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Autonomous Self-Driving Vehicles - Design of Professional Laboratory Exercises in the Field of Automotive Mechatronics

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Abstract

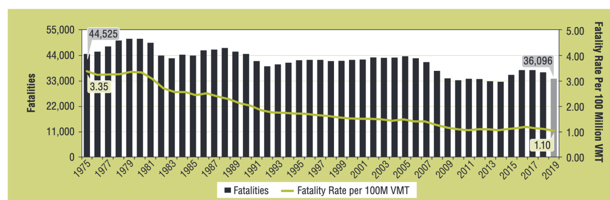
Self-driving cars are gradually making their way into road traffic and represent the most important component of a new form of mobility. Large companies such as Tesla, Google, and Uber are researching the continuous improvement of self-driving vehicles and their reliability. Therefore, it is of great interest for future professionals to become familiar with and master the principles and requirements of autonomous driving. The aim of this work is to develop the innovative concept of a university course at bachelor/master level for students in the automotive industry dealing with autonomous and self-driving cars. Simple hardware is used for the hands-on course, which nevertheless has all the necessary sensors and requirements for a comprehensive practical introduction to the topic of self-driving automotive technology. The course includes lectures and exercises on a variety of topics, including computer vision, the Python programming language, artificial intelligence, the Linux shell, and more.

Keywords

Autonomous Self-Driving Vehicles, Smart Cars, Computer Vision, Autonomy, Robot-Cars, New Mobility, Automotive.

Introduction and Motivation

Autonomous self-driving vehicles are an advancing technology that can reshape mobility by improving the safety, accessibility, efficiency, and convenience of automotive transportation [19]. The safety benefits of automated vehicles are significant. The potential of automated vehicles to save lives and reduce injuries is based on a tragic but crucial fact: 94% of serious accidents are due to human error [1]. Approaching this problem objectively from a mathematical perspective, it is clear that automated vehicles can remove human error from the accident equation, which not only helps to protect drivers and passengers. All road users, such as cyclists and pedestrians, as well as children playing along the road, could benefit. Considering that more than 35,000 people die each year in motor vehicle crashes [1] in the United States alone, the life-saving benefits of driver assistance systems become apparent.



Sources: FARS 1975-2018 Final File, 2019 ARF; 1975-2018 VMT – FHWA's Annual Highway Statistics; 2019 VMT – FHWA's September 2020 TVT

Figure 1. *Fatalities and Fatality Rate per 100 Million VMT, 1975-2019*

Among the safety-critical tasks an autonomous self-driving vehicle must perform are planning movements in a dynamic environment shared with other road users such as vehicles and pedestrians and executing them reliably and, most importantly, safely. Autonomous self-driving cars relieve drivers of routine tasks, increase traffic safety, offer new opportunities and services in individual mobility, and increase traffic efficiency while reducing environmental pollution [2]. In the process, new fields of technology and expertise are being linked with the classic fields of automotive engineering, mechanical engineering, mechatronics, and electrical engineering. This is because autonomous self-driving vehicles have to manage many demanding and complicated tasks. Autonomous vehicles are essential carriers of technological applications and fundamental innovations such as artificial intelligence, cloud computing, and computer vision, from whose vast development other branches of industry benefit greatly. Autonomous self-driving and digital mobility are thus also drivers of innovation and change. Like autonomous vehicles in general, the components of automated mobility systems can be divided into environment recognition technologies and core technologies [17]. Environment detection technologies, which consist of sensors, actuators, and human-machine or machine-machine interaction, are required for environment detection, communication, and the execution of commands. The base technologies of autonomous systems include perception, processing, learning, action, and self-regulation [3]. Based on raw data from sensors, autonomous self-driving cars use perception technologies such as computer vision and artificial intelligence to process environmental data [4]. The system then plans its actions based on various technologies and many complicated algorithms. These actions consist, for example, of planning and making decisions about driving tactics and strategy. In automated driving, the vehicle's actuator system translates lateral and longitudinal guidance instructions into steering movements as well as braking or acceleration operations [4]. Far more than just a good camera is needed for these functions to work reliably in less structured environments and unknown situations. Various approaches are considered promising methods to cope with the increasing complexity of autonomous self-driving vehicles due to the infinite variety of possibilities that traffic scenarios and the underlying nonlinear relationships hold. Simple rule-based systems cannot cope with this task because the road traffic regulations are a list of rules, but their interpretation and compliance are a matter of the infinite number of road users. Here, the focus of the development of autonomous self-driving cars is increasingly shifting from hardware to software. In addition to sensors, partially or fully autonomous driving requires robust software-based driver assistance systems and the intelligent collection and analysis of vast amounts of data [14, 15]. This means that the development of systems for automated mobility is increasingly concerned with the question of how these data volumes can be stored, structured, and then optimally used. Developing today's partially automated and later fully automated vehicles requires well-founded IT competence. Acquiring this IT competence is the subject of this course. Step by step, a simple remote-controlled car will be converted into an autonomous self-driving vehicle.

Definition of Objectives and Goals

This thesis aims to provide participants with a comprehensive introduction to the topic of autonomous self-driving vehicles and enable them to work independently with the tools, technologies, and algorithms they have studied. After successful participation, the participants will be able to redesign a model car so that it can recognize its environment and keep the lane on an arbitrarily prepared route. For this purpose, tasks for several laboratory exercises will be designed. These are to provide, first of all, knowledge about necessary rebuilding measures. The participants will learn which elements of a vehicle can be easily controlled digitally and where adjustments are necessary. After that, the participants will be introduced to the Linux working environment created for the car and start with the first programming tasks. This is followed by the first driving tests. At this point, the car is still controlled by a human. The aim of this particular aspect of the course is to become familiar with the programming environment and the modifications made to the car, test them, and improve them. After this part of the course is completed, the introduction to the algorithms and basics of autonomous driving is divided into four parts. Participants learn how to turn an average remote-controlled car into an autonomous self-driving vehicle in nine practical exercises that will enable them to work independently step by step in the world of autonomous self-driving vehicles.

All exercises are designed to meet the requirements of a laboratory exercise. The knowledge acquired in this course will be reinforced through immediate practical application and practiced in real-world scenarios. Each theory step is immediately implemented on the vehicle and can be evaluated in the real world. The accompanying theory is designed to explain the precise technical and functional relationships of the specified steps of autonomous self-driving vehicles to be implemented in a practical full-scale task.

The practical exercises allow participants to familiarize themselves with the tools and technologies presented; a lecturer supervises the exercises. This allows the participants to memorize and understand the theoretical content of the course on their own. However, direct and individual attention is given to the participants in case of questions and problems. In this way, the participant's interest in the topic of autonomous self-driving vehicles is to be awakened, and thus more specialists in this field are to be trained. The acquired knowledge will be retained for a longer time due to the embedding of practical tasks and independent but accompanied learning. This should motivate participants more strongly and help them achieve a sense of achievement.

Participants will learn the theory steps of self-driving cars, their practical application, and implementation, and choose the suitable methods and tools to implement them in practice. By combining theory and practice in practical scenarios, participants expand their expertise and apply what they have learned directly in their professional environment. In this way, the participants learn the theoretical basics of autonomous self-driving vehicles and apply them.

Additional competencies can be improved and strengthened, e.g., logical thinking, evaluation of clues, and concentrated and thorough approach, for example, when collecting measurement data or modeling components for 3D printing. The tasks are designed so that they can be performed by a group as well as by an individual participant.

Delimitation

The technologies, algorithms, and concepts of mathematics, computer vision, and artificial intelligence that together enable autonomous self-driving vehicles as well as the massive amount of data that needs to be analyzed to enable such a vehicle to drive autonomously, are pervasive and, depending on the classification, consist of a large number of different components [5]. In this thesis, the aim is to create a teaching program that allows master students to modify a low-cost remote-controlled car step by step to the point where it can autonomously follow an arbitrary course, perceive its environment, plan its driving maneuvers, adapt them if necessary and execute them. For this purpose, mainly tools from the field of computer vision are used [16, 18], such as the Hough transformation, the Canny algorithm, and other concepts and algorithms that have proven themselves in practice in order to enable efficient training. Especially Artificial Intelligence, although belonging to the field of autonomous self-driving vehicles, is not considered in this thesis. The necessary computational capacities of the related and necessary expensive hardware, concepts, and algorithms are beyond the scope of a single course and thus related exceed the scope of this thesis.

Autonomous Self-Driving Vehicles

In this work, the term "autonomous" is used in the context of self-driving vehicles to mean the actual state of independent decision-making in the process of driving [6]. This means that there is neither direct control by a driver nor indirect control by actuators. There is also no remote control via a connected control unit. Based on algorithms and defined control cycles and thresholds, the vehicle finds its way independently within a certain framework of decision-making freedom. This has the consequence and can be verified by the fact that the vehicle will never take the exact same path twice, given the same starting point [7]. However, the autonomy here also lies in the overcoming of the given form as we know the control of vehicles for centuries. For a long time, an integral part of using a vehicle was (remote) steering [9]. A vehicle without a driver was an impossibility. Driverless vehicles not infrequently caused great damage. Today, vehicles driven by computers are often already considered safer, and less prone to errors and accidents than vehicles driven by humans [8, 10]. The given form of dependence on and external control by a human driver is bypassed with autonomy, making the autonomous vehicle an independent decision-maker in road traffic. An autonomous vehicle is characterized by the fact that it recognizes its surroundings and can drive without human assistance [11]. A human driver does not need to take control of the vehicle at any time, or in some cases, not even be in the vehicle. An autonomous vehicle has the freedom to drive like a conventional vehicle and to do everything that an experienced human driver would do and decide.

The term ”self-driving” is often used synonymously with ”autonomous” [12]. However, it is something different. A self-driving car can drive itself in some or even all situations, but a human passenger must always be present and ready to take control. Self-driving cars would fall under conditional driving automation or high driving automation. Unlike fully autonomous vehicles that can drive anywhere, they are subject to geofencing [13].

Course Objectives

The developed teaching concept and the corresponding exercises are designed for students of a master’s program in the field of Automotive Technologies. They are also aimed at bachelor students of the Applied Mechatronic Systems program. A complete course comprises nine-course units. The time frame for each unit is, on average, four to six hours.

The aim of this teaching concept and accompanying laboratory exercises are designed to give participants a comprehensive overview of the topic of autonomous self-driving vehicles and enable them to work independently with the tools, technologies, and algorithms studied. Upon successful completion, participants will be able to redesign a model car to recognize its surroundings and maintain lanes on an arbitrarily prepared route.

The assignments are designed for several laboratory exercises to achieve the stated goals. These exercises are primarily intended to impart knowledge about necessary modification measures. Participants will learn which elements of a vehicle can be easily controlled digitally and where adjustments are necessary. Participants are then introduced to the Linux working environment created for the vehicle and begin the first programming tasks. This is followed by a first test of the driving capabilities. At this point, the car is still controlled by a human. This part of the course aims for the students to become familiar with testing, improvements of the vehicle, the programming environment, and the changes made to the car. After this part of the course is completed, the introduction to the algorithms and basics of autonomous driving is divided into four parts. Through nine hands-on exercises, participants will learn how to transform an average remote-controlled car into an autonomous self-driving vehicle so that they can work independently in the world of autonomous self-driving vehicles, step by step.

The hands-on exercises will allow participants to become familiar with the tools presented, while an instructor will also supervise the exercises. This allows the participants to memorize and understand the theoretical content of the course on their own. However, they will be addressed directly and individually in case of questions and problems. In this way, the participant’s interest in autonomous self-driving vehicles is to be awakened, and thus more specialists in this area are to be trained. The acquired knowledge will be retained over a more extended period of time due to the embedding of practical tasks and independent but accompanied learning. This should motivate participants more and help them achieve a sense of achievement.

The cognitive goals of the course are to gain a basic understanding of the field of autonomous self-driving vehicles and to know what tools are available and how to use this knowledge to prepare and collect information. The primary practical goal of the course is a case-specific application of the tools taught in the course, to be achieved through hands-on laboratory exercises. The effective goal is to train awareness and sensitivity to the significant problems of the autonomous self-driving vehicle topic. How can parts of the vehicle be controlled digitally? How can the mass of data be decomposed in a meaningful way to process the necessary knowledge as quickly as possible to make decisions in real-time? These are just a few of the many questions that the course participants will ask themselves during the course.

By combining theory and practice in practical scenarios, participants expand their expertise and apply what they have learned directly in a real-world environment. Participants will go through the complete evolution of developing an autonomous self-driving vehicle from a simple remote-controlled car. This way, participants learn the basics of autonomous self-driving vehicles and their applications.

This is followed by the three main parts of the course, which consist of exercises on various topics related to autonomous self-driving vehicles. In the three main parts, participants will receive a comprehensive introduction to the topic of Autonomous Self-Driving Vehicles and will be enabled to work independently with the tools, technologies, and algorithms studied. Upon successful completion, participants will be able to redesign a model car to recognize its surroundings and maintain lanes on an arbitrarily prepared route.

The first central part of the course focuses on the construction and modification of vehicles. This part consists of 3 exercises in which the participants must gradually achieve the objectives of the first central part. For this purpose, groups with a maximum of four participants will be formed at the beginning. These groups will each receive a kit of the remote-controlled vehicle used throughout the course. This kit will be built up and modified step by step during the first central part. In the second exercise, the steering of the vehicle is modified. In the third exercise, the course participants worked on the camera of the vehicle and constructed a suitable mount.

In the second central part of the course, the prototype created in the first part is then used and iteratively developed further. For this purpose, the participants go through 2 exercises. First, the first exercise introduces the software environment. For this purpose, the participants receive an introduction to the software environment, the programming interfaces, and the operating system CarOS, which was created especially for this course. In the second exercise, remote control is programmed, allowing the participants to review and revise the modifications made in the first central part of the course.

In the third and final part of the course, participants will receive a comprehensive introduction to autonomous self-driving vehicles' technologies, concepts, and algorithms. This part is divided into four exercises that introduce the concepts step by step. The first exercise focuses on color spaces and masking unnecessary information. The second exercise builds on this to explain how a computer can detect edges. Building on this concept, the third exercise continues with the Hough transform. Finally, in the fourth exercise, we implement and fine-tune. Here, it is shown how to convert the large amount of information gained into a steering motion and how to stabilize it.

All three parts together provide a comprehensive overview and in-depth knowledge in the field of autonomous self-driving vehicles and enable the participants to work independently in this area.

Course Structure

The New Mobility Course consists of the following 3 sections with 9 exercises:

1. Construction and Experimental Modification
   (a) Exercise 1: Kit Construction
   (b) Exercise 2: Kit-Modification – Steering
   (c) Exercise 3: Exercise 3: Kit-Modification – Camera
2. Software Setup and Iterative Testing
   (a) Exercise 4: Linux Shell and CarOS Fundamentals
   (b) Exercise 5: Software Setup and Iterative Testing
3. Autonomous Lane Navigation and Implementation
   (a) Exercise 6: Autonomous Lane Navigation Part 1/4 – Color spaces and Masking
   (b) Exercise 7: Autonomous Lane Navigation Part 2/4 – Canny-Edge-Detector
   (c) Exercise 8: Autonomous Lane Navigation Part 3/4 – Hough Transform
   (d) Exercise 9: Autonomous Lane Navigation Part 4/4 – Steering and Stabilization

Detailed Course Description

The course created in this thesis consists of a total of nine exercises that are divided into three different parts. The first part of the course is dedicated to the construction of the hardware, i.e., the setup and modification of the remote-controlled vehicle. After that, the vehicle's software and the programming interfaces will be discussed. Furthermore, the modifications from the first section will be tested and iteratively developed in this section. The theory of autonomous self-driving cars is addressed in the third and last part of the course. Here, all necessary algorithms, concepts, and techniques are discussed. Further modification and testing will be done until an autonomous self-driving vehicle is finally created.

1. Construction and Experimental Modification

In the first part of the course, everything is focused on the construction and modification of the vehicle. This part consists of 3 exercises in which the participants will be introduced to the course step by step. For this purpose, groups with a maximum of four participants are formed at the beginning. These groups will each receive a remote-controlled vehicle kit for the course. This kit will be built and modified step by step during the first part. In the second exercise, the steering of the vehicle is modified. In the third exercise, course participants work on the vehicle's camera and construct a suitable mount.

Exercise 1: Kit Construction

In this exercise, a vehicle kit is built that will accompany the participants throughout the course. Based on the car that is constructed, the exercises will be performed and the acquired knowledge will be applied step by step. Participants will become familiar with the car during the build and learn about its parts, functions, and sensors in order to realize the course goal: an autonomous, self-driving car.

Exercise 2: Kit Modification – Steering

In this exercise, the smart car kit that was built in Exercise 1 by the participants will be modified. The focus of this modification exercise is set on the steering behavior. The students are challenged to think critically about how to improve the steering of their smart car and discuss ideas as a group.

Exercise 3: Kit Modification – Camera

In this exercise, the smart car kit that was built in Exercise 1 and modified in exercise 2 will now be modified a second time. The focus in this modification exercise is set on the camera. The students are challenged to think critically about how to improve the camera position and camera angle of their smart car and discuss ideas as a group.

2. Software Setup and Iterative Testing

In the second part of the course, the prototype created in the first part will now be used and iteratively developed. For this purpose, participants will go through two exercises. First, the software environment is introduced in the first exercise. The participants will be introduced to the software environment, the programming interfaces, and the operating system CarOS, which was created especially for this course. In the second exercise, the remote control will be programmed, allowing participants to review and revise the changes made in the first part of the course.

Exercise 4: Linux Shell and CarOS Fundamentals

This exercise is about getting to know the software environment of the car better. It will be discussed how to work in the environment, where important places are, and what to do if something breaks in the software.

Exercise 5: Software Setup and Iterative Testing

This exercise is about getting to know the software environment of the car better. The first programming task is to be implemented. Most parts of the remote control are already written. Only parts have to be replaced.

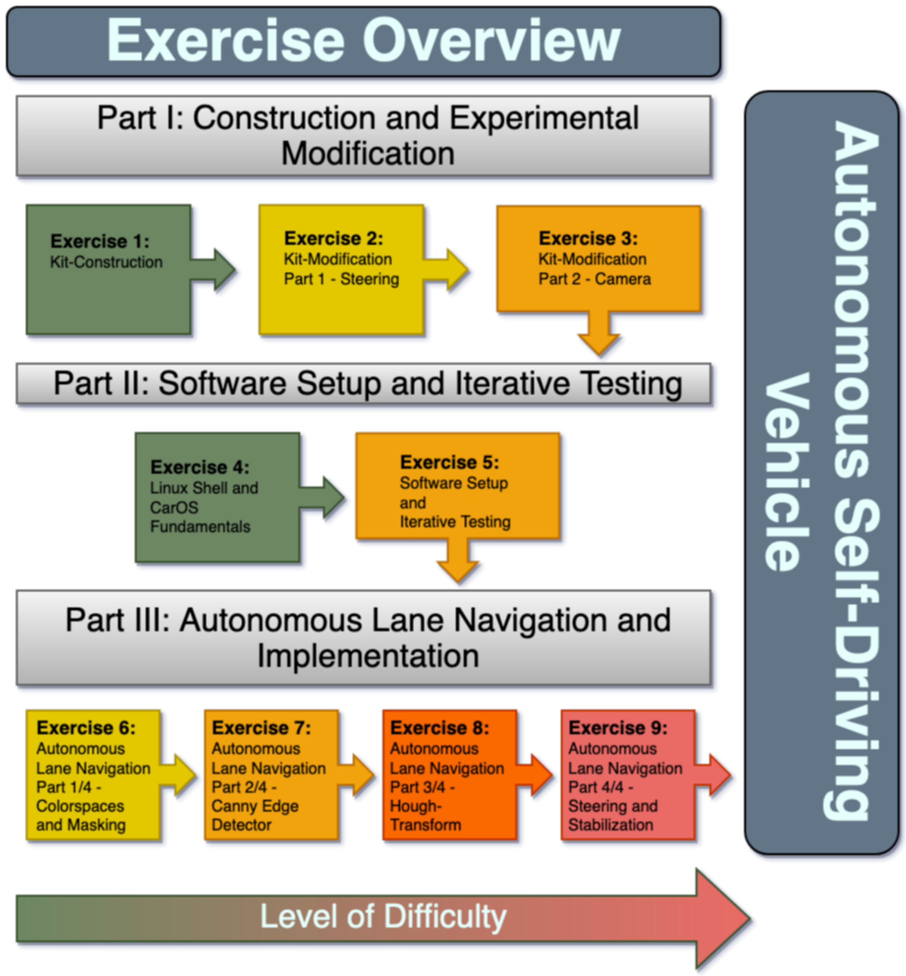


Figure 2. *Course Outline with 9 Exercises*

3. Autonomous Lane Navigation and Implementation

In the third and final part of the course, students will receive a comprehensive introduction to autonomous self-driving vehicle technologies, concepts, and algorithms. This part is divided into four exercises that introduce each concept step-by-step. The first exercise deals with color spaces and masking out unnecessary information. The second exercise builds upon this and explains how a computer can detect edges. The third exercise expands on this and continues with the Hough Transform. Finally, the fourth exercise shows how to convert the large amount of information gained into a steering movement and how to stabilize it. This exercise is also about implementation and fine-tuning.

Exercise 6: Autonomous Lane Navigation, Part 1/4 – Color Spaces and Masking

This exercise will introduce participants to the computer vision software OpenCV. Also, this exercise aims to familiarize with the HSV color space and understand the advantages of converting between RGB color space and HSV color space. Such a conversion of the color spaces will find a practical application and be tested as an example. The concept of masking is also part of this exercise. It should give the course participants a deeper insight into the world of computer vision, especially into the applied field of lane navigation.

Exercise 7: Autonomous Lane Navigation, Part 2/4 – Canny Edge Detector

In this exercise, the Canny algorithm is introduced and explained step by step. This is an algorithm for edge detection. This algorithm is the next step after the application of the HSV color space in lane line detection. The concrete goal of this exercise is to understand the Canny algorithm and how it works and to apply it to the practical example of the autonomous self-driving vehicle.

Exercise 8: Autonomous Lane Navigation, Part 3/4 – Hough Transform

This exercise introduces the Hough Transform which is explained step by step. The Hough Transform is an algorithm for line detection. This algorithm represents the logical next step after the application of the Canny Edge Detection for Lane Line Detection. The objective of this exercise is to understand the Hough Transform and how it works. The algorithm is then implemented in the Python programming language and applied to the practical example the autonomous self-driving vehicle.

Exercise 9: Autonomous Lane Navigation, Part 4/4 – Steering and Stabilization

This exercise deals with the steering and stabilization of a self-driving vehicle. There are several possible solutions to implement autonomous steering for a self-driving vehicle. These steering solutions are explained and can be applied in the second step of this exercise. At the end of this exercise, the course participants know the different implementation variants of the steering and stabilization of an autonomous vehicle and can apply them appropriately to the concrete course example of their own autonomous vehicle.

Course Materials

The instructional materials for the Autonomous Self-Driving Vehicle course described in this paper were structured and created to be as simple as possible. The created exercises follow a clear and recurring structure that is always similar. The participants should find their way around the exercise material as easily as possible and distinguish the theoretical part from the practical part quickly and easily. In addition to issuing the training material, including the exercise section, in printed form, it is only necessary to ensure that each participant has access to a PC with an Internet connection. This Internet connection needs to be also available to the vehicles. Apart from a simple text editor, no special programs need to be installed on the PC. Additional literature or own hardware or software is not necessary. The instructor has a sample solution available for all exercises to provide quick and targeted assistance in answering the questions.

Summary and Outlook

Autonomous driving has become an important component of the future of mobility. The digitization of mobility is developing rapidly worldwide. Automated driving technologies and assistance systems that relieve the driver, assist him, or partially or completely replace him - as in the process of parking, for example - have already been established in automotive manufacturing. At least partial automation of driving has become a common feature of everyday life. Highly and fully automated systems that can change lanes, brake, or steer without human intervention are already fitted as standard in many new cars. Both in Germany and in the USA, there are already numerous test tracks on which autonomous vehicles are allowed to drive, and it is only a matter of time before they make it into regular road traffic. Driverless robot cabs and buses are already being tested for local public transport. This development in mobility and the automotive industry creates a high demand for educated professionals. The field of autonomous driving and its evolution on it is a very diverse field of education with many different components and issues. Autonomous self-driving cars use a variety of sensors and sophisticated technology such as video cameras, radar sensors, LiDAR sensors, GPS systems, high-performance computers, and electronic controls to name a few. The engineering of automated self-driving cars also requires data processing and excellent software engineering skills. High-performance computers are needed to calculate all signals and data to name another requirement. These are a lot of requirements for suitable employees in this sector. For that reason, fundamental education should be provided as early as possible - for example, during a bachelor's or master's degree program. For this purpose, a professional laboratory exercise course in the field of Automotive Mechatronics was designed. The course created in this thesis gives participants a comprehensive overview of the topic of Autonomous self-driving Vehicles. It allows them to work independently practically on the development of their own autonomous self-driving vehicle. For this purpose, tasks were designed in several laboratory exercises. In nine practical exercises, the participants will learn the exact procedure that will enable them to work independently in the autonomous self-driving vehicle world step by step. The first evaluations of the course showed consistently positive results. The methods were conveyed understandably. The encouragement of personal initiative is also highly praised. As the amount of work and time required to create the individual tasks was very high, not all ideas such as, for example, the detection of traffic signs could be implemented. The creation of the sample solutions also required a lot of time and technical effort. Not all sources of error were foreseeable. The world of Autonomous self-driving Vehicles is fascinating and vast. Vehicles that no longer need human operators are on the verge of becoming part of our transportation system. This can provide many benefits such as a new level of convenience or the prevention of accidents caused by human error. However, autonomous driving also raises ethical issues e.g. about how an autonomous car should decide in the event of an unavoidable accident. The framework of a master thesis is not like that. In order not to completely go beyond the scope of this already very extensive work, only a fraction of the components of Autonomous self-driving Vehicles could be considered. Of all the areas of Autonomous Driving, the area of artificial intelligence is developing the fastest.

Future Work

Future work and advanced courses could focus on the application of artificial intelligence. Furthermore, detecting obstacles on the roadway could be a component of future exercises. Future work and further exercises could also focus on the recognition and associated reaction to traffic signs.

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