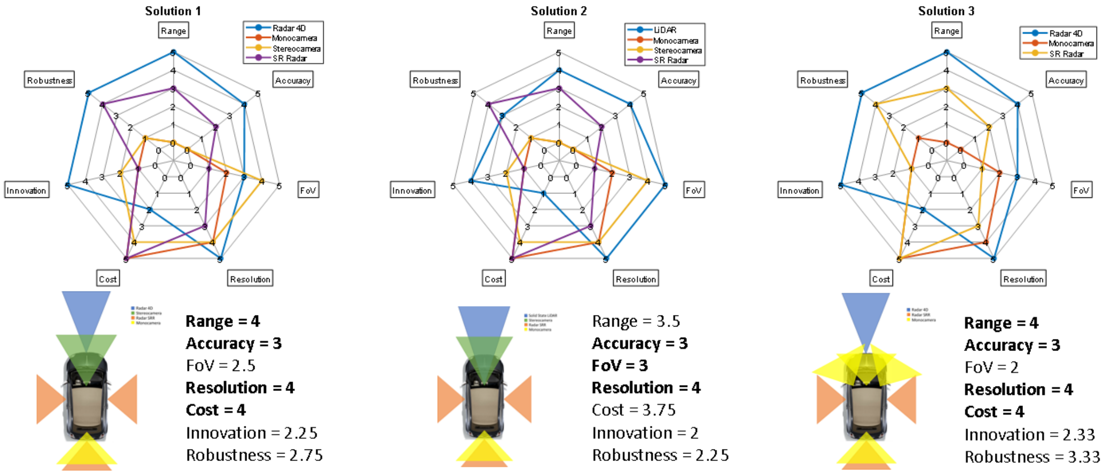


Figure 4.13: Sensors' kits characteristics comparison

different sensors. The study compares three kits and investigates the differences between the adoption of a 4D radar and a solid-state LiDAR. The range parameter is better satisfied with the use of the radar, as illustrated in the figure 4.13. Thus, in motorway applications, using radar is more suitable for ACC technology. One drawback of utilising this sensor relates to the partially obstructed field of view, resulting in a sparser point cloud compared to a LiDAR. It is imperative to meet this requirement, particularly in high-level autonomous driving applications. Cost-wise, the specifications are comparable. In this instance, a 4D Radar, slightly cheaper than Solid State LiDAR, was selected, with accuracy and resolution levels being equally satisfied.

The chart 4.14 provides an overview of the analysed sensor categories. It is evident that 4D radar covers a wider range of features needed for the application in question than solid-state LiDAR, which justifies the choice made.

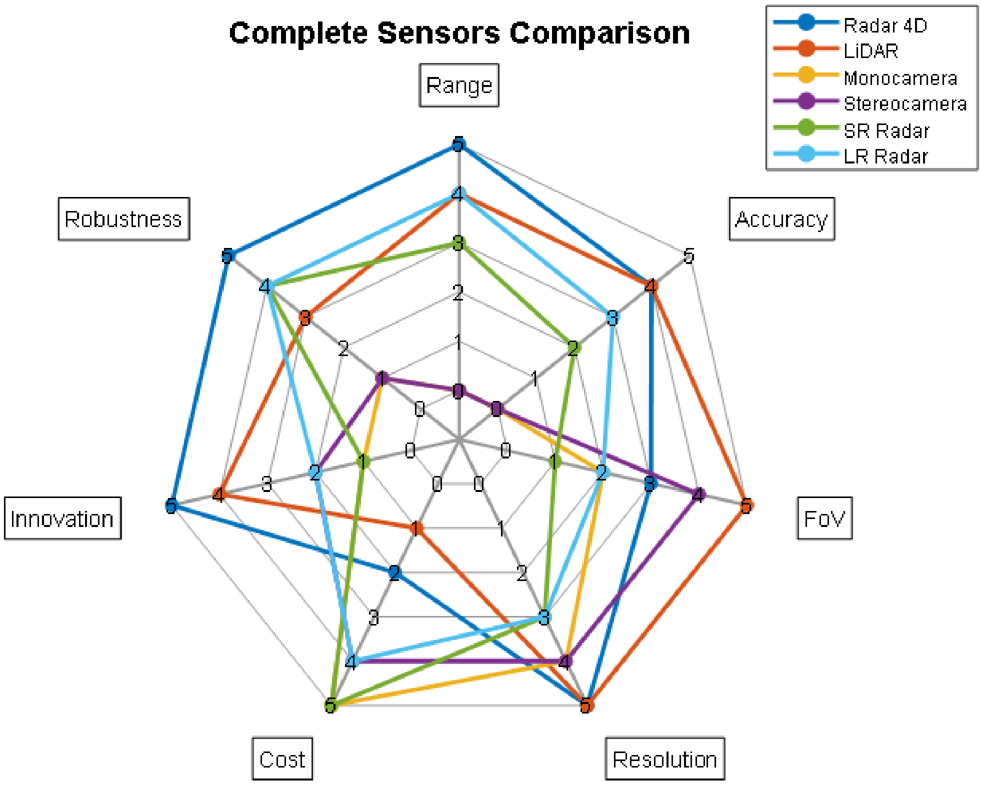


Figure 4.14: Complete Sensors comparison

Chapter 5

Conclusions and Future Works

Technological advancements in recent decades have significantly impacted the automotive industry, resulting in the evolution of conventional internal combustion engines into hybrid or fully electric alternatives. In terms of driving safety, specific systems have been created to assist the driver in certain contexts, including fatigue and/or distraction whilst driving. The initial driver assistance systems (DAS) were gradually developed and modern Advanced Driver Assistance Systems (ADAS) technologies are now a common feature in vehicles. Their primary objectives are to optimize driving comfort and ensure the safety of all road users, including pedestrians, cyclists, while reducing accidents between vehicles. This study focuses on determining the most suitable sensor architecture to be implemented in an urban MOST prototype in order to meet the Energy Management requirements, specifically in reducing vehicle battery energy consumption through the use of ADAS technologies.

The study commenced with an overview of current practices concerning energy management in the automotive sector. Advanced driver assistance systems (ADAS) offer a promising means of enhancing energy management and boosting eco-driving in vehicles, and therefore, the study concentrated on analysing the sensors implemented in ADAS technologies in terms of their principles of operation, associated costs, advantages, and drawbacks. An important focus was understanding the ways in which the sensors transmit the information acquired to the vehicle, therefore the communication protocols. After developing a knowledge baseline, the research then proceeds to categorize the types of sensors available in the market based on their applications, which include automotive, industrial, and robotic grade sensors. The sensor kit on the examined vehicle is evaluated, and potential upgrades for the prototype are analysed based on the basic components. The aim is to develop a sensor architecture that satisfies the requirements set in the design phase, particularly reducing battery power consumption.

After identifying the potential sensors to be evaluated in the development of the kit, a benchmark is established for each sensor category. The objective is to compare the main characteristics and determine which sensor best meets the project specifications. Two analyses are performed. Firstly, a general evaluation is performed taking into account cost factors, total requirements and critical requirements to programme the sensors based on the percentage value of the parameters covered. Second, an AHP analysis is conducted that provides a hierarchical scale, defining in more detail the importance of features for the specific sensor. From the results obtained, the best performing devices for each sensor category are: Robosense RS M1, Continental ARS 548 RDI, NileCAM25 CUXVR GMLS2, Continental SRR 520 and ZED. Sensor kits capable of covering the characteristics required by ADAS technologies are defined, taking into account the redundancies of the short-range radar, which aims to satisfy the needs related to ACC, and the camera, which covers the entire FoV. Subsequently, the kits are also analysed with the AHP metric and it is understood which one is more powerful, with particular focus on the choice of 4D radar instead of solid state LiDAR, evaluating the advantages and disadvantages. The result obtained by using a kit with 3 front cameras without using the stereoscopic camera is also compared. Using the spider diagrams, it is easy to understand the areas of coverage of the basic features for each solution evaluated, in order to have a clear assessment of the efficiency of the chosen set of sensors.

Future work will involve developing the ADAS algorithms and applying the sensors to the donated vehicle in order to carry out tests so that the percentage of kWh/km saved compared to the original configuration can actually be assessed.

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Ad meliora et maiora semper!

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