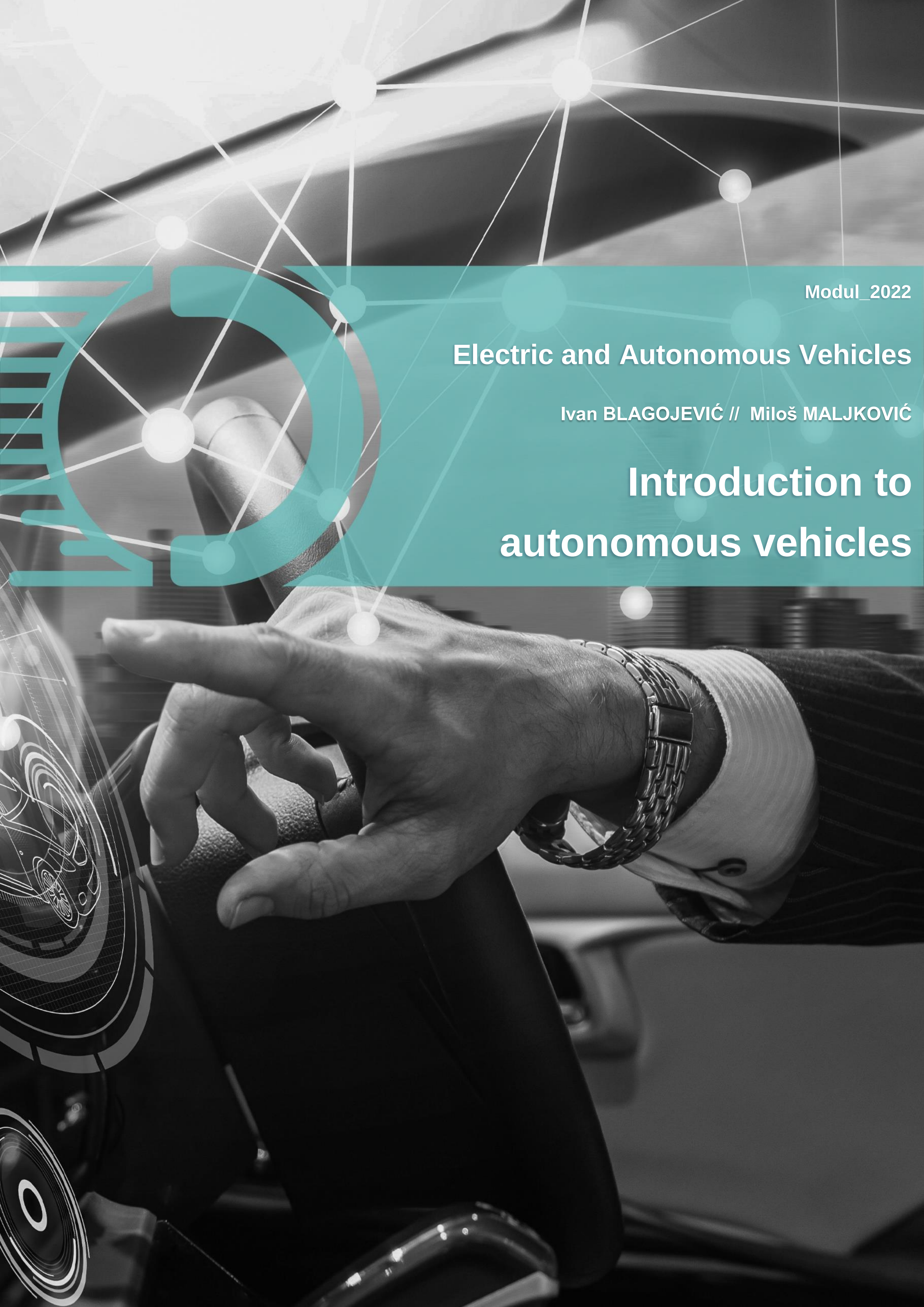

Modul_2022

Electric and Autonomous Vehicles

Ivan BLAGOJEVIĆ // Miloš MALJKOVIĆ

Introduction to autonomous vehicles

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Introduction to autonomous vechicles

DRIVEN

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1. INTRODUCTION

1.1. AUTONOMOUS VEHICLE HISTORY

It is not an easy task to describe the history of autonomous vehicles. The beginning may be pretty clear, but the end – there is no end. Just when one would think that we witnessed the final important event, a new one occurs.

1.1.1. BEGINNINGS

Back in 1478 Leonardo da Vinci created a sketch of a programmed trolley (Figure 1-1.) which, if it had been made, according to the inventor, driven by a mechanism similar to the one in clocks, would have been able to travel forty meters along the straight known and programmed road. This can be considered the beginning of the idea of an autonomous vehicle – an idea that, centuries after its creation, will be the guiding principle for engineers around the world.

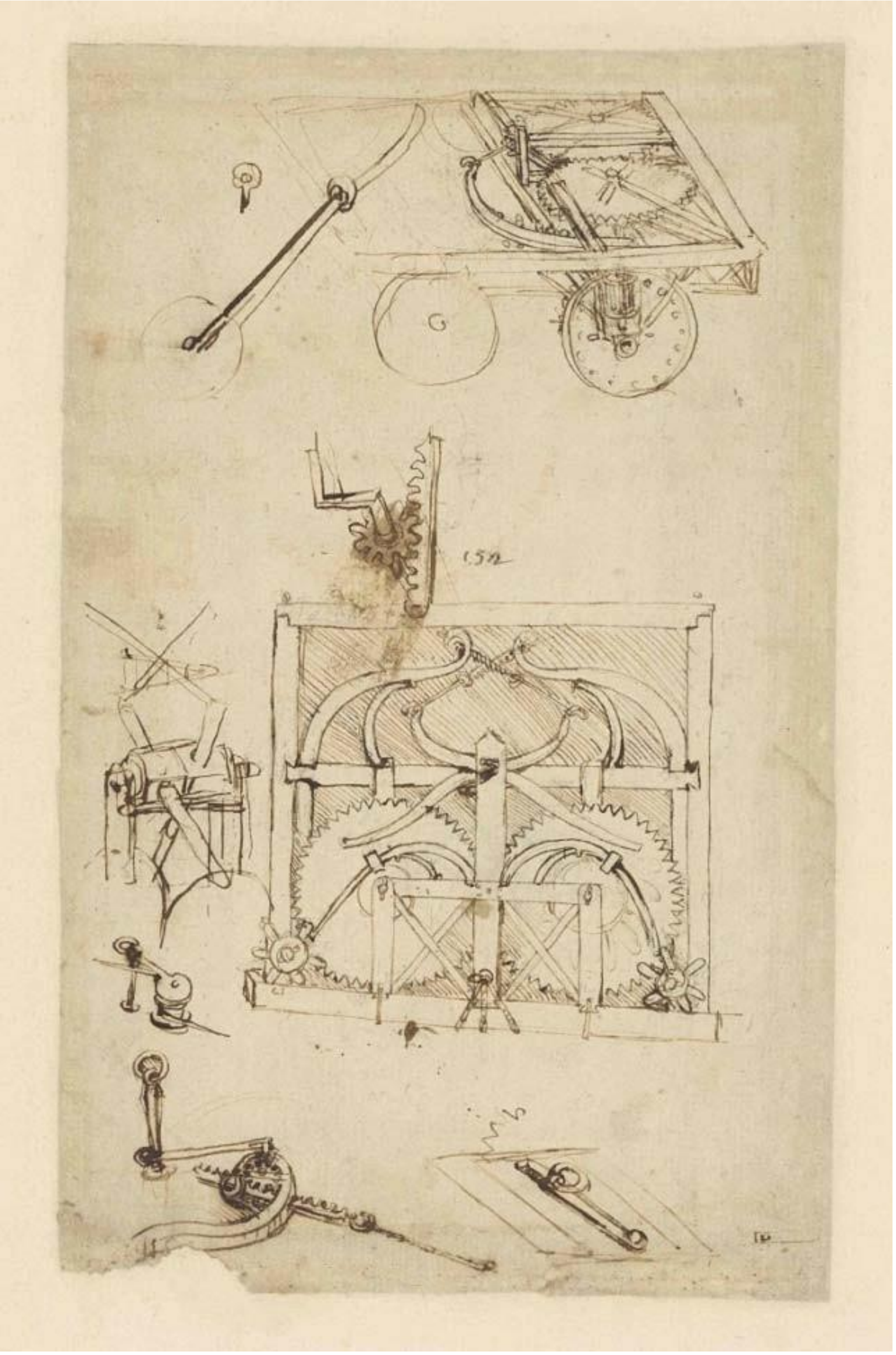
Just as autonomous vehicles would not exist without driver assistance systems that paved the way for them, so Da Vinci's trolley would not exist without the inventions of his predecessors. Figure 1-2. presents inventions created in ancient Greece, which the author (and the curator of several museums of such inventions) considers to have laid the foundations of a modern vehicle. Among them is the Heron's automated puppet show from the first century AD, presented as the forerunner of the "autopilot" in the vehicle.

Nearly 450 years after Da Vinci's project, in 1925, the company *Houdina Radio Control* presented a car capable of running without a driver. A vehicle called the *Linrrican Wonder* (Figure 1-3.), actually *Chandler Metropolitan Sedan* with built-in electric motors as actuators controlled by radio waves from the transmitter in the vehicle behind, drove along New York's Fifth Avenue and Broadway through heavy traffic. Although the vehicle control signals were provided by an operator from the vehicle behind, this experiment paved the way for the subsequent attempts to create a fully autonomous vehicle.

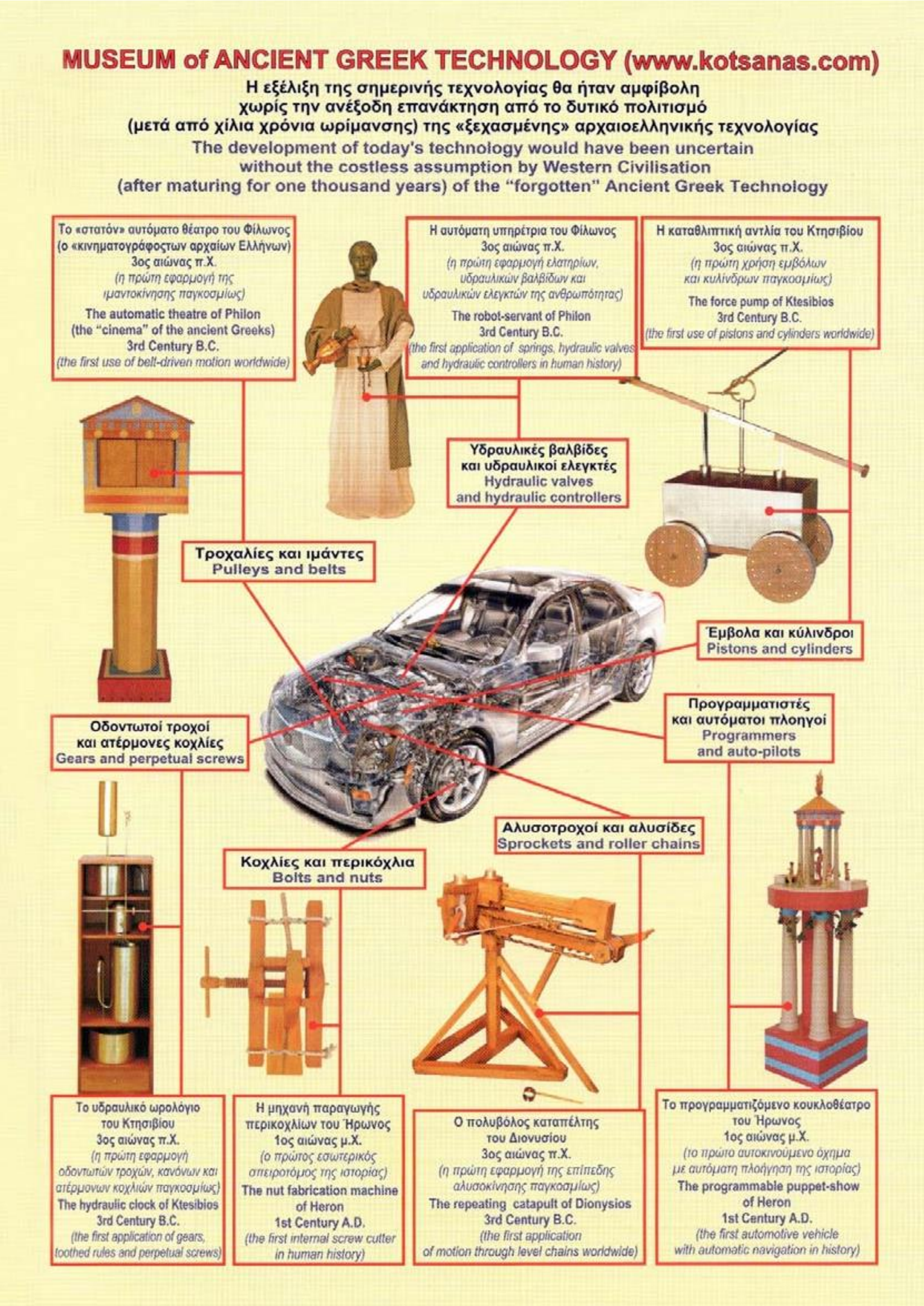
1.1.2. YEARS OF DAYDREAMING

For the next five decades, attempts to create an autonomous vehicle have largely ended up as mere concepts. In 1939, General Motors sponsored an exhibition titled *"Futurama"* by Norman Bell Geddes (Figure 1-4.), which showed the vision of the city of the future with electric vehicles driven by radio waves as part of a world exhibition in New York.

In the 1950s and 1960s, General Motors presented a series of prototypes of vehicles called *Firebird*, which they claimed were supplied with electrical systems capable of operating vehicles on the highway without driver assistance. One of the cars from that series is a 1958 Firebird III (Figure 1-5.).

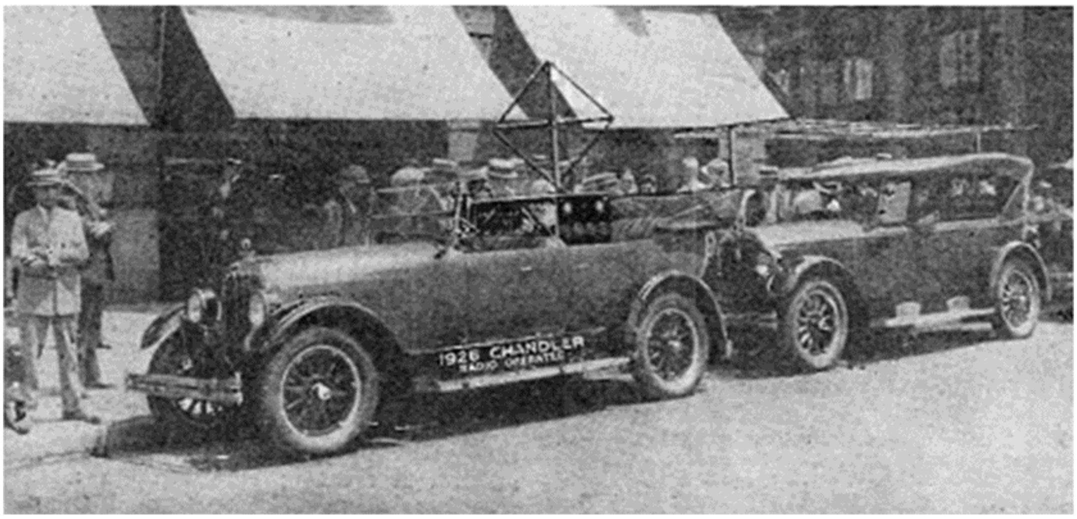


1-1. Figure Sketch of Da Vinci's programmed trolley



1-2. Figure Inventions of ancient Greeks as the foundation of a modern car

In 1958, *RCA*, in collaboration with the government of Nebraska, presented a 120-metre stretch of highway on the outskirts of the city of Lincoln with built-in electric circuits that were able to detect the vehicle and send it control impulses. For this project, General Motors equipped two vehicles with radio receivers and actuators in the steering system, to control the operation of the drive unit and the braking system. Two years later at the headquarters of the *RCA* laboratory in Princeton, journalists were allowed to take a drive in these cars (Figure 1-6.).



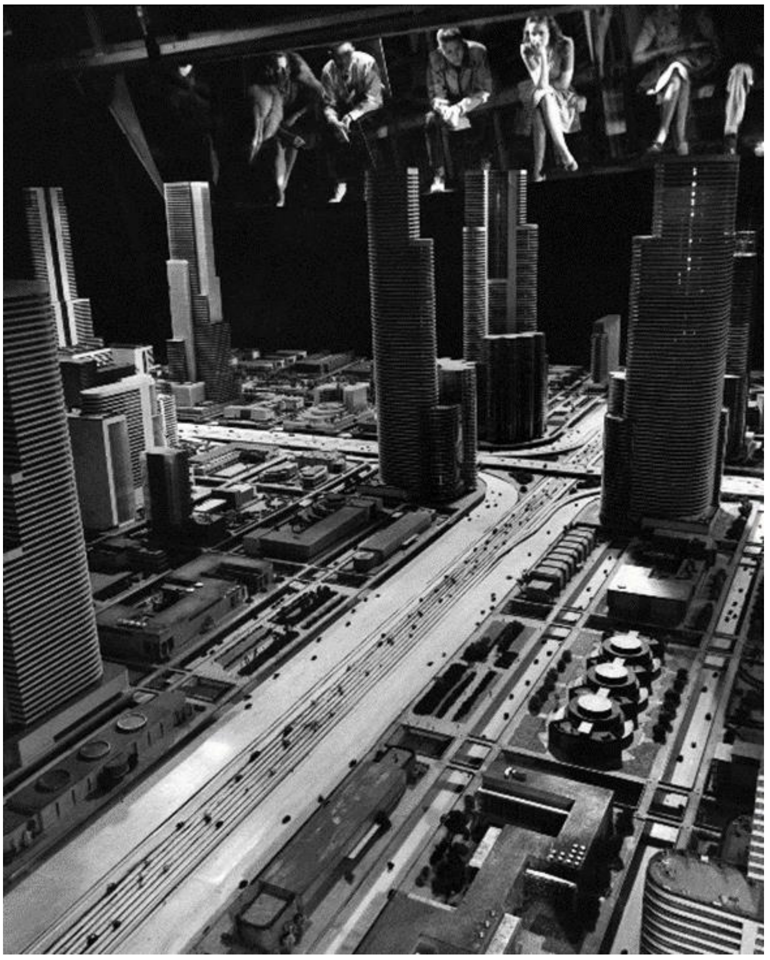
1-3. Figure Linrrican Wonder and accompanying vehicle

1.1.3. DREAM BECOMES A REALITY

During the 1960s, the UK Traffic and Road Testing Laboratory developed the Citroen DS (Figure 1-7.), which was operated with cables embedded in the road. The vehicle was able to pass the test track at 130 km/h without deviating from the set speed and direction in all weather conditions. Tests continued in the first half of the 1970s, and analyses from that time predicted that investments in road reconstruction would be repaid by the end of the century, increasing the capacity of roads by at least 50% and reducing the number of accidents by 40%. Funding for the project was cut off in the mid-1970s.

In 1977, the *Tsukuba* laboratory from Japan presented the first computerized autonomous vehicle (Figure 1-8.) that was able to reach a speed of 30 km/h following the white markings on the road recorded by the camera.

In the early 1980s Ernst Dickmanns and his team from the Munich State University started a series of projects to create an autonomous vehicle. The first result of their efforts was shown in 1986 – a modified Mercedes-Benz TN called *VaMoRs* (Figure 1-9.) operated on the basis of data from a camera installed in the vehicle. The vehicle was tested on roads without traffic, and was able to reach speeds of about 100 km/h. In the same year, *EUREKA* started a EUR 749 million project called “Prometheus” (*PROgraMme for a European Traffic of Highest Efficiency and Unprecedented Safety*). The result of this project is two “twin” vehicles developed by the Dickmanns team on the basis of Mercedes-Benz Class C – *VaMP* and *VITA-2*. In 1995, one of the two vehicles crossed the road from Munich to Odense (1758 km) moving at speeds of up to 175 km/h, 95% of the route moving completely autonomously, performing lane change and overtaking manoeuvres.



1-4. Figure "Futurama" Exhibition

1-5. Figure General Motors Firebird III

1-6. Figure RCA "autonomous" vehicles

1-7. Figure Citroen DS reworked by the Laboratory for Traffic and Road Testing

1-8. Figure Tsukuba autonomous vehicle

1-9. Figure VaMoRs

The 1980s brought a project called *ALV (Autonomous Land Vehicle)*, funded by the United States Defense Advanced Research Projects Agency (*DARPA*), involving the University of Maryland, Carnegie Mellon University, the Institute for Environmental Research in Michigan and SRI International. In 1989, an artificial neural network was used for the first time at Carnegie Mellon University to operate an autonomous vehicle, creating the basis for the autonomous vehicle controlling strategies that are still in use today. Six years later, the Carnegie Mellon University project called *Navlab* (Figure 1-10.) crossed a road of about 5,000 km, 98.2% of which was completely autonomous. This venture was named *“No Hands Across America”.* This vehicle, however, was semi-autonomous – the neural network was used to control the actuators in the steering system, while the control of the drive unit and the braking system, primarily for safety reasons, was performed by human.

1-10. Figure Navlab

In 1996, professor Alberto Broggi of the University of Parma launched a project called *ARGO* with the task of enabling the modified Lancia Thema (Figure 1-11.) to follow the lines on the unmodified highway. A thousand autonomous miles (*Mille Miglia in Automatico*) is the name given to the road travelled by this vehicle in the length of about 1900 km along the motorways in northern Italy at an average speed of 90 km/h, 94% of the time completely autonomous. The vehicle was equipped with only two cheap black and white cameras and an algorithm for stereoscopic analysis of the surrounding. Fourteen years later, a team of professor Broggi under the name of *VisLab* carried out the first intercontinental ride of an autonomous vehicle on a 15,900km route from Parma to the world exhibition in Shanghai. It took a hundred days for four electric vehicles to reach their destination. The project was funded by the European Union.

1-11. Figure Driving in a Lancia Thema modified for ARGO project purposes

In 2004, the US *Defense Advanced Research Projects Agency* (*DARPA*) organized a competition called the *Grand Challenge*. A US $1 million reward is offered to any team that creates an autonomous vehicle able to cross the 150-mile track in the Mojave Desert for no more than 10 hours. No vehicle has been able to travel more than 5% of the length of the track. Next year, the second edition of the competition was held, this time more successfully – five vehicles finished the race, four of them within the stipulated deadline. The vehicle *Stanley* of the Stanford University Artificial Intelligence Laboratory won. Second and third place were taken by the vehicles of Carnegie Melon University – *Sandstorm* and *H1ghlander* (Figure 1-12.). Two years later, in the third competition, this time in urban setting, the Carnegie Melon University vehicle called *Boss* won the 97 km race.

1-12. Figure Winners of the "Great Challenge II" – Stanley, H1ghlander and Sandstorm

At the end of 2008, testing of the first commercial autonomous dump truck by *Komatsu* began (Figure 1-13.) at the Pilbara mine owned by Rio Tinto. By April 2020, the number of autonomous dump trucks owned by this company had increased to over 130.

A project called *SARTRE* (*SAfe Road TRains for the Environment*), funded by the European Commission, was implemented from 2009 to 2012. The aim of the project was to develop road trains (platoons) in which passenger vehicles would follow a freight vehicle operated by a professional driver. In this way, in addition to increasing safety (assuming that a professional driver is much less likely to cause a traffic accident than an amateur driver), savings in fuel consumption could be achieved due to a reduction in air resistance in such formations (Figure 1-14. shows one).

1-13. Figure First five autonomous dump trucks in Pilbara mine

1-14. Figure Road train within the SARTRE project

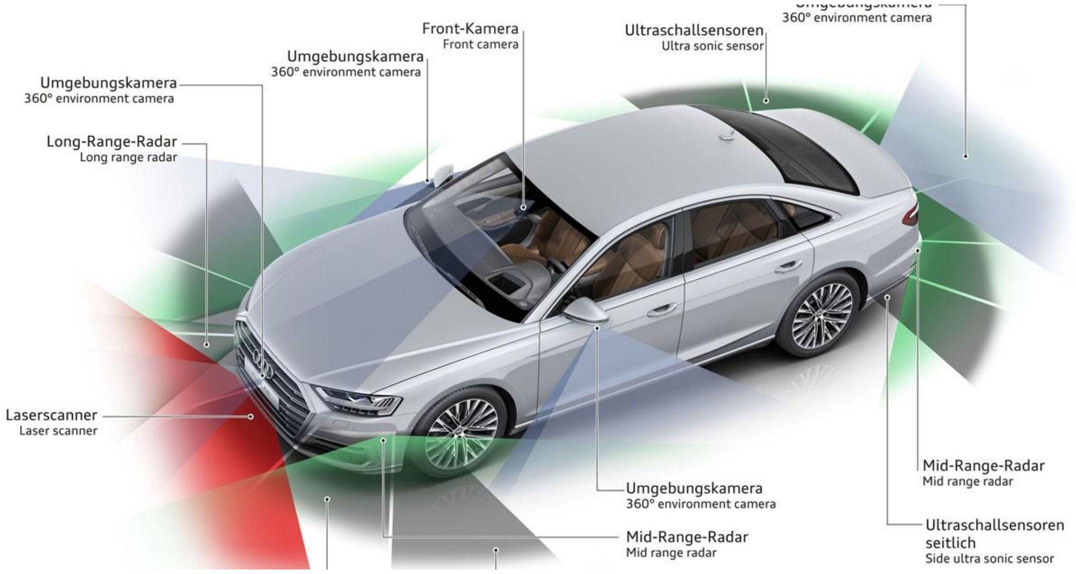
1.1.4. PRESENT

Modern driver assistance systems that are installed in serially manufactured vehicles have already brought “regular” vehicles closer to autonomous vehicles. These systems include the following:

- Collision prevention;
- Driver monitoring;
- Recognition of traffic signs;
- Adaptive lights;
- Blind spot monitoring;
- Lane departure prevention;
- Parking assistance;
- Active suspension.

Modern safety systems on vehicles have a large number of sensors – Figure 1-15. shows the sensors of the *Pre Sense 360˚* system on an Audi vehicle, which combines the functions of several different systems (collision prevention, driver monitoring, traffic sign recognition, blind spot monitoring, lane departure prevention and parking assistance). Therefore, such systems must be seen as parts of a unified system that helps the driver to drive safely, and it is inevitable to notice that such a system has almost all the elements necessary for autonomous vehicle control.

A large number of manufacturers, including Nissan, Mercedes-Benz, Tesla, Volvo, Toyota and Volkswagen are engaged on developing their own autonomous vehicle. The general public is perhaps the most familiar with the project by Google, which began developing an autonomous vehicle in 2009. Now the development is taking place within Google's subsidiary *Waymo*, on vehicle platforms such as Toyota Prius, Audi TT, Lexus *RX450h*, Chrysler Pacifica and Jaguar I-Pace, but also around a hundred vehicles developed specifically for the needs of the company.



1-15. Figure Audi Pre Sense 360˚

All the efforts made so far are aimed at making autonomous vehicles an everyday thing on our roads. A symbolic step towards this goal is the undertaking of Diamler and the Karlsruhe Institute of Technology from 2013, when a vehicle (Mercedes-Benz C-class) equipped with a stereo camera and radars completely independently crossed the road of about 100 km from Mannheim to Pforzheim – the same road that *Bertha Benz* had traveled 125 years before, and which was recorded as the first long distance travelled by a car in history.

1.2. AUTONOMOUS VEHICLES AND REGULATIONS

Who is obliged to pay the penalty if an autonomous vehicle commits a traffic violation? What happens if the vehicle doesn't stop on the officer's signal? Who is responsible in the event of an accident caused by an autonomous vehicle – the owner, manufacturer or the authority that registered the vehicle? These are all questions that come to mind when we think about the possibility of autonomous vehicles moving on the same roads that vehicles are moving today in the way they have always moved – with the driver behind the wheel. As someone asked – autonomous vehicles will soon be (and may already be) ready for the roads, but are the roads ready for autonomous vehicles? Figure 1-16. illustrates the current situation – a police officer stopped an autonomous Google vehicle in the US during a road test due to too low speed, although the vehicle was granted a license to travel on roads with a speed limit of 40 km/h set by the manufacturer.

The first driver's death in a partially automated vehicle (when in January 2016 a Tesla Model S vehicle hit a garbage truck on the Hong Kong-Macao highway) and the first pedestrian death (caused by an automated vehicle, which occurred in the US state of Arizona, when a specially equipped Volvo *XC90* owned by Uber hit a pedestrian crossing the street outside a pedestrian crossing) further arose the expert, but also the general public, and made it clear to everyone that the safety of autonomous vehicles must be given full attention.

Issues of ethical principles, responsibilities and insurance are still open, but they are not the primary area of interest here.

1-16. Figure Police officer stops Google autonomous vehicle (photo: Zandr Milevski)

1.2.1. EUROPE

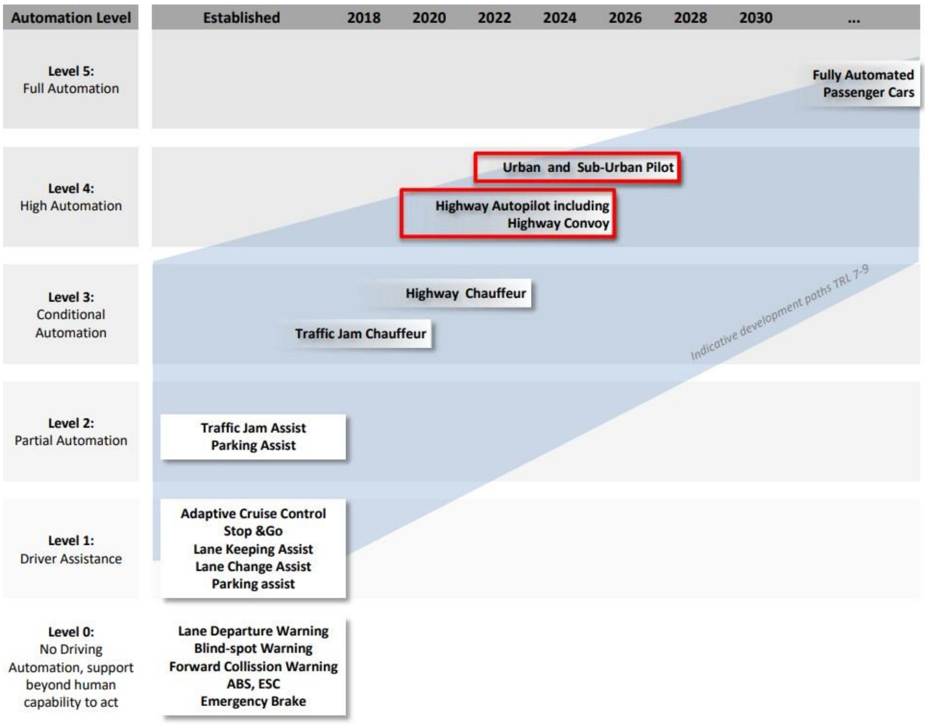
The Vienna Convention on Road Traffic from 1968 stipulates that every vehicle or group of vehicles moving must have a driver who is at all times allowed to operate a vehicle. Some countries saw this provision as an obstacle to the introduction of autonomous vehicles into traffic. Amendments to the text of the convention that entered into force in 2016 allowed autonomous movement of vehicles, but as long as the autonomous control system can be overridden or deactivated by the driver.

Figure 1-17. shows the development plan for autonomous passenger vehicles in Europe published by the *European Road Transport Research Advisory Council (ERTRAC).*

In 2013, the UK government approved the testing of autonomous vehicles on public roads. In order to be able to perform the test, the vehicle must be covered by insurance, the vehicle must have a trained and experienced driver whose obligation is to monitor the behavior of the vehicle and be on standby throughout the journey in order to take control of the vehicle if the need arises. In addition, the vehicle must have a device for recording vehicle movement data (so-called “black box”), which in the event of a traffic accident would provide sufficient data to investigate its cause, and above all information on whether the vehicle was in an autonomous or “manual” mode. In addition to the above, the manufacturer must assure the authorities that the vehicle has previously successfully passed laboratory tests and tests on closed roads or test sites. The first four infrastructure projects were launched in 2017, developing two closed and two open (within public roads) test sites for autonomous vehicles in West Midland and London.

The Dutch government has adapted legislation to tests of autonomous vehicles on public roads. As a next step, the Assembly gave its approval to enact legislation that would allow autonomous vehicles to be tested without presence of drivers. The Netherlands is currently a leader in autonomous vehicle platoons research.

In July 2014, France launched a project called “Plan for Autonomous Vehicles” within the framework of the strategy entitled “New French Industry”, and appointed the then CEO of the Renault-Nissan Group, Carlos Ghosn, as the manager. The plan includes, among other things, test zones for testing autonomous vehicles, but also changes in driver training.



1-17. Figure Plan for the development of autonomous passenger vehicles in Europe

In the spring of 2015, the Swiss Ministry of the Environment, Transport, Energy and Communications allowed *Swisscom* to perform testing of Volkswagen Passat modified into an autonomous vehicle on the streets of Zürich.

In September 2015, the German government adopted the “Strategy for Autonomous and Connected Vehicles”. The strategy envisages the modification of the term driver in the Vienna Convention on Road Traffic (to include “systems with full control over the vehicle”), the allowed speed of up to 130 km/h with autonomous change of traffic lanes (with the revision of UN Regulation No. 79 which defines the requirements for steering systems) and an amendment to the Law on Road Traffic which defines the rights and responsibilities of drivers during the automated driving phase and the development of ethical guidelines for the programming of automated driving systems. For the time being, any province in Germany may, by way of exemption, allow autonomous vehicles to be tested on public roads, with the obligatory presence of drivers with full responsibility for the safe movement of vehicles.

With the help of Volvo, the Swedish government has launched an initiative called *Drive Me*. Motivated by a vision of traffic without human casualties, the initiative will enable research within different areas related to autonomous vehicles. Since 2017, in the Goetheborg area, "ordinary" people drive Volvo autonomous vehicles every day with the aim of their development. This was made possible by a government regulation allowing autonomous vehicles to be tested.

In 2015, the Spanish Directorate-General for Transport adopted a regulation permitting the testing of autonomous vehicles in four dedicated test sites.

Since 2017, there have been three test sites for autonomous vehicles in Austria.

The current Finnish legislation is liberal and enables automated control of vehicles on open roads (including remote control), with the issuance of special plates for such vehicles. The 75 km Aurora test site with a specially equipped section of 10 km along the E8 highway in northern Finland is actively used.

1-18. Figure ZalaZone test site

By decision of the Minister of June 13, 2015, Greece allowed the usage of fully automated vehicles without drivers in urban areas and on public roads for research purposes, with detailed analysis of the proposed routes, vehicle approval, appropriate training for operators (including remote operators), supervision by specialized research or academic bodies and active support from local authorities. The first fully automated vehicles were licensed for traffic on October 29, 2015 in Trikala.

Hungary bases its strategy on the *ZalaZone* Autonomous Vehicle Test Site (Figure 1-18.) in the Zalaegerseg area. As of April 12, 2017, testing of prototypes of autonomous vehicles on public roads is allowed in Hungary. It should be said that there are many similar test sites around the world, but a good part of them are in the development phase.

1.2.2. USA

The first country where regulations allow testing of autonomous vehicles is the USA. Currently, thirty states in the USA enacted such regulations (among them, Nevada leads the way – figure 1.19). In 2013, the National Highway Traffic Safety Administration proposed a formal system of vehicle division according to the level of autonomy:

- LEVEL 0 – The driver fully controls the vehicle at all times;
- LEVEL 1 – Certain vehicle controls are automated (such as electronic stability control or collision prevention system);
- LEVEL 2 – At least two controls are automated simultaneously (for example, adaptive cruise control and lane centering);
- LEVEL 3 – The driver can fully cede the control over all safety-critical functions under certain conditions. The vehicle "senses" when conditions require the driver to take control and leaves the driver sufficient time to react;
- LEVEL 4 – The vehicle operates all safety-critical functions at all times, and the driver is not expected to operate the vehicle at any time. As this vehicle controls all functions from starting to stopping the vehicle, including parking functions, this level can also indicate vehicles without passengers.

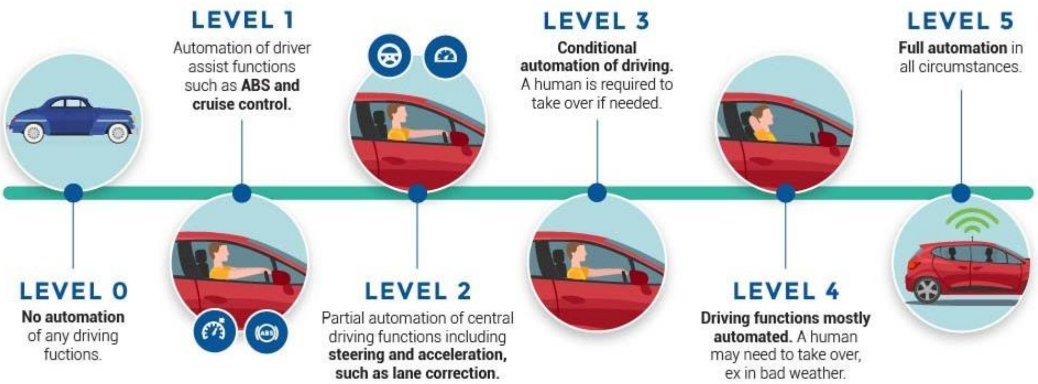
1-19. Figure First registered autonomous truck in the U.S. State of Nevada

Subsequently, this division was amended by SAE J3016 and as such became generally accepted. Table 1-1. and Figure 1-20. (in simplified form) show this division.

Common to US states that have allowed the use of autonomous vehicles is the requirement of vehicle type approval and insurance. Driver attendance is also required, except in the case of Florida. In Nevada, the use of mobile phones and portable communication devices while driving is prohibited for drivers of conventional vehicles, while it is allowed for users of autonomous vehicles. In January 2017, the Ministry of Transport designated ten locations for testing autonomous vehicles.

1-1. Table Automation levels

Level	Name	Narrative definition	DDT: Sustained lateral and longitudinal vehicle motion control	DDT: OEDR	DDT fallback	ODD
Driver performs part or all of the *DDT*						
0	No Driving Automation	The performance by the *driver* of the entire *DDT*, even when enhanced by *active safety systems*.	*Driver*	*Driver*	*Driver*	n/a
1	Driver Assistance	The *sustained* and *ODD*-specific execution by a *driving automation system* of either the *lateral* or the *longitudinal vehicle motion control* subtask of the DDT (but not both simultaneously) with the expectation that the *driver* performs the remainder of the *DDT*.	*Driver* and *System*	*Driver*	*Driver*	Limited
2	Partial Driving Automation	The *sustained* and *ODD*-specific execution by a *driving automation system* of both the *lateral* and *longitudinal vehicle motion control* subtasks of the *DDT* with the expectation that the *driver* completes the *OEDR* subtask and *supervises* the *driving automation system*.	***System***	*Driver*	*Driver*	Limited
ADS ("*System*") performs the entire *DDT* (while engaged)						
3	Conditional Driving Automation	The *sustained* and *ODD*-specific performance by an *ADS* of the entire DDT with the expectation that the *DDT fallback-ready user* is *receptive* to *ADS*-issued *requests to intervene*, as well as to *DDT performance-relevant system failures* in other *vehicle* systems, and will respond appropriately.	*System*	***System***	*Fallback-ready user (becomes the driver during fallback)*	Limited
4	High Driving Automation	The *sustained* and *ODD*-specific performance by an *ADS* of the entire *DDT* and *DDT fallback* without any expectation that a *user* will respond to a *request to intervene*.	*System*	*System*	***System***	Limited
5	Full Driving Automation	The *sustained* and unconditional (i.e., not *ODD*-specific) performance by an *ADS* of the entire *DDT* and *DDT fallback* without any expectation that a *user* will respond to a *request to intervene*.	*System*	*System*	*System*	**Unlimited**



1-20. Figure Automation levels (simplified view taken from www.caa.ca)

1.2.3. REST OF THE WORLD

Testing of autonomous vehicles on public roads with a special permit has been possible in Japan since September 2013. The two largest Japanese manufacturers, Toyota and Nissan, are currently working on autonomous vehicle projects. In 2017, a series of tests was started, including those on the roads near the locations where the Summer Olympics were held in Tokyo. This is a logical consequence of Japan's aspiration to move from Industry 4.0 to Society 5.0, one of the basic pillars of which is autonomous vehicles.

1-21. Figure Hyundai Genesis autonomous vehicles

In March 2016, the South Korean Ministry of Land, Infrastructure and Transport held a ceremony at a government complex in the city of Sejong on the occasion of the first traffic permit issued for an autonomous vehicle in South Korea, to the domestic manufacturer Hyundai Motors, with a validity of five years. Three weeks before that, the manufacturer applied for a licence for one vehicle, *Hyundai Genesis* (Figure 1-21.) and two drivers, at least one of whom must be in the vehicle whenever it moves. The vehicle is marked in a special way so that drivers of other cars are aware that it is a vehicle without a driver. Vehicle movement is limited to two sections of highway and four sections of roads for motor vehicles (320 km in total).

In December 2019, Beijing designated an area of 40 km^2 for testing autonomous vehicles with passengers. The city also issued a license for passenger transportation to 40 autonomous vehicles owned by the Internet giant Baidu.

South Australia is the first Australian state to adopt autonomous vehicle regulations. These regulations will allow manufacturers to test autonomous vehicles on the roads of South Australia with the permission of the Ministry of Transport. This decision should also be seen through the prism of shutting down the plant of the Australian manufacturer Holden in this part of Australia, so the local government hopes that autonomous vehicle manufacturers will fill the gap thus created.

1.2.4. CONCLUSION

It can be concluded that the development of accompanying regulations falls well short of the development of autonomous vehicles – and even when national laws on the movement of autonomous vehicles on public roads are enacted, their application is largely limited to vehicle testing by manufacturers. One could conclude that regulations are becoming a key obstacle in the application of autonomous vehicles, but the question remains how much the current level of technology development deserves the trust of the legislators. Most current regulations therefore require the presence of a driver in the vehicle in order to react in case of need. Therefore, existing regulations should be seen as a kind of transitional provision – when tests show that autonomous vehicles are sufficiently reliable, the presence of drivers will likely no longer be mandatory. A further challenge in the future will certainly be the problem of high-tech crime – it has already been shown that attacks of this kind can endanger the safety of conventional vehicles, and in the case of autonomous vehicles, the danger becomes even greater.

1.3. ACCESSIBILITY OF TECHNOLOGY

The technology (in terms of hardware) that enables vehicle autonomy is increasingly affordable. This is also supported by the fact that perhaps the most active companies in the field of autonomous vehicles are currently software companies (Google, Uber, Nvidia…).

1-22. Figure Student exercises from the vehicle mechatronics course

1-23. Figure Software for the recognition of traffic participants as a result of the Master's thesis in the Department of Motor Vehicles

The price of components for the automation of lower scale vehicle models has also dropped significantly, allowing students around the world to develop their vehicles without drivers on similar principles as is done with real vehicles. This opportunity was used by the Department of Motor Vehicles of the Faculty of Mechanical Engineering, University of Belgrade and allowed its students to “play around” by assembling their “autonomous” vehicles (Figure 1-22.). The result of such a “play” are Master’s Theses the outcomes of which are similar to those of development teams of world-renowned companies (Figures 1-23. and 1-24.).

1-24. Figure Software for the recognition of traffic signs as a result of the Master's Thesis in the Department of Motor Vehicles

1.4. AUTONOMOUS VEHICLE APPLICATION POSSIBILITIES

Transport is certainly the domain most affected by the application of autonomous vehicles. Significant media attention and investments in research and development in the field of autonomous vehicles lead to the emergence of many start-ups in this field.

Autonomous vehicles, whether they are intended for the user's (owner's) own needs or for transport sharing between users (for example, robo-taxis), are undoubtedly a technology that changes our idea of vehicles, not only our behavior when driving in such vehicles, but also related issues such as insurance, responsibility and many others. Although most vehicle manufacturers strive for complete autonomy of vehicles, the race to develop autonomous vehicles has caused, as previously mentioned, an increasing number of “new players” that do not belong to the traditional automotive industry. Autonomous vehicles used in public transport are likely to reach the highest levels of autonomy (level 4 or even level 5) in the near future. These autonomous vehicles typically move on private or public roads within a particular controlled and restricted environment. They also have predefined routes, such as, for example, transporting people from a railway station to an airport terminal, between buildings on a large campus or from one to another sightseeing point in a large theme park. A higher level of autonomy can be achieved more easily compared to private passenger vehicles, due to the significantly lower complexity of the environment in which they operate.

Due to the limited and predefined vehicle radius, the entire environment can be mapped very accurately to allow precise localization. In addition, these vehicles usually move at low speeds along predefined routes, and are usually allowed to stop in the event of an emergency and wait until the unforeseen situation is resolved. An example of an autonomous public transport vehicle is given in Figure 1-25. Autonomous public transport is mainly supported by operators who manage the fleet of vehicles by organizing departures, monitoring the condition of vehicles, displaying information to passengers in the vehicle, controlling the ticketing system, etc. A system like this can be operated by humans, or it can be fully automated where people just monitor the operation of the system and react as needed.

1-25. Figure Autonomous vehicle intended for public passenger transport

Delivery of goods from the distribution center to the end user creates a long and complex logistics chain. Delivery to the end user is the last part of this chain, which includes the movement of goods from the local distribution center to the end user at the final destination. According to various analyses, the delivery of goods from the local distribution center to the end user accounts for 50% or more of the total delivery costs. There are several reasons why delivery from the local distribution center to the end-user is the least efficient in the supply chain. Traffic jams and lack of parking spaces in urban areas, longer journeys to remote areas and repeated delivery attempts due to unavailability of user negatively affect the efficiency of the goods delivery process. Therefore, many logistics companies recognize the potential of autonomous vehicles to make delivery more efficient and cheaper. Driverless delivery vehicles and delivery drones are two examples that can lead to higher efficiency of the delivery of goods from the local distribution center to the end user. Autonomous goods delivery robots, as shown in Figure 1-26., pick up goods from the distribution center and move independently to reach the end user's address.

Although autonomous movement in 3D airspace is more challenging than 2D space for ground moving vehicles, the basic technologies applied are common - for example in the field of perception and navigation.

1-26. Figure Goods delivery robot

In addition to the delivery of goods from the local distribution centre to the end user, autonomous vehicles also have the potential to improve safety and efficiency in the second part of the transportation sector, i.e. in the long-distance transport of goods by road. According to the statistical report on transportation in the European Union, published in 2018, the vast majority of freight is transported by road. However, road transport operators in Europe (and also in the US) face an increasing shortage of truck drivers, which makes autonomous trucks (Figure 1-27.) a solution that has a perspective. However, according to the same report, a shortage of drivers in Europe will still be an issue, even with the introduction of autonomous trucks. The grouping of two or more trucks with semi-trailers travelling in a convoy is the most common way of applying autonomous driving in the sector of road freight transport. Convoy vehicles follow the lead vehicle, maintaining a safe distance from each other. In addition to reducing fuel consumption and increasing traffic safety, the movement of trucks in such a formation can also improve traffic flow.

1-27. Figure View from the cab of the autonomous truck

2. OVERVIEW OF SENSORS USED IN AUTONOMOUS VEHICLES

2.1. INTRODUCTION

There are many strategies used to control an autonomous vehicle. Different inputs are used to control the vehicle – signals from video cameras, global positioning system transmitters, acceleration sensors, radars, ultrasonic and laser sensors, etc. Also, there are different types of controllers. Many of them are based on artificial intelligence – mainly neural networks. By studying the literature, it can be concluded that about 60% of the described autonomous vehicle models use cameras, 20% use radars and 20% use global positioning system sensors as the primary recognition device. In the same group, about 80% of the models are controlled by artificial neural networks, and about 20% by fuzzy logic controllers. Thus, control based on a camera signal processed by an artificial neural network is the most common combination in the literature.

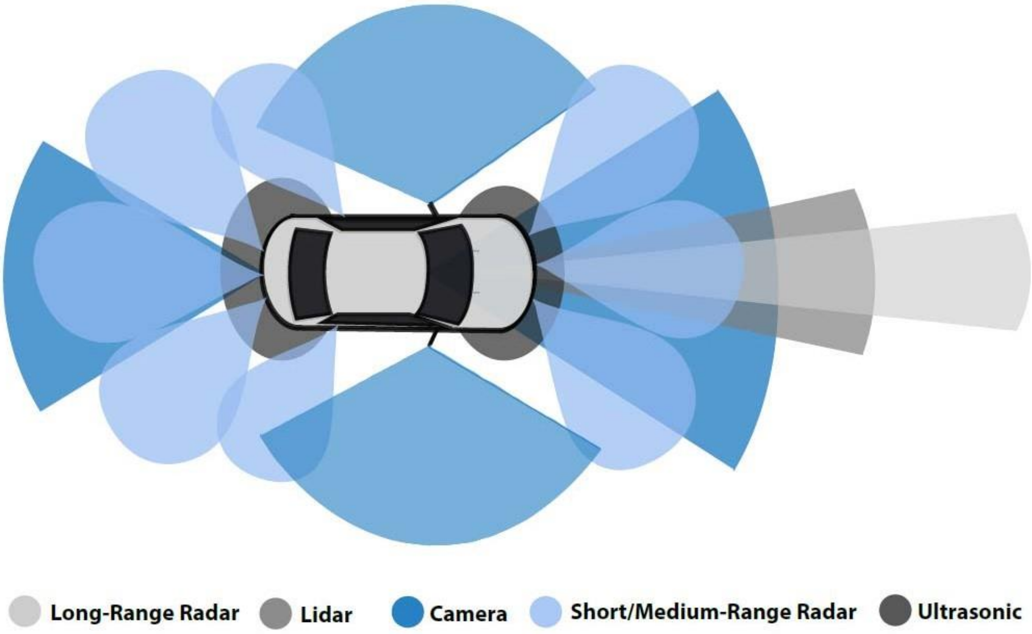
Table 2-1. shows the collected data on sensors used in existing autonomous vehicles. The number of sensors, if known, are given in parentheses. The exact methods used to control the vehicle are the manufacturer's secrets, but we can safely say that they are based on artificial intelligence.

Manufacturers want to make their vehicles as reliable as possible using the redundancy principle, because only one mistake of an autonomous car can lead to a fatal outcome. For this reason, almost as a rule, the autonomous vehicles have more than one sensor, which "monitors" the same variable (same distance, for example).

2-1. Table Sensors used on existing autonomous vehicles

	Vehicle	Camera	Radar	LiDAR	Ultrasonic	GPS
1	**Waymo (Google Car)**	Yes	Yes	Yes	No	No
2	**Tesla (Autopilot)**	Yes (1 v1, 6 v2)	No	No	Yes (12)	No
3	**MadeInGermany**	Yes (3)	Yes (2)	Yes (7)	No	Yes
4	**Spirit of Berlin**	Yes	No	Yes	No	Yes
5	**Stanley (2005 DARPA Challenge Winner)**	Yes (1)	No	Yes (5)	No	Yes
6	**Boss (2007 DARPA Challenge Winner)**	Yes (1)	Yes (2)	Yes (4)	No	Yes
7	**LUTZ Pathfinder**	Yes	Yes	Yes	No	No
8	**Uber Autonomous Car**	Yes (3)	Yes	Yes (4)	No	Yes
9	**Autonomous Hyundai Ioniq**	Yes (3)	Yes (2)	Yes (1)	No	Yes
10	**Intelligent Pioneer**	Yes (1)	No	Yes (3)	No	Yes

After all, there is no such thing as a perfect sensor, so, as noted above, a combination of different types of sensors is usually used, as shown in Figure 2-1. Even within certain types of sensors, there are differences between sensors of different manufacturers and models of a single manufacturer that must be taken into account. A good understanding of the advantages and limitations of each sensor is therefore a key prerequisite for choosing the best configuration on one vehicle. A brief description of the various sensors commonly used in autonomous vehicles will be given below.



2-1. Figure Example of sensor placement on an autonomous vehicle

2.2. OVERVIEW OF SENSORS

RADAR

Radar, which is an abbreviation for radio detection and ranging, uses radio waves, that is, electromagnetic waves of a length greater than infrared light, to detect and track objects. The first serious experiments using radio waves to detect distant objects were carried out in the early 1930s, but the development gained momentum during World War II when both the Allied and Axis powers realized the potential of new technology for military applications. In the late 1980s, Toyota was the first manufacturer to deploy radars in its vehicles. Since then, other vehicle manufacturers have embraced the technology and continued further development. The development of radars operating at a frequency of 77 GHz (and, more recently, 79 GHz) in order to improve radars operating at a frequency of 24 GHz has led to higher accuracy and resolution, both of which are necessary for the safe and reliable operation of the autonomous vehicle. Radar has become one of the most widespread sensing devices in modern vehicles, playing a key role in a number of advanced driver assistance systems (*ADAS*), including adaptive cruise control (*ACC*), blind spot monitoring and lane change assistance. Figures 2-2(a) and 2-2(b) show long and medium range radars used on vehicles.

2-2(a). Figure Long range radar

2-2(b). Figure Medium range radar

The radar emits radio-wave pulses which are then reflected from the surrounding objects and detects the return waves. The return waves provide information about the direction, distance, and estimated size of the detected object. Radars can also be used to determine the direction and speed of movement of an object by releasing multiple consecutive pulses. There are two basic types of radar: return wave detection radar and Doppler radar. The radars detecting the return waves operate according to the principle described above. By obtaining data from two or more radars detecting return waves positioned at different locations on the vehicle, it is also possible to collect additional information about the position of the object, such as its angle with respect to the vehicle. The Doppler radar further enhances this capability by analyzing the phase of the wave by tracking each wave and detecting differences in the position, shape of the obstacle and the shape of the wave as it returns to the radar. This information can be used to determine whether a wave has undergone a positive or negative shift. The negative shift indicates that the object is most likely moving away from the radar, while the positive shift of the wave indicates that it is moving towards the radar. The shift size can be used to determine the speed of an object.

Thanks to the ability to measure a wide range of distances and the ability to operate according to the Doppler principle, radar has become the primary sensing device for detecting and tracking distant objects. It offers a number of key advantages, for example, the radar can be used in all lighting conditions (including direct sunlight and complete darkness), in severe weather conditions (for example rain, fog, wind and snow), and during vehicle operation at high speeds. Radars also offer adequate resolution even when measuring longer distances (up to 250 m), and are available at a reasonable price in series production (although some other types of sensors are cheaper). So, both the position and the speed of the detected objects can be estimated thanks to the Doppler effect. Radar deficiencies include errors in measuring the distance from non-metallic objects and its relatively narrow beam. Some radars come with features that allow dynamic beam and range adjustment depending on vehicle speed. When the vehicle is moving at high speed, the system reduces the beam width to allow maximum range. When the vehicle is travelling at a lower speed (for example in urban traffic conditions), the beam has a maximum width, which leads to a reduction in range, thus enabling better detection of pedestrians, cyclists and other objects in the immediate vicinity of the vehicle.

LiDAR

LiDAR is an acronym for light detection and ranging. The LiDAR operation is based on the same principle as the radar - determining the location and distance of objects based on the reflection of the transmitted energy. However, the LiDAR uses laser beams instead of radio waves. Since they were invented, in the late 1950s, lasers have had an increasingly wide range of applications. The usage of LiDAR in autonomous vehicles is just one example of this trend. Unique features such as high resolution and detection of non-metallic objects have made LiDAR a popular choice for 3D mapping. This is perfectly in line with the development of autonomous vehicles, which rely on the availability of high definition maps for precise localization and navigation. Figure 2-3. shows the different LiDAR models manufactured by *Velodyne*.

2-3. Figure LiDARs manufactured by Velodyne: Alpha Puck, Velarray and VelaDome

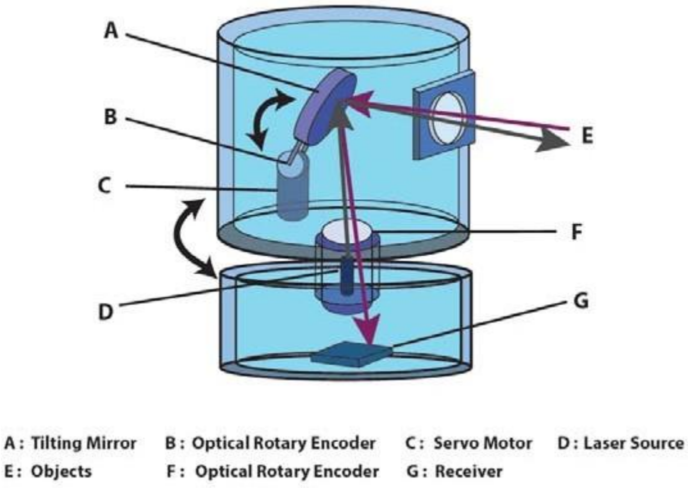
In order to ensure that the laser pulses emitted by LiDAR do not adversely affect the human eye, the energy of the beam emitted by LiDAR used in the vehicle is strictly limited to a level that is safe for the human eye (defined by the appropriate standard for Class 1 laser products). So, LiDARs that are not used in vehicles use beams of much higher power - when mapping terrain from the air, for example, impulses should have enough energy to penetrate the treetops and reach the forest floor.

As mentioned above, LiDAR works in a similar way to radar. Whenever the emitted laser beam "strikes" the object, the beam is reflected back to the sensor. The distance of the object can then be calculated by measuring the beam travel time. So, the basic difference is that LiDAR uses light (laser) waves. LiDARs are capable of emitting laser beams at rates of up to several hundred thousand times per second. Modern LiDARs are also capable of emitting multiple vertically aligned beams during a single scan, giving information about the height of the object. This can be useful for certain perception algorithms, such as interference filtering and object recognition.

LiDARs are basically consisted of three main components: a laser diode for generating laser beams, a photodiode for receiving return (reflected) beams, and a movable mirror for directing the laser beam in both horizontal and vertical directions. The reflected beams are received by the photodiodes and processed by the signal processing control unit. The LiDAR displays the detected objects as a set of points in space, each pixel representing the measured distance and the exact location in 3D coordinates relative to the LiDAR, as shown in Figure 2-4. LiDARs using more complex algorithms can give a list of recognized objects such as a vehicle, a pedestrian, and so on.

2-4. Figure Visualization of data obtained by LiDAR

Figure 2-5. shows the key components of LiDAR and illustrates their mode of operation. The emitted laser beams are guided through a mirror which is rotated by means of a servo motor. This mirror can be positioned to transmit beams at different angles in the vertical direction. The servo motor receives feedback from the optical encoder, in order to enable precise control of the position of the mirror and the direction of the emitted laser beam. Reflected (return) beams are received by a detector (typically a series of photodiodes) and processed by a signal processing control unit.



2-5. Figure Simplified representation of LiDAR operating mode

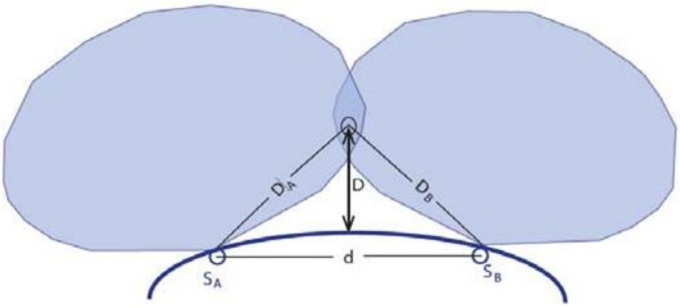
Due to the low beam width and relatively long range, LiDARs have become the best choice for high-resolution 3D terrain mapping. LiDARs also play an important role in indoor positioning, as well as in other conditions where satellite navigation is not available. Due to the ability to measure the intensity of the received infrared light, LiDARs also have the potential to be used as a reliable day/night detector, since the sun's rays transmit significantly more infrared light than the laser rays generated during the day. Despite the convenience of LiDAR for the application in the field of vehicles, the high price remains the biggest obstacle to the wider application of this technology in serially manufactured vehicles. The development of LiDAR without moving parts is under way, which will lead to a significant reduction in the price and size of the LiDAR itself. Since laser beams are also reflected from small particles such as fog and dust, LiDARs are more sensitive to adverse weather conditions than radar, making it more complex to install LiDARs in vehicles. Although signal filtering algorithms often help in reduction of interferences caused by snowflakes or raindrops, they are much less effective if the laser beams are distracted by dust, ice or snow on the surface of the LiDAR itself. This problem can be avoided by placing the LiDAR behind the windscreen, but such placement behind the windscreen with wipers may prevent 360º perception, while other sensing devices placed in a similar position, such as cameras and rain sensors, in this case can interfere with the LiDAR operation.

ULTRASONIC SENSORS

Ultrasound is a sound whose frequency is above the upper limit of audible range for the human ear, which is 20 kHz. As the name suggests, ultrasonic sensors use high-frequency sound waves to detect objects and determine distances from them. Animals, such as bats, use similar principles to detect and locate their prey in low light conditions. For decades now, ultrasonic sensors are used for monitoring and diagnostics in medicine, maritime and other industries. But it wasn't until the 1980s that they entered the automotive industry, when Toyota introduced a parking assist system based on ultrasonic sensors, which was quickly accepted by other vehicle manufacturers. Today, in-vehicle ultrasound sensors offer more than just parking assistance. For example, they are also used as part of the human-machine interface (*HMI*) to identify movements that enable touch-free control of the multimedia system. Figure 2-6. shows an example of ultrasonic sensors used in vehicles, as well as their application within a parking assistance system.

2-6. Figure Ultrasonic sensors

Like LiDAR-s and radars, ultrasonic sensors work by transmitting waves and calculating how long it takes for the waves to return. It is mandatory for the sound waves used in ultrasonic sensors to be inaudible to humans, because the waves must be transmitted at high amplitudes (>100 dB) in order for the sensors to receive clear reflected waves. The sensing device essentially consist of a transmitter, which converts the AC voltage into ultrasound, and a receiver, which generates alternating voltage when a force is applied to it. Both functions can be combined into a single transceiver. Due to the wide beam of sound waves - and assuming optimal placement of sensors in the vehicle - it is possible to determine the exact position of the detected objects by means of trilateration of overlapping signals, using the same principle as satellite positioning, as shown in Figure 2-7. - the distance to the detected object (D) can be determined by applying the Pythagorean theorem to the distance of the object from each sensor (D_A and D_B) and the distance between the two sensors (d).



2-7. Figure Ultrasonic trilateration

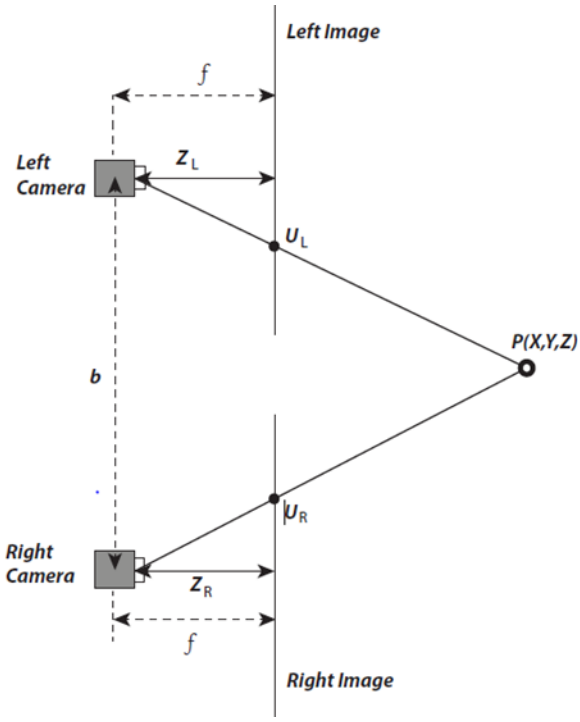
Due to their relatively affordable price, ultrasonic sensors are usually used as an economical means of detecting the presence and position of objects in the vicinity of the vehicle, in a parking assistance systems, as mentioned earlier. Ultrasonic sensors operate satisfactorily in most situations, as they are not affected by most weather conditions. Although ultrasonic sensors provide relatively little information, they are not affected by lighting conditions, which may be an advantage in cases where insufficient or too much light can lead to errors in measurement of distance to the appropriate objects. They also work well in rain, fog and snow, as long as the sensor itself is not covered in dirt, snow or ice. In indoor, urban or peoplepacked environments, their ability to detect non-metallic objects offers an added benefit in terms of pedestrian detection. However, there are several concerns that need to be addressed when using ultrasonic sensors. They typically have low resolution and low range, and have limited functionality in situations involving high wind speed or high vehicle speed, which are situations where optimal sensing performance is critical. Moreover, they are affected by noise in the external environment - high-frequency sound emitted in the vicinity (for example, sound emitted during the movement of a railway vehicles) may adversely affect the measurements performed by these sensors. The angle of the sensor, as well as the material of the reflected objects, also influence the received reflected waves. As the angle of the ultrasonic wave increases, the intensity of the wave, and therefore the accuracy of the readings of the sensor, decreases. This may cause errors in the assessment of the distance or presence of other objects around the vehicle.

CAMERAS

Cameras have been around for a long time and are undoubtedly one of the most significant inventions in human history. The discovery of digital cameras in the late 1980s disrupted the market for traditional analogue cameras. Today's digital cameras are cheap and available almost everywhere, primarily thanks to their integration into smartphones. The first application of on-board cameras was by General Motors, in a 1956 *Buick Centurion* concept vehicle. The vehicle had a television camera mounted in the back that sent a picture to a TV screen mounted inside the vehicle. However, only three decades later, Toyota was the first to launch a series production of vehicles with integrated reverse cameras. Today, cameras are used not only to provide parking assistance, but also as a key element of various driver assistance systems, from lane departure warnings and traffic sign recognition to augmented reality and autopilot. In some countries, cameras are taking on an even more significant role in the field of motor vehicles. In the US, for example, reversing cameras are required in all vehicles manufactured after May 2018. Figure 2-8. showes one type of the stereo cameras that are used in vehicles, as well as an illustration of one of the methods of their installation.

2-8. Figure Stereo camera

Cameras, unlike LiDAR, radar or ultrasonic sensors, are passive sensors. So, the cameras passively receive light waves and do not actively emit any form of energy, although there are exceptions here, which will be discussed later. Cameras consist essentially of three main components: optics, image sensor and image processors. The design of the lenses and filters that make up the camera optics depends on the field of application of the camera. Cameras mounted at the front end of the vehicle typically use long-focus lenses with a large aperture to be able to "see" as far as possible in low-light situations, while cameras mounted laterally or at the rear of the vehicle use wide-angle lenses with small apertures to capture objects in a closer environment. The image sensor and the image processor are responsible for receiving, filtering and processing the received light waves into digital raw video recordings that can be transmitted via low voltage differential signaling (*LVDS*) or an Ethernet interface. Some intelligent camera systems also have a powerful digital signal processor (*DSP*) that detects objects and traffic lanes in real time, recognizes signs, etc., and transmits lists of detected objects as separate messages via a bus. Stereo cameras are basically two mono cameras facing the same direction. This setup mode has two separate input video streams, one for the left camera and one for the right. Figure 2-9. shows an example of depth calculation for stereo cameras (assuming both left and right cameras have the same focal length f, the actual point P is projected as U_L and U_R, respectively. The distance between two projected points is called a disparity and is calculated as fb/z, where b is the distance between two cameras. Thus, the z, or the distance from the cameras to the actual point P, can be determined using the formula: z = fb/disparity).



2-9. Figure Determination of depth in stereo cameras

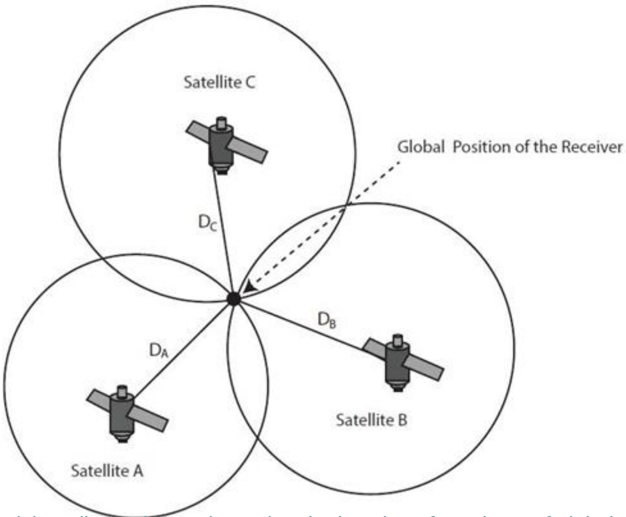
One of the key features of stereo cameras is the ability to perform a search that involves looking for similarities when communicating with different sensors on the vehicle, in order to create a complete picture of the environment in which the vehicle is located. Various algorithms can be used for this. Surface-based algorithms consider a small area of one image and look for a similar area in another image. In contrast, feature-based algorithms identify unique features in each image to match common points. Instead of calculating the surface area, calculations can be made from much smaller recognized image elements, including edges, angles, and lines. Epipolar geometry can be used as a basis for reducing the complexity of determining image matching, as long as there are several pixels in one image that correspond to the pixels in the other image. Matching can be determined using epipolar lines, a process in which an object detected by one camera is projected onto the image plane of another camera.

This technique allows the system to identify similarities and combine images. A similar principle is used to generate an image of surroundings (360º) using four or more "fish eye" cameras with folded horizontal field of view (*FOV*). Time-of-flight (*ToF*) cameras can capture a 3D environment from a fixed position and determine the distance of specific objects. The infrared light source is used to determine the distance of objects based on the operating principle used in LiDAR, radar and ultrasonic sensors. This method makes distance determination in *ToF* cameras far simpler than in stereo cameras. Compared to distance sensors such as LiDAR, radar and ultrasonic sensors, cameras record a wider range of frequencies, including colors. This allows for a richer interpretation of the environment, including detection of traffic lanes, recognition of traffic signs, and so on. In some cases, visual localization using cameras can yield better results than LiDAR-based localization, such as in situations where landmarks such as buildings are more easily distinguished by their texture rather than just their structure. An additional advantage is that cameras usually have a lower price than radar and LiDAR. Cameras, however, are sensitive to ambient lighting and weather conditions. Cameras perform poorly in direct sunlight, and their efficiency is also significantly reduced in poorly lit environments. Weather conditions such as heavy rain, snow or fog drastically reduce the efficiency of cameras, making them almost unusable.

GLOBAL NAVIGATION SATELLITE SYSTEMS (GNSS)

Similar to radar, *Global Navigation Satellite Systems* (*GNSS*) were primarily deployed for military purposes. The first fully functional GNSS was *Navstar*, the predecessor of the modern global positioning system developed in the USA (GPS). The *Navstar* (*Navigation system using timing and ranging*) was developed in the 1970s by the US Department of Defense to provide a fast and efficient means of locating military units anywhere in the world, especially submarines for launching missiles operated by the navy. The great importance of global navigation satellite systems, applied for both military and civilian purposes, has led to the development of several different satellite systems. This includes Galileo (European Union), GLONASS (Russia) and *BeiDou* (China). Easily accessible satellite navigation with global coverage has led to several key innovations that are important for the development of autonomous vehicles. With the help of a digital map and a suitable on-board computer, vehicles can be automatically located on a global map, possible routes can be determined and navigation provided to the desired destination. In the early 1980s, the Japanese company Honda became the first car manufacturer to launch a commercial navigation system for vehicles with a map display. Nowadays, drivers can get useful information about their traffic status in real time, using apps such as e.g. *Google Maps*, which provide drivers with an immediate route update, to help them avoid delays many miles ahead of them. With regard to its specific use for autonomous vehicle navigation, it is important to remember that GNSS has limited precision and cannot be relied upon in every situation. Nevertheless, the GNSS will undoubtedly continue to play an important role in the development of autonomous vehicles for years to come.

GNSS relies on satellites spread across the sky, in different orbital planes. In the case of *GPS*, global coverage requires a constellation of at least 24 operational satellites that continuously transmit signals back to Earth, including the identification of each of the satellites, current time and location. Receivers of global navigation satellite systems are passive and exteroceptive. In the case of *GPS*, the receiver needs signals from three or more different satellites to determine its location on Earth. Three satellites are required if the *GPS* receiver has a built-in atomic clock. However, most *GPS* receivers have simpler clocks, so signals from at least four satellites are usually needed to compensate for timing errors. The position of a receiver is calculated on the basis of a mathematical principle called trilateration. The method works by first calculating the propagation time of each signal, in other words the time difference between the moment signal left the satellite and when it was received. The distance to the satellite can then be calculated by multiplying the propagation time of the signal by the travel speed of the signal, which is equivalent to the speed of light. The position of the receiver is accurately indicated as the area where all signals intersect, as shown in Figure 2-10. Knowing the location of satellites A, B and C, as well as the distances to each of them, i.e. D_A, D_B and D_C, the location of the receiver can be determined.



2-10. Figure Applying trilateration to determine the location of receivers of global navigation satellite systems

Global coverage GNSS systems, such as *GPS* or GLONASS, can be used to determine the position of the respective receiver anywhere on the Earth's surface. GNSS is based on absolute positioning, which means that it does not have an accumulated error that affects the operation of inertial measurement units (IMUs) and sensing devices that measure the distance travelled when used in synergy with global navigation satellite systems. *GPS* receivers have become common and affordable, and are now available almost everywhere thanks to their usage in modern smartphones.

One of the biggest disadvantages of GNSS-based positioning is that it requires a stable and direct signal between the receiver and the satellite to function reliably. This means that GNSS-based positioning works best on open areas, while it does not work at all in confined spaces such as garages and tunnels. In certain environments, for example in densely populated areas with tall buildings that are closely compacted side by side, GNSS signals have a problem with the occurrence of multiple signal paths. This occurs when the signal is reflected from other objects in the environment and reaches the receiver via several different paths, potentially leading to a significant deterioration in positioning accuracy. Another problem is that publicly available *GPS* can only achieve a positioning accuracy of approximately 3 meters, which is not precise enough for use in autonomous vehicles. The locating accuracy can, however, be significantly improved through the use of technologies such as differential global positioning system (*DGPS*) or real-time kinematic *GPS (RTK GPS)*, although both technologies require dedicated base stations at fixed locations and are therefore not available everywhere.

3. PERCEPTION

The human brain is extremely good at perceiving the environment around it. Indeed, it is so good that we often take our ability for granted. When we cross the road, we look for approaching vehicles. If we see a vehicle coming towards us, we can quickly estimate the speed at which it is approaching and we can decide whether it is safe to cross or not. Many of the things we do in this way are pure reflexes and are based on prehistoric instincts that keep us safe. When we look at a particular situation, our eyes only record the patterns of light and color that are transmitted to the brain. Our brain then uses past experiences to interpret these patterns and create a real picture. Because of the optical characteristics of the eye, we're actually looking at these images upside down, but our brain is able to interpret them correctly, so we can perform actions like catching a ball. However, the reproduction of this type of capability in autonomous vehicles is a challenging task. As we have seen in the previous chapter, autonomous vehicles rely on a number of different sensors. But, like our eyes, the raw data produced by these sensors is essentially meaningless. The software's job is to interpret this data and use this interpretation to create an image of the environment around the vehicle. Specifically, perception and navigation software perform this job of interpretation. If it detects a 1.5 m tall, slender object moving slowly across the road in front of the vehicle, it could identify it as a pedestrian and transmit this information to the control software. This software can then decide whether the vehicle should take avoiding action or not. The goal of perception is to achieve the most complete and accurate understanding of the vehicle environment, in order to provide a basis for decision making in the next iteration that represents navigation. Perception provides answers to the questions “where am I?” and “what's around me?”. Reliable perception is key to ensuring the smooth and safe operation of the autonomous vehicle. Generally speaking, perception in dynamic environments, i.e. environments with moving objects, can be broken down into two main sub-functions: *Simultaneous Localization And Mapping (SLAM)* and *Detection and Tracking of Moving Objects (DATMO).* This chapter will detail how autonomous vehicles perceive the world around them.

3.1. LOCALIZATION

Localization is the process of determining the position and orientation of a vehicle based on a map. This map can be a global map for fully autonomous vehicles moving on public roads, or it can be a map intended for vehicles moving within a restricted environment such as a factory, for example. A large number of research on robot localization techniques is present in the literature. However, there are some significant differences between these robots and autonomous vehicles. Robots generally operate in environments that have already been mapped with precision, which helps to simplify the localization problem. On the other hand, autonomous vehicles move in a much more challenging and dynamic environment, with different objects that can move, while also being able to move at high speeds.

There are two approaches to localization. The local or relative localization compares the current location with the previous location. Global or absolute localization uses external references to determine the current location. These references may include satellites or known landmarks. Approaches based on relative localization are usually fast and require less resources compared to global localization. However, they may lead to errors or a significant deviation. A serious problem with relative localization can arise when the vehicle "moves" to an unknown location, without information about the starting position. This can occur if the system (vehicle) is restarted, for example. In practice, this means that both techniques are usually used in combination. The relative location is used to track the current location, but periodically also absolute localization is used to eliminate any deviations or for the purpose of locating the vehicle after a system restart.

Global Navigation Satellite Systems (GNSS) are a highly prevalent localization technique, as they offer an easy and inexpensive way to localize vehicles. As noted earlier, they use the trilateration principle to determine the absolute position of vehicles anywhere in the world. However, this approach requires the smooth transmission of signals from at least three satellites, and is therefore not suitable for certain working environments where satellites are obstructed, for example, indoors, in a tunnel, etc. Another disadvantage is the relatively low precision.

Localization on the basis of data on distance travelled measured using the wheel speed sensor is a relative localization, while in addition to these sensors, a vehicle directional sensor is used. Localization is done using the *dead-reckoning* method, a simple technique used in ancient naval navigation. This technique evaluates the position of the vehicle based on the projected direction and the distance travelled in relation to the known initial position of the vehicle. Since localization based on distance travelled measured using the wheel speed sensor does not require any data on the environment, this approach works in all possible working environments. As a method of relative localization, this technique suffers from cumulative errors caused by wheel slippage, uneven road surface, etc. Therefore, the localization result is usually used only in the short term to compensate for the temporary unavailability of other localization methods, as in the case of tunnel driving.

Similar to the localization mode above, localization using an inertial navigation system is also a relative localization technique that does not require any information about the environment. The localization based on the inertial navigation system is based on the application of the dead reckoning technique to the measured data that provide information on the manner of movement of the vehicle provided by the inertial measuring unit, which usually consists of an accelerometer, a gyroscope and a magnetometer. Although localization based on the inertial navigation system generally provides a more accurate estimate of the position than localization based on data on the distance travelled measured using the wheel speed sensor, it is sometimes not immune to the error accumulation, so it should be corrected by other (absolute) localization techniques.

The next method of vehicle localization is to install additional devices or appropriate infrastructure within the vehicle's working environment. The infrastructure may be composed of passive devices that only receive signals, such as magnets and visual markers, or active devices that send appropriate signals, such as *Wi-Fi* or *Bluetooth* transmitters. Localization based on supporting infrastructure is typically used for indoor environments where other localization approaches do not produce good results. Depending on the technology and layout of the devices used, precise vehicle location can be achieved. However, infrastructure upgrades are not always feasible, making this approach less suitable for operation in larger areas.

Localization based on data obtained with the help of LiDAR uses “natural” landmarks, e.g. buildings, walls, trees, etc. from the operating environment. Since the localization realized in this way does not require any special infrastructure, this technique is more suitable for application on a wider scale, because the installation of the appropriate additional infrastructure is too expensive or, in most cases, simply impracticable. LiDARs can be used for both local and global localization within a known map. Localization is usually done by multi-scan pairing. Multi-scan pairing is a technique that should allow geometric matching of two scans, so scans are optimally overlapped. The resulting geometric scan match must match the changes in the environment caused by translatory and rotational movements of the vehicle, i.e. the change in the position of the vehicle in the operating environment. By monitoring the translatory and rotational movement of the vehicle, the current location can be estimated, based on all recorded changes in the way the vehicle moves relative to the initial location. As for global localization, some scan matching techniques can also be applied to detect vehicle entry into a closed loop, i.e. whether the vehicle has returned to the same location again. Scan matching is also an effective method for the step before correcting the results of the localization process, which is performed on the basis of data on distance travelled measured using the wheel speed sensor, when defining the environment map, which can lead to a significant improvement in robustness and accuracy of large-scale environment mapping.

Like LiDAR-based localization, visually based localization or camera-assisted localization requires no additional infrastructure. Localization is performed using visual characteristics of the environment recorded by mono, stereo or RGB-D (color and depth) cameras. There are several approaches to localization using cameras. Visual localization is achieved by evaluating camera movement based on recorded consecutive images. Similar to the distance travelled measured using the wheel speed sensor, the vehicle path is obtained by iteratively updating the estimated location of the vehicle relative to the initial location. In contrast, *Visual Simultaneous Localization And Mapping (VSLAM)* produces globally consistent localization within the map, not only in relation to the initial location of the vehicle. The two approaches can also be used simultaneously to obtain a better motion estimation compared to, for example, localization based on an inertial navigation system.

Under realistic driving conditions, autonomous vehicles use a combination of the above-mentioned approaches to obtain an optimal result in any situation they may find themselves in. When localization based on global navigation satellite systems is not reliable, for example when passing between tall buildings, localization should rely on other methods, such as camera or LiDAR localization.

3.2. MAPPING

The localization techniques listed in the previous section are based on the assumptions that a very accurate and correct map is already available in advance. In reality, however, high definition maps are generally not publicly available and generally have to be generated most of the time. So there are multiple types of maps that are used in autonomous vehicles. The choice of the appropriate map type depends on several factors, including the type of sensor used on the vehicle, the memory capacity and the computer platform used, the localization algorithm used, etc.

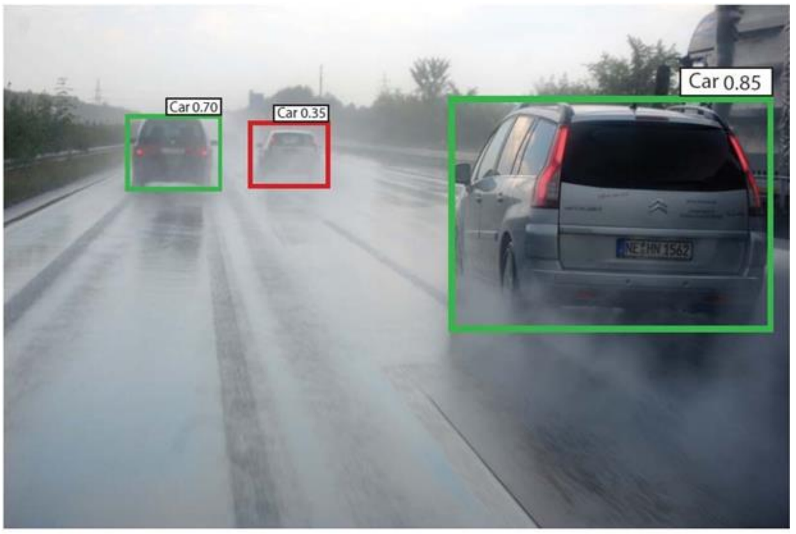
3.3. RECOGNITION

One of the basic “skills” that autonomous vehicles need is the recognition or detection of objects. Not only is the recognition of objects essential for the safe movement of the autonomous vehicle, i.e. for the prevention of collisions or traffic accidents, but it is also important that the vehicle has a proper understanding of the environment, so that it is able to make the best possible decision in every situation in which it can find itself. As drivers, people perform multiple simultaneous object recognition, sometimes unconsciously. Drivers must recognize not only other moving objects in the environment, such as vehicles, pedestrians, cyclists, but also static objects such as lanes, traffic signs, traffic lights, and more. Right now, it's still very challenging for computers to mimic this ability of humans. However, some technologies such as deep learning are promising, which means that the gap is rapidly narrowing.

Object recognition is usually divided into the following subproblems:

- Localization of the objects, i.e. determining the boundaries of detected objects;
- Classification of objects, i.e. categorization of detected objects into one of predefined classes;
- Semantic segmentation, i.e. dividing the image into semantically significant parts and classifying each part into one of the predetermined semantic areas.

Figures 3-1. and 3-2. show the differences between these sub-problems.



3-1. Figure Localization and classification of objects

3-2. Figure Semantic segmentation

Object recognition using a computer has been actively investigated since the mid-1960s. There are many suggestions for solving this problem. In general, solving the problem of object recognition includes the following steps:

Pre-processing

The pre-processing step “normalizes” the image, i.e. it performs the adjustment of the raw image, so that it matches the expected output towards the next step called feature extraction. This may include rotating and resizing the image, adjusting contrast, and so on. The tasks to be performed are specific to each of the possible approaches to this problem. Some approaches even completely skip the pre-processing step.

Feature extraction

The feature extraction step removes irrelevant or redundant information from the image and stores only relevant information (or features) for classification. This transforms the image into another format representing the so-called features map.

Classification

The last step connects the features map to previously defined reference feature maps representing each of the predefined classes.

4. ARCHITECTURE

The previous chapter showed how autonomous vehicles perceive the environment around them through a combination of localization, mapping and object recognition techniques. Here we will briefly show how the autonomous vehicle combines this knowledge of its environment with other data such as destination, traffic rules and data on its own capabilities to reach the destination and safely transport itself to the destination. Autonomous vehicle software can be viewed from two perspectives. One involves the functions that the software should perform. This includes the perception made up of localization, mapping and object recognition. The second involves planning and operating the vehicle. The system architecture should combine these functions in order to realize a system that is capable of achieving the desired level of autonomous driving.

The architecture consists of three main parts: perception (which has already been discussed), planning and operating the vehicle.

PERCEPTION

So, perception involves answering the questions “where am I?” and “what's going on around me?”. The main functions of perception are localization, mapping and object recognition. These functions were briefly described in the previous chapter.

PLANNING

Planning includes answering the question “how do I get to my destination?”. Planning activities can be described on the basis of the so-called top-down approach, which defines a three-layer hierarchy: route, behavior and movement planning.

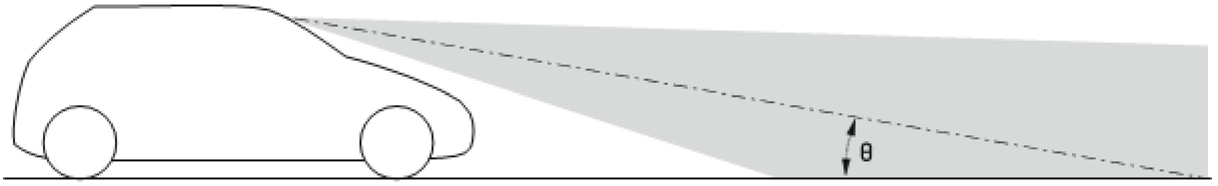
OPERATING THE VEHICLE

The task of the part of the architecture related to control over the vehicle is to execute the decision made in the previous steps, while ensuring the safe movement of the vehicle. Vehicle control typically involves translating the calculated path into a set of control commands for the actuators, ensuring vehicle stability and reducing the impact of sudden and unwanted events/situations. The latter is crucial, given that the probability of sensor/hardware failure, as well as measurement errors or even certain commands implementation errors, are never zero. Modules that need to meet high safety requirements are usually used to operate the vehicle, while they are operated separately from other autonomous vehicle modules. Independence from other modules is necessary since the vehicle control modules are used as redundant safety systems and act as the last safety instance, which can override a decision made in a higher level of control software, in order to avoid traffic accidents or reduce the consequences of a traffic accident, when it is unavoidable. In addition to safety requirements, the vehicle control modules are also responsible for steering the vehicle in the lateral and longitudinal directions. Some of the simpler control tasks that the aforementioned part of the architecture needs to perform are keeping the vehicle in the traffic lane, controlling the speed and maintaining the appropriate distance from the vehicle in front, autonomous change of the traffic lane, and so on.

5. RECOGNITION OF ROAD BOUNDARIES, ROAD USERS AND OBSTACLES

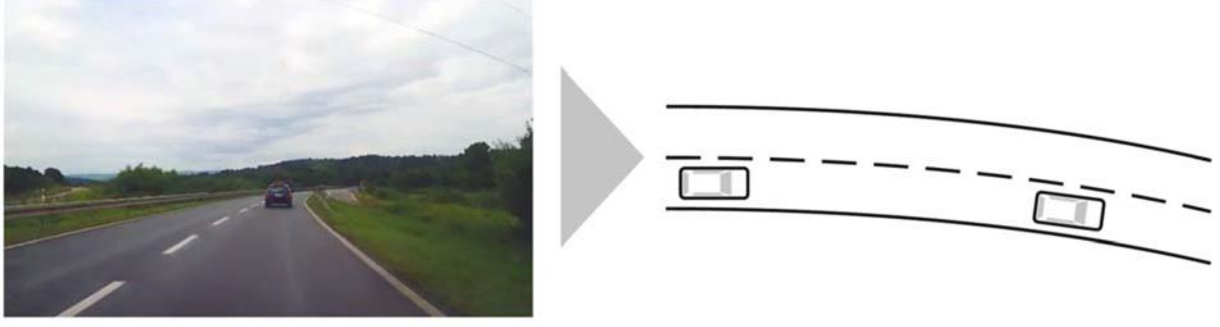
5.1. RECOGNITION OF ROAD BOUNDARIES AND OBSTACLES USING A CAMERA

A camera can be used to identify the boundaries of the road and obstacles on it (including other vehicles, cyclists and pedestrians). At this point, we will not deal in detail with how the footage from the camera is translated into “layout” of the road in front of the vehicle, i.e. to the below described universal polygon. However, some basics of photogrammetry will be presented with the aid of which the image provided by the camera is “copied” on the road in front of the vehicle observed from a bird's-eye view. Recognition of the boundaries of the road and obstacles is most often left to an artificial neural network, the structure and manner of functioning of which will not be detailed here. Nowadays, the recognition of the boundaries of the road with a camera is quite developed. This is supported by the fact that some of the leaders in the research and implementation of autonomous vehicles are IT companies (Uber, Google, Nvidia), not classic vehicle manufacturers.



5-1. Figure View of the vertical angle of the camera’s view and its inclination (θ)

Figure 5-1. shows the angle of the camera's view in the vertical plane and its inclination with respect to the horizontal road (*θ*). Assuming that the road along which the vehicle is moving is horizontal, that is, the slope of the road is unchanging, so that the angle that the axis of symmetry of the camera’s view angle forms with the ground at all times corresponds to the angle of inclination of the camera, as shown in the figure 5-1. This assumption will facilitate later calculations, and the model can be improved relatively easily later so that it also takes into account the change in the slope of the road ahead.

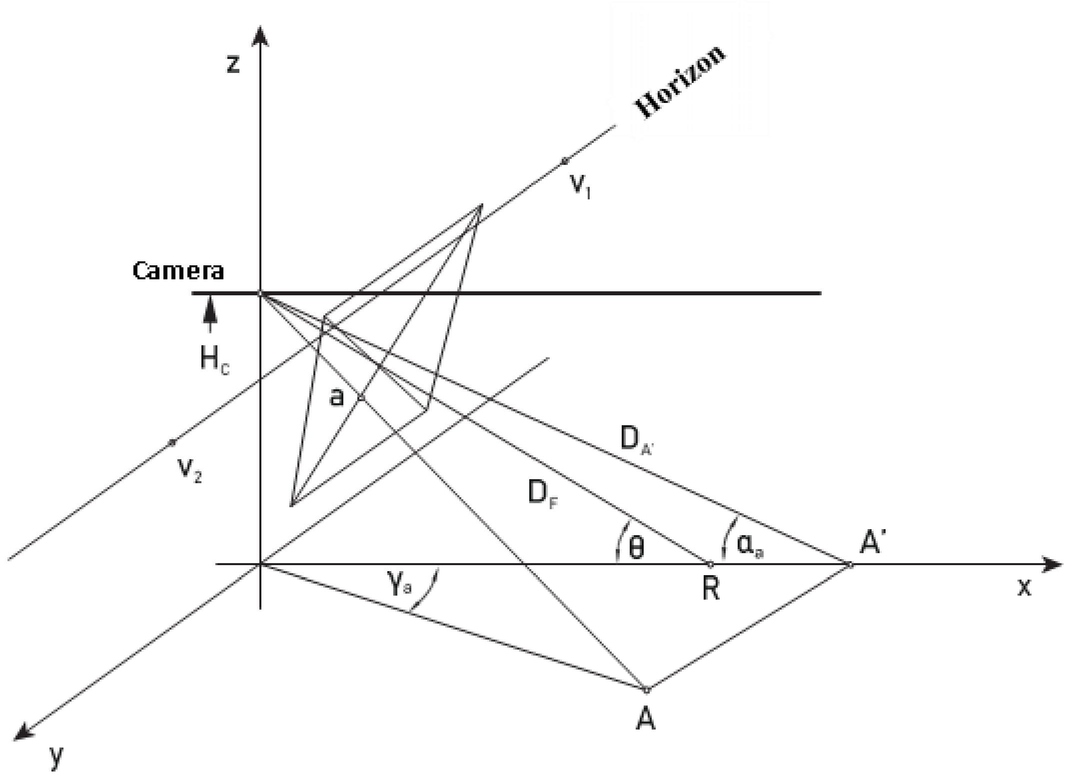


5-2. Figure From the camera footage to the “layout” of the road ahead

The aim of the system is to draw up a “layout” of the road in front of the vehicle with the displayed moving and fixed obstacles, based on the camera footage, as shown in Figure 5-2. The principles of photogrammetry shown in the following figures and defined by the accompanying equations will be used for this.

Figure 5-3. shows the position of the camera (actually its lens, i.e. the lens focus) in relation to the vehicle coordinate system (*x* – longitudinal direction, *y* – transverse direction, *z* – vertical direction), inclined by an angle θ in relation to the horizontal plane. Point *a* represents the position in the photograph of point *A* located on the road in front of the vehicle, with the following markings:

- *A'* – projection of point *A* on the *x*-axis;
- γ_a – azimuth;
- α_a– angle of depression;
- *R* – point of penetration of the axis of symmetry of the angle of the camera's view through the plane of the road;
- D_F – camera distance from point *R*;
- D_A– camera distance from point *A'*;
- *Hc* – height of the focus of the lens in relation to the plane of the road;
- v_1, v_2 – points on the horizon.

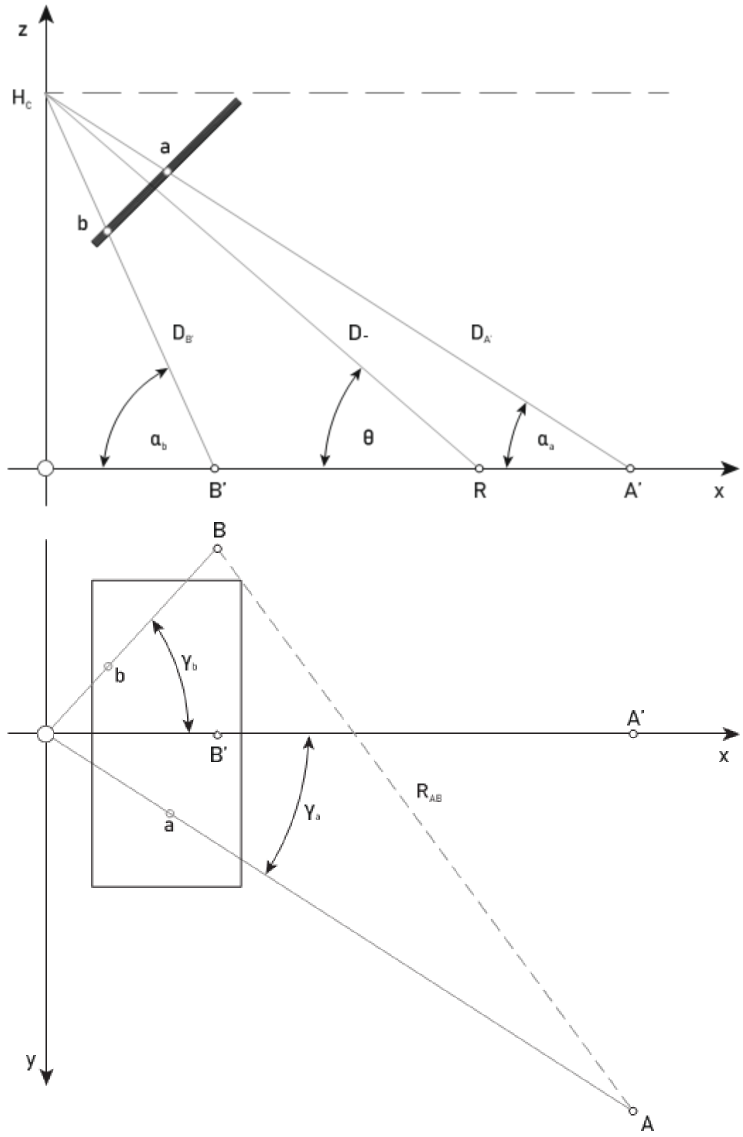


5-3. Figure From the camera footage to the “layout” of the road ahead

The position of the photography is displayed between the lens and the observed objects, at a distance from the lens that corresponds to the focal length multiplied by the magnification of the positive compared to the negative (as the photo magnifies when transferred from the photographic film to the paper) and can be viewed as an illuminated part of the photographic film or the digital camera's photosensitive chip. The film, that is, the chip, is always located behind the lens, at a distance corresponding to the focal length, and here it is shown “in the mirror” for simplification, as a positive.

Figure 5-4. shows the position of the camera in the vertical and horizontal plane, but also the position of points of interest. Unlike the previous image where only point *A* and the equivalent point *a* on the photograph were displayed, this image also shows point *B* and its equivalent on the photo *b*. The marks are analogous to the marks in the previous figure, with the addition of the mark R_{AB} representing the distance between points *A* and *B*.

Figure 5-5. shows the position of the camera in relation to the photograph (positive) with a width of *W* and the height *H*, at which the point *a* is located, corresponding to the point *A* on the road ahead.



5-4. Figure Position of the camera and points of interest in the vertical (above)

The virtual distance between the lens and the positive is:

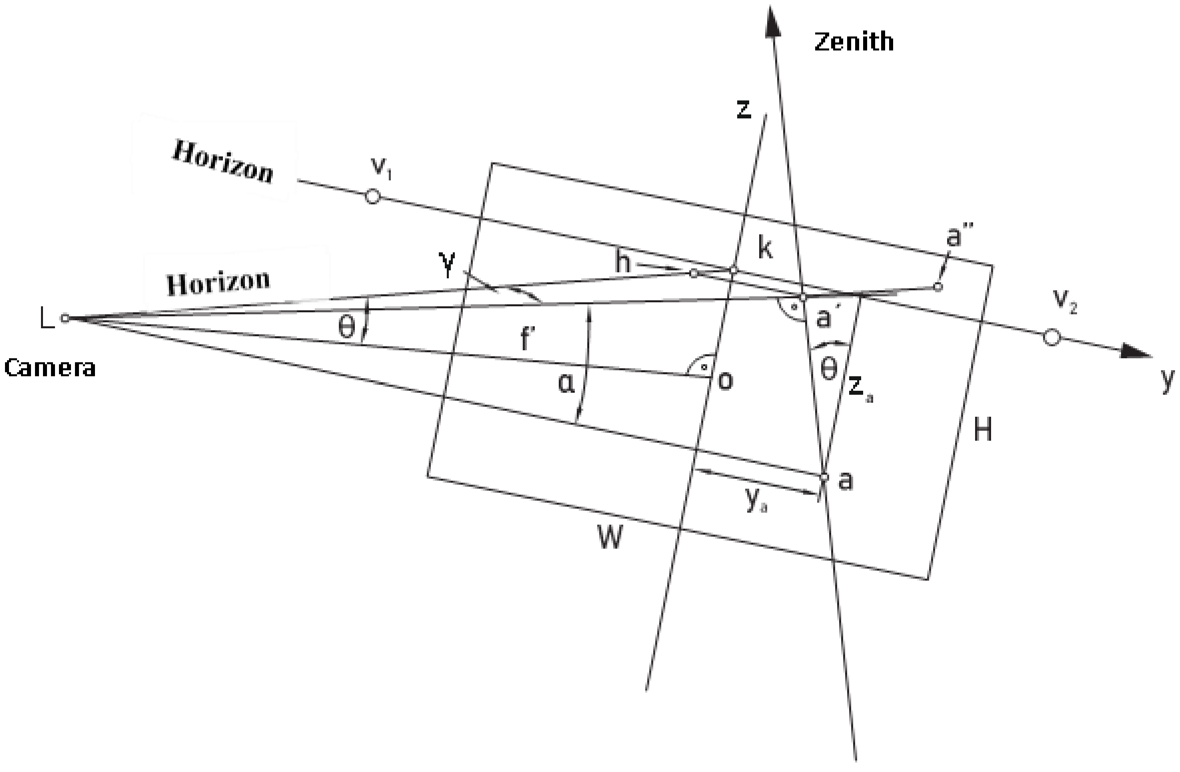
$$f' = e_a f,$$

where:
f – the focal length of the lens;
e_a – magnification ratio of the negative to the positive.

The camera inclination angle can be determined as:

$$\theta = \text{arctg}\frac{\overline{ko}}{f'} = \text{arctg}\frac{z_o}{f'},$$

where:
k – the point of penetration through the positive of the shortest line that can be withdrawn in the horizontal plane from the focus of the lens and the center of the *zky* coordinate system in the photo;
o – point of penetration of the perpendicular line from the lens to the positive;
z_o – *z* coordinate of the point o in the *zky* coordinate system.



5-5. Figure Camera position relative to photo

The azimuth of point a can be calculated using the following equation:

$$\gamma_a = \text{arctg}\frac{ha'}{\overline{Lk} - \overline{hk}} = \text{arctg}\frac{y_a}{\dfrac{f'}{\cos\theta} - z_a \sin\theta},$$

where y_a and z_a are the coordinates of the point a on the positive.

The angle of depression is calculated using the following equation:

$$\alpha_a = \text{arctg}\frac{aa'}{La'} = \text{arctg}\frac{aa'\cos\alpha_a}{\left(\overline{Lk}-\overline{hk}\right)} = \text{arctg}\frac{z_a\cos\theta\cos\gamma_a}{\left(\dfrac{f'}{\cos\theta}-z_a\sin\theta\right)}.$$

Then the coordinate *x* of the point *R* can be calculated as:

$$X_R = \frac{H_C}{\text{tg}\,\theta},$$

on the basis of which previously defined distances can be calculated:

$$D_F = \sqrt{X_R^2 + H_C^2},$$

$$D_A^{'} = D_F\frac{\sin\theta}{\sin\alpha_a}$$

and

$$D_{B'} = D_F\frac{\sin\theta}{\sin\alpha_b}.$$

This further allows us to calculate the distance between points A and B:

$$R_{AB} = \sqrt{\left(X_{A'}-X_{B'}\right)^2 + \left(Y_A - Y_B\right)^2},$$

wherein the required distances are calculated as

$$X_{A'} = D_{A'}\cos\alpha_a,$$

$$X_{B'} = D_{B'}\cos\alpha_b,$$

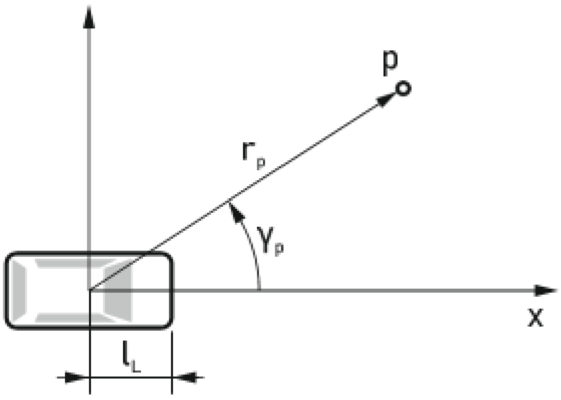
$$Y_A = D_{A'}\text{tg}\gamma_a \text{ и}$$

$$Y_B = D_{B'}\text{tg}\gamma_b.$$

The position of all points on the path of interest, but also their mutual distances can be calculated in a manner analogous to that shown. This would allow the vehicle control unit to obtain the aforementioned desired “layout” of the road in front of the vehicle that is free for its passage.

5.2. RECOGNITION OF DISTANCE FROM OBSTACLES USING LiDAR

The LiDAR can be used to identify obstacles around the vehicle. In the following example, it is mounted on the roof of the vehicle and rotates around the vertical axis to be able to “observe” the entire 360° of surroundings. Therefore, it is particularly important that the distance from the obstacle is calculated based on the time it takes for the beam deflected from the obstacle to return to the receiver. Figure 5-6. shows the observed obstacle *p* and the measured distance from it r_p.



5-6. Figure Determination of distance from obstacle

Based on the measured distance and the known angle of the LiDAR beam in relation to the longitudinal axis of the vehicle, the coordinates of the obstacle (its parts closest to the vehicle – this is of interest to us) can be calculated using the following equations:

$$x_p = r_p \cos \gamma_p ,$$

$$y_p = r_p \sin \gamma_p .$$

The distance of the vehicle from the obstacle in front is then $x_p - l_L$.

In order to determine as accurately as possible the free space around the vehicle, it is also necessary to take into account the time deviation of the generation of the obstacle position information and the given moment, the maximum value of which is calculated using the following equation:

$$t_k = \frac{r_p}{c} + t_o + \frac{1}{f_L}$$

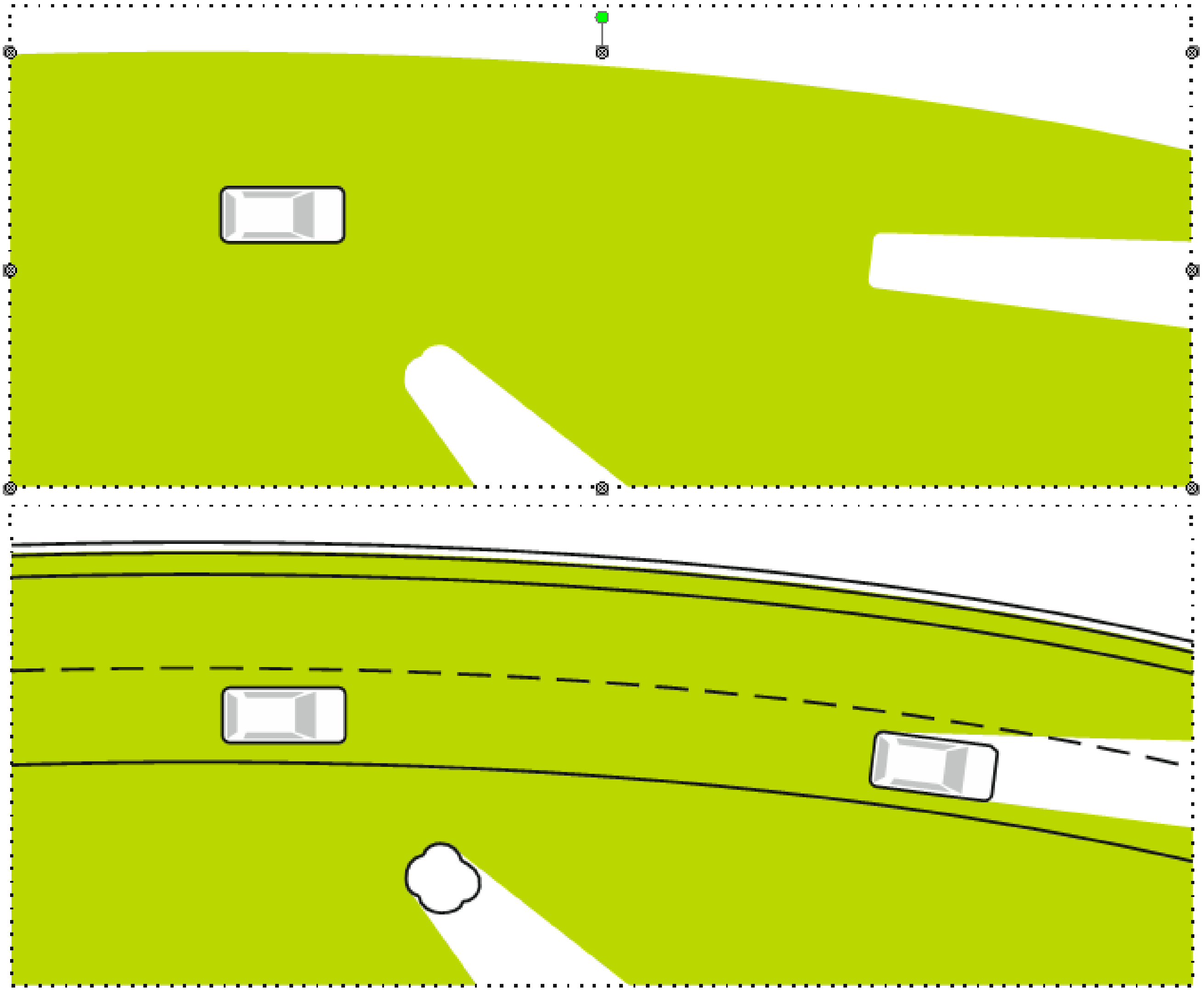
where:

c – LiDAR wave velocity
t_o – signal processing time
f_L – frequency of LiDAR rotation

It is therefore recommended to adjust/correct the measured values of the distance from the obstacle, taking into account the speed of movement of the vehicle v:

$$r_p' = r_p - v \cos \alpha \cdot t_k .$$

Figure 5-7. shows the free space determined by the LiDAR (marked in green). The free space thus determined must coincide with the "layout" determined by the camera, if the precision of both methods of determining the environment is high enough.



5-7. Figure Free space defined by LiDAR (above) and its match with the ground "layout"

5.3. USING THE GLOBAL POSITIONING SYSTEM SENSING UNIT

The Global Positioning System sensor is most commonly used only for the purpose of verifying the accuracy of the current vehicle position information. The precision of such sensors is not high enough to correct a certain position of the vehicle in the transverse profile of the road it is moving on, but it can be used to correct the position of the vehicle in the longitudinal profile, especially if it turns out that the previous two sensing units (LiDAR and camera) did not predict the coming curve precisely enough.

5.4. USING THE MATLAB SOFTWARE PACKAGE FOR DETERMINING VEHICLE SURROUNDING

The MATLAB software package offers the Automated Driving Toolbox from its version R2017a. In this way, autonomous vehicle operating technology has also entered our (student) dorms – students around the world now have a tool available for the design of autonomous vehicle control systems. The mentioned package offers, among other things, the following functions:

- Fusion of data from different sensors;
- Visualization of data from sensors and their representation in a bird's-eye view;
- Simulation of a frontal collision warning system;
- Simulation of the system for recognizing the traffic lane and preventing its departure;
- Visualization of automatic parallel parking using three-dimensional simulation;
- Simulation of the adaptive cruise control system;
- Visual perception using a monocular camera;
- Identification of objects (stationary and mobile) based on camera footage;
- Processing signals from LiDAR and creating a three-dimensional map of the environment.

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