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Development and construction of actuators for an autonomous inner-city logistic vehicle

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Acknowledgement

Already at the beginning of my studies I was certain that I wanted to concentrate on automotive engineering and production engineering, with a special focus on economic aspects. During my master studies I was particularly enthusiastic about topics such as autonomous driving. At the Institute of Automotive Engineering, I found an interesting master thesis with the topic "Development and construction of actuators for an autonomous vehicle".

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(Andreas Schreiner)

Abstract

Delivery services and parcel deliveries have been done for decades by classic trucks. Especially in the cities this represents a big challenge for traffic optimization and pollutant emission reduction, to name only two examples. Increasing digitalization and networking is also considered to be important measures for optimizing the supply chains, because many companies are working on innovative solutions in this area. One field of research includes the development of autonomous vehicles. In cooperation with Österreichische Post AG, Energie Steiermark and i-Tec Styria, an autonomously-operated, electrically powered vehicle of the L6e class has been developed at Graz University of Technology. The basic vehicle, the Jetflyer, is already used by the Post AG and Energie Steiermark in major cities such as Graz, Linz and Vienna. However, the current solution is manually operated. The future solution - an autonomous vehicle - allows deployment of new scenarios for independent delivery as well as for the support of parcel delivery services. The current project is aimed at controlling a vehicle autonomously with walking pace to defined destinations in the inner-city area. The aim of this master thesis is to develop and to construct specified actuators of the vehicle, as well as to support the conversion of the base vehicle into an autonomous vehicle equipped with transport boxes.

Kurzfassung

Lieferverkehr und Paketzustellungen werden bereits seit Jahrzehnten auf Basis klassischer LKW durchgeführt. Gerade in Städten bedeutet dies eine große Herausforderung für die Verkehrsoptimierung oder die Reduktion entstehender Schadstoffemissionen, um nur zwei Beispiele zu nennen. Die zunehmende Digitalisierung und Vernetzung gilt auch im Lieferverkehr als wichtige Entwicklung zur Optimierung; nicht zuletzt deshalb arbeiten viele Unternehmen an innovativen Lösungen in diesem Bereich. Ein Forschungsfeld ist die Entwicklung autonomer Fahrzeuge für den Lieferverkehr. In Zusammenarbeit der Österreichischen Post AG, Energie Steiermark und i-Tec Styria wird an der TU Graz ein autonom geführtes elektrisch betriebenes Fahrzeug der L6e-Klasse entwickelt. Das Basisfahrzeug, der Jetflyer, ist bereits in Großstädten wie Graz, Linz und Wien für die Post AG und die Energie Steiermark im Einsatz; allerdings noch nicht autonom betrieben, sondern bemannt. Die zukünftige Lösung als autonomes Fahrzeug ermöglicht neue Einsatzszenarien zur selbstständigen Lieferung wie auch zur Unterstützung von Paket-Zustellerdiensten. Ziel im angeführten Projekt ist es, das Fahrzeug mit Schrittgeschwindigkeit autonom an eine definierte Zieladresse im innerstädtischen Bereich zu führen. Inhalt dieser Diplomarbeit ist die Entwicklung und Konstruktion ausgewählter Aktuatorik des Prototypen, sowie der Umbau des Basisfahrzeuges zu einem autonomen, mit Transportboxen ausgestatteten Fahrzeug.

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List of Abbreviations

GDB	Gross domestic product
€	Euro (European currency)
a	Center distance [mm]
b	Width [mm]
dp	Effective diameter [mm]
z	Number of teeth [-]
EGR	Exhaust gas re-circulation
SCR	Selective catalytic reduction
NOx	Nitrogen oxides
CO	Carbon monoxide
SO_x	Sum of Sulphur oxides
VOC	Volatile organic compounds
SPM	Floating pollutants
$LiFePo_4$	Lithium iron phosphate
BLDC	Brushless DC motor
GFK	Fiberglass reinforced plastic
SLAM	Simultaneous localization and mapping
dB (A)	Decibel (dB)
ATV	All-terrain vehicle
CAD	Computer-aided design (software for construction)
LIDAR	Light detection and ranging
RADAR	Radio Detection and Ranging
FMCW	Frequency Modulated Continuous Wave

1. Introduction: Delivery traffic in urban areas

Delivery traffic and parcel deliveries have been conducted for decades by use of classic trucks. Due to the constantly increasing traffic (and delivery traffic), especially in cities (1), the challenges of minimizing or optimizing the associated burdens such as noise, pollutant emissions, traffic jams, etc. have risen, too. Advanced digitalization and networking solutions are also considered as an important development in delivery traffic, thus many research activities and industrial developments can be experienced in this area. One field of research includes the development of autonomous vehicles for delivery traffic. In order to illustrate the need for the automation of delivery traffic, the following chapter deals with the current state of road transportation and with its aims. In the course of the present thesis, it will be also explained why a transformation of the traffic is necessary and will be undertaken. Furthermore, autonomous delivery vehicle solutions will be presented as well as concepts for the future, which will also serve as a benchmark for further conceptual development of the project, described in this master thesis. The mind map in figure 1.1 gives an overview of the content of this thesis.

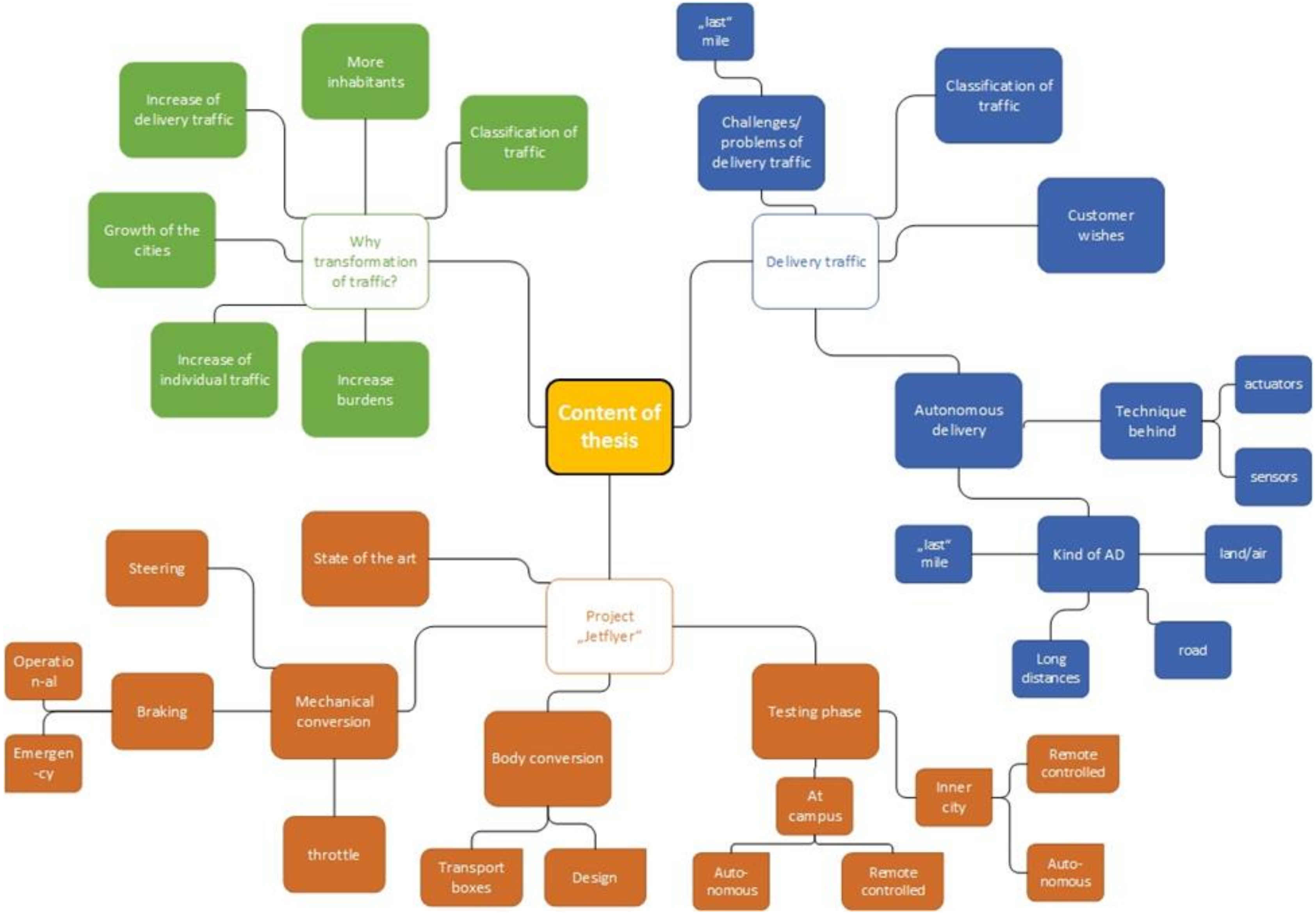


Figure 1.1 Overview of the content and influencing factors of the thesis

1.1 Classification of the traffic

In order to better understand the burden of the overall traffic situation and its appearance, city traffic is divided into the following categories (see figure 1.2):

- **Freight transport** is required for the transport of materials needed in the urban area for business activities and services. This includes supply and disposal traffic.
- **The economic traffic,** which comprises all kinds of passenger transportation in the context of business activities and services. This includes service traffic (e.g. craftsman), public service traffic (e.g. garbage collection), business travel and official communication traffic.
- The **total traffic**, which includes, e.g., freight transport and economic traffic, as well as moving traffic, commuter traffic, shopping traffic, training traffic (driving school), leisure traffic, tourism traffic or school transport.

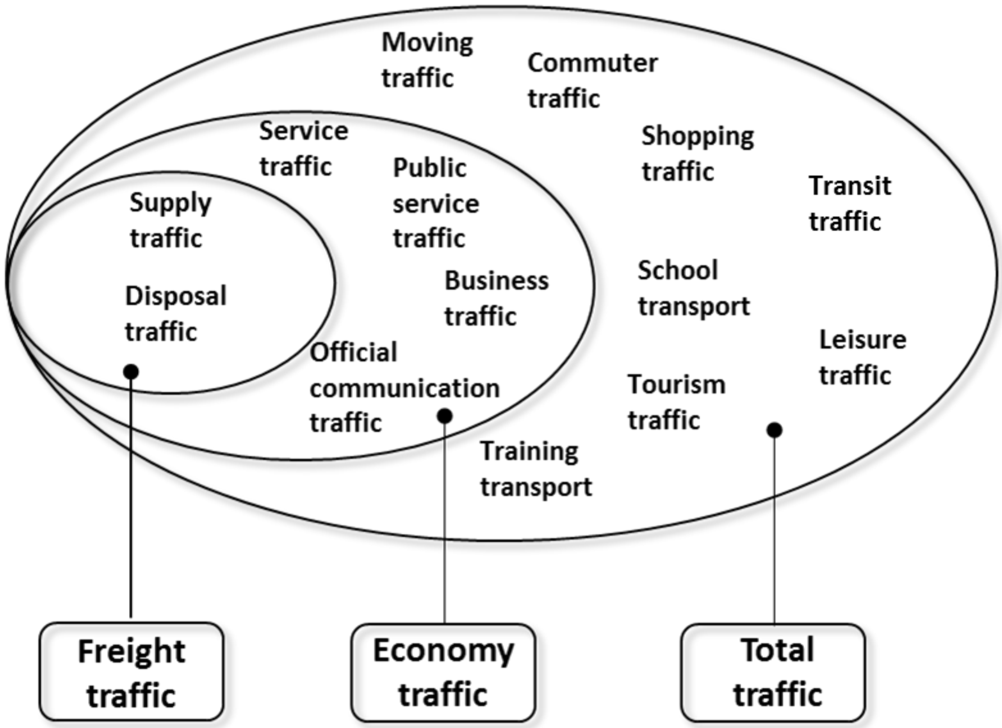


Figure 1.2 Classification of traffic in cities (2)

By dividing traffic into different categories, it's easier to understand delivery or freight traffic. This category consists of the delivery and the collection of goods. The project of this master thesis falls into this category and focuses on a potentially positive contribution to the reduction of traffic.

According to the *United Nations Department of Economics and Social Affairs*, the global population in urban areas has increased constantly since 1950, which also led to an increase of the previously mentioned types of traffic. (2) Actually, 55 % of the world's population already lives in urban areas and this development is said to advance. According to a UN study it will reach 68 % by 2050 and the main part of the increase can be expected in countries on the Asian and African continents. The increase in population is probably due to the gradual shifts of population from rural to urban areas and to the general growth of the world population. (3)

An illustration of the demographic trend can be seen in figure 1.3. Here, the cities are divided in size by population starting with cities with less than 500,000 inhabitants, to so-called megacities with more than 10 million inhabitants. (2) The considered development starts in 1970 up to 2025 and shows an increase in all city categories. The ever-growing megacities are a particularly vivid example of the impact of the ongoing urbanization.

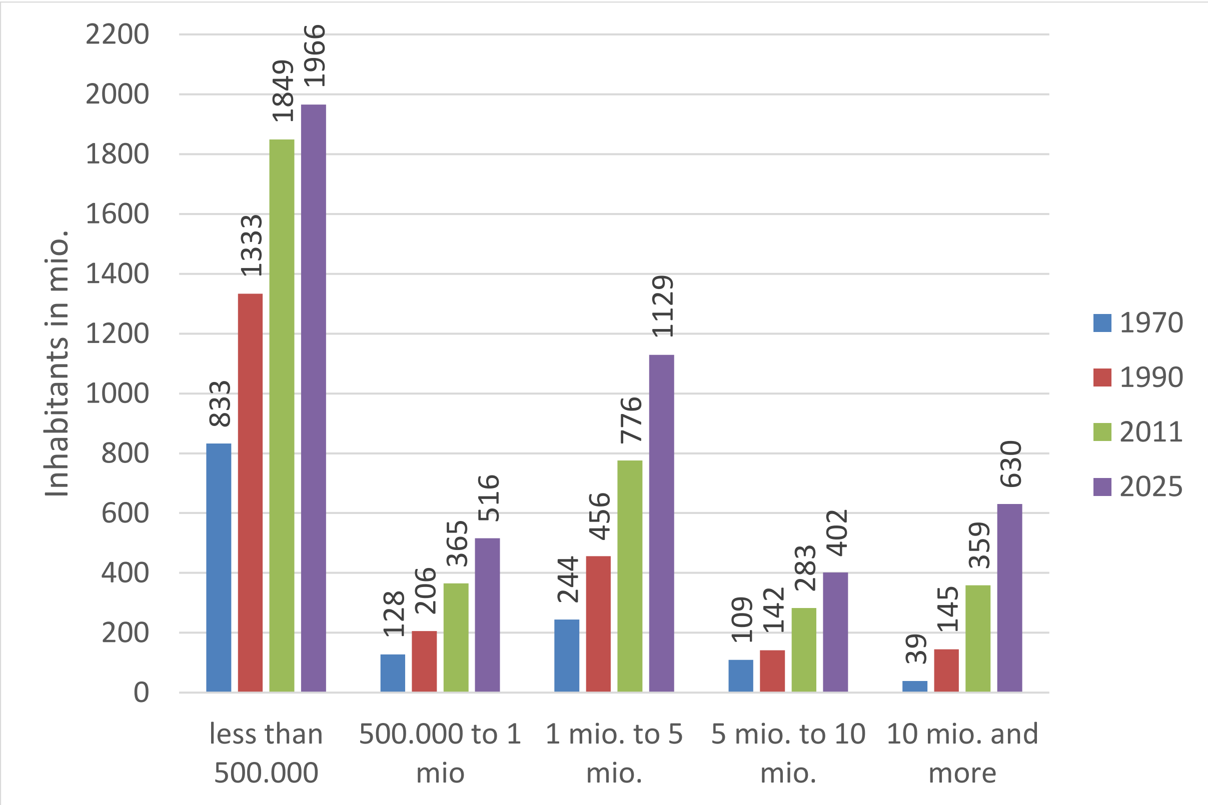


Figure 1.3 Overall development of the population over the years (2)

As the population increases, traffic and logistics effort does so. In addition, further expansion of online commerce will boost individual parcel delivery. There is an ever increasing concentration of traffic and long waiting times due to congestions, especially at rush hours. (4) Many logistics service providers tend to lose time and money. (5) The total costs for road users in Austria are around 1.9 % of GDP[1] or € 5-6 billion a year. (6) In this context, the last kilometers of delivery from the distribution centers to the delivery address of the customer are essential. These are the hardest to implement because they are often complex and individual. The costs of transportation of these last kilometers (from the distribution centers to the end customer) is estimated to be around € 62 billion per year worldwide (excluding pick-up and sorting). (2) At the same time, it is a fast-growing market with an increase of 7-10 % only in economically mature countries and up to 300 % in developing countries such as India. This means that in mature markets such as Germany, deliveries might double in the next 10 years. (7)

Regarding increasing goods delivery traffic, figure 1.4 clearly shows an increasing number of parcel deliveries from 2000-2016 at an example of Germany. During this period, the number has almost doubled. Above all, the development of e-commerce, which is depicted in figure 1.5, illustrates the need to solve the last mile problem. It is expected, that sales of purchases via the Internet will increase by up to 45 % by 2022. (8)

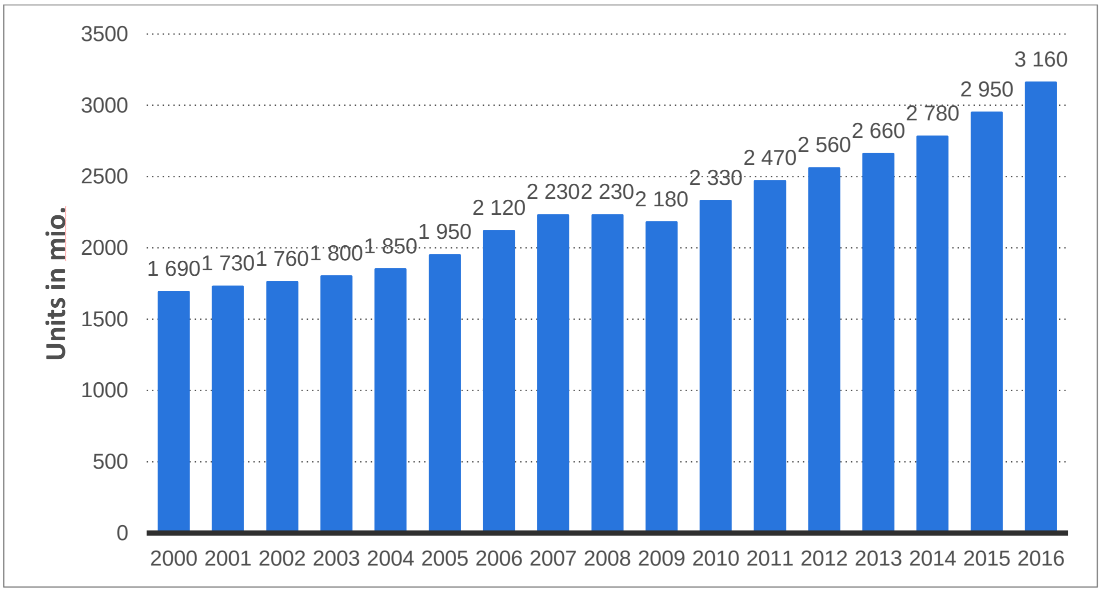


Figure 1.4 Number of courier, express and parcel service (CEP) shipments in Germany from 2000 to 2016 (in millions) (8)

[1] Gross domestic product

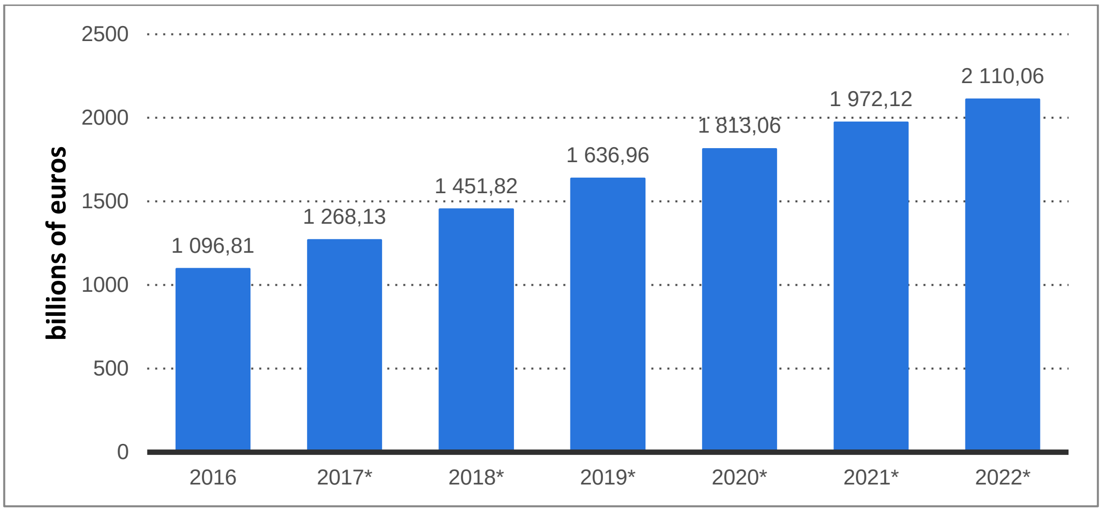


Figure 1.5 E-commerce sales worldwide 2016, forecast until 2022 (8)

1.2 Consumers' wishes/conceptions

An effective individual delivery of goods needs to be adapted to the customers' wishes. The following scenario shows the importance of properly planned distributor-customer-interaction: Imagine that you are waiting nervously for a package. You don't hear the bell and the deliverer is gone. You have to make another delivery appointment or you must even go to the next shop and pick up the package the next day. Usually, the delivery happens also in the morning, when most customers are not at home and you often have to pick up the goods from a partner shop of the logistics company. The challenge is to create a reliable, fast delivery with an exact timeframe. A survey of 4,700 people in China, Germany and the US revealed that around 25 % are willing to pay more for shipping if delivery is made on the same day. 70 % are still for the cheaper option. The remaining 5 % would prefer reliable delivery in a pre-selected time slot (see figure 1.6). (7)

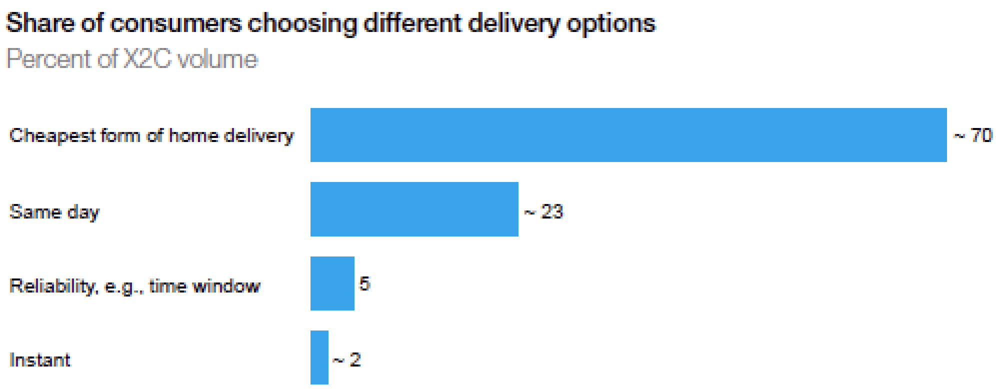


Figure 1.6 Preferred types of delivery, numbers in % (7)

However, the willingness of the customer to pay for a faster delivery is also dependent on what is delivered. People tend to pay more for things that satisfy the basic needs (e.g. food) or even relieve the physical comfort (e.g. medication) than for secondary needs (e.g. cosmetics, clothing, books, etc.). A detailed breakdown is shown in figure 1.7.

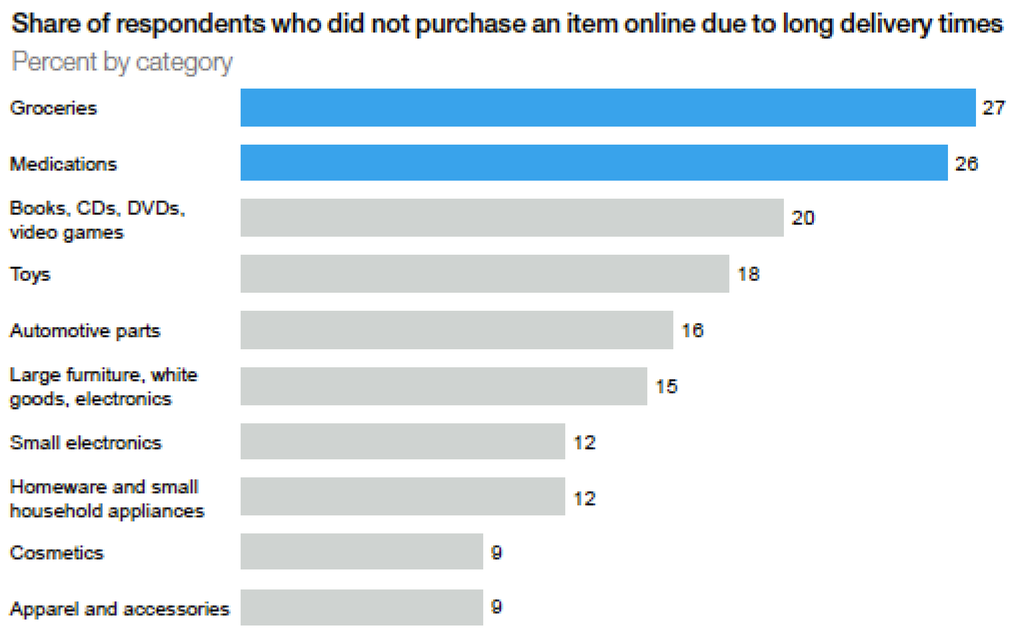


Figure 1.7 Goods and their desired delivery time, figures in % (7)

1.3 Inner-city delivery traffic

As mentioned at the beginning, the constantly increasing freight traffic also causes problems for the overall traffic. This chapter aims at giving more details on the problems and negative effects of the ever-increasing freight traffic.

Problems and negative effects of urban freight transport:

1. **Insufficient capacity of transport areas:** The increase of the volume of traffic means that the space needed for traffic and deliveries is gradually reduced. An expansion of area or capacity in large cities is often no longer possible. As a consequence, this impacts the flow of traffic and leads to an increased congestion. (2)
2. **Bottleneck loading ramp at recipients:** Companies with high delivery volumes and limited resources for delivery (insufficient loading ramps, too less loading forklifts, etc.) are increasingly experiencing delivery bottlenecks from suppliers. They often wait on the access roads for unloading operations, which can impact the traffic flow of the passing vehicles. (2)

3. **Limitation of delivery time:** Especially in big cities, but also in Graz (inner city), there are legal regulations when goods can be delivered to shops. This should contribute to the general relief of traffic during the day. However, it also leads to a very slow flow of traffic, especially during these delivery times. As mentioned in point 1, suppliers often park on lanes and this always leads to traffic jams in the morning. (2)
4. **Change in shipment structure:** In recent years, internet trading has grown strongly. More and more products are shipped after purchasing online. The average weight per order is decreasing, i.e. smaller and lighter items are ordered and delivered personally to the customer. This leads to a reduction of order quantities and to an increase concerning order cycles at the same time. As a result, suppliers have to make more and more individual stops and more suppliers are needed. (9) This contributes to an increase of traffic volume. Table 1 shows the comparison of typical characteristics of deliveries from different companies (B2B Business-to-Business) and deliveries to the end customer (B2C Business-to-Customer). (2)

Delivery to retail shop	Home delivery
Small quantities	One piece delivery
Boxes, crates, roll cages, etc.	Parcels
Homogenous loads	Heterogeneous loads
Large trucks	Small vans
One stop	Many stops
Transport companies and own transport	Mostly use couriers and parcel services
Vehicle movements to and within shopping areas	Vehicle movements to and within residential areas
No delivery failures	Possibility of many delivery failures

Table 1 Comparison of retail- and home delivery (9)

5. **Uneven temporal use of available transport capacity**: The peak of supply traffic over time is very unevenly distributed. Reasons for this are mostly legal boundary conditions. In the city centre of Graz, for example, B2B delivery activities with the use of powered vehicles (e.g. cars, trucks) are permitted from 5:00 am to 10:00 am. (10) Generally, between 57 % and 72 % of the daily deliveries are carried out during these hours. Furthermore, urban supply traffic is affected by commuter traffic in the morning hours. (11) A distribution of the deliveries over the day can be seen in figure 1.8. It can be deduced that up to 2/3 of all deliveries take place until noon. Towards evening, the frequency of deliveries is decreasing again almost constantly. (2) This is due to a

major reason: Hardly any deliverer (with the exception of food deliverers) works after 7 pm. With the conventional forms of delivery (delivery by the courier driver), there cannot be achieved any decrease of the traffic due to delivery purposes. As a consequence, alternative delivery forms are necessary (see chapter 1.6).

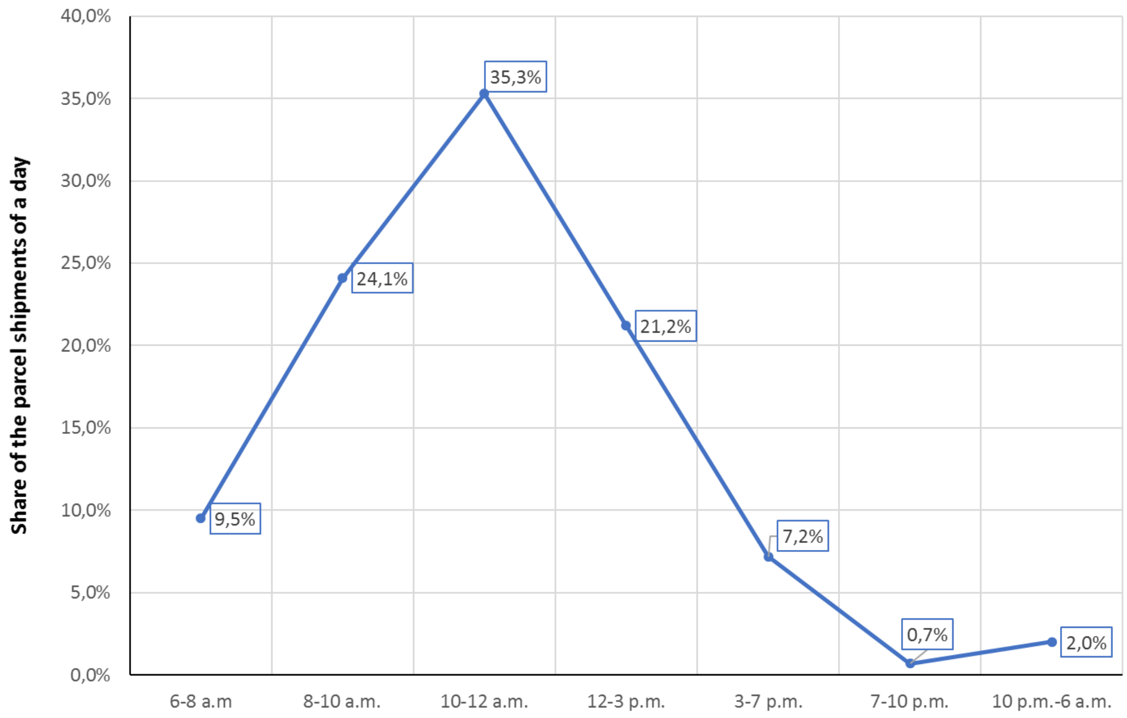


Figure 1.8 Distribution of deliveries over the day on an example in an average metropolis (2)

6. **Effects of urban freight traffic on traffic flow and road safety:** Accidents in which trucks are involved are generally less frequent, but they are more serious and often result in fatalities. In 2016 alone, 1291 accidents with trucks over 3.5 tons happened in Austria. However, they claimed 17 % of all road deaths. (12) Reasons for such accidents are usually:
    - Increased crossing of other lanes
    - Loading operations on sidewalks or additional lanes
    - A bad overview from inside the trucks (blind spot)
    - Ruthless handling especially of cyclists compared to trucks
    - Stressed truck drivers, often due to deadline pressure in combination with traffic jams. (2)
7. **Ecological impacts of urban freight transport:** Freight transport contributes to global emissions of pollutants and climate-relevant substances. Especially the air quality in big cities suffers

strongly (see figure 1.9). (13) In this figure the PM 2.5[2] average value from selected cities is shown. In contrast, the red line shows the limit that is recommended by the World Health Organization (10 µg/m³). Although modern vehicles have different exhaust after treatment measures (particulate filters, EGR[3], SCR[4]-catalyst, etc.), public transport and individual traffic, especially in megacities of developing countries like India, still rely on older models, which do not have these exhaust gas upgrading technologies.

Traffic causes particularly the following emissions:

- Air pollution: these include CO[5], NO_x[6], CO_2[7], HC[8], VOCs[9] and SPM[10]
- Noise pollution
- Other nuisances such as smells and vibrations

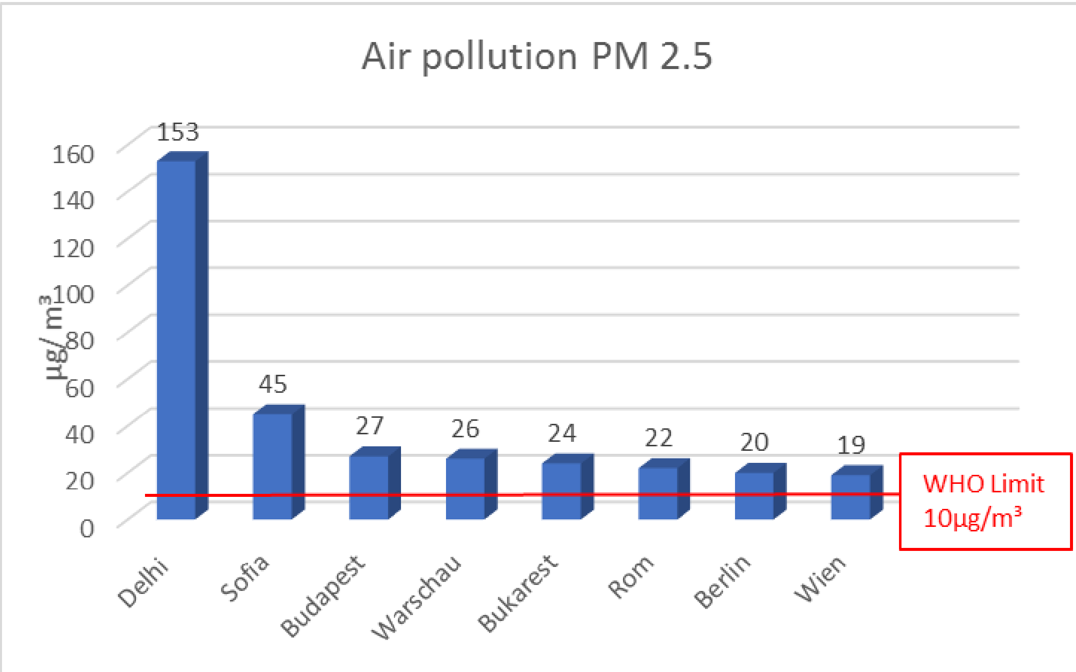


Figure 1.9 Air pollution in selected cities 2013 (14)

[2] Pm 2.5 = particular matter with diameters generally 2.5 micrometers and smaller
[3] Exhaust Gas Re-cirulation
[4] Selective Catalytic Reduction
[5] carbon monoxide
[6] nitrogen oxides
[7] carbon dioxide
[8] hydrocarbon
[9] volatile organic compounds
[10] suspended particulate matter

One aim of future delivery concepts is to reduce or to avoid the described problems. There should be a special focus on the “last mile[11]” delivery. Autonomization may make it possible to use resources in a more efficient way, to reduce ecological impacts and to elaborate on costumer wishes. An option is to use the delivery time slot in the evening. Hence traffic jams are defused at the rush hours and customers are more satisfied to get their parcels when they are at home.

1.4 State of the art of automated and autonomous delivery vehicles

Autonomization can contribute to reduce or completely eliminate certain delivery issues, which are discussed in previous chapters, while responding to the customer's individual needs. The potential for this is explained in more detail in chapter 1.6. This chapter discusses the current uses of automated and autonomous delivery systems for passenger and goods transport, which also serve as idea generation for the project Jetflyer. But first, the topic "autonomous vehicles" has to be introduced. What does autonomous driving mean, what kind of technology is needed? What is the difference between autonomous and automated driving? This chapter also provides a short explanation of the most important terms.

“Autonomy” derives from ancient Greek and means "self-determination", "self-reliant". (15) “Automated” comes also from the Greek and means “independently”, “self”. (16) In short, in "autonomous driving", the vehicle should drive, steer and park in a targeted and autonomous manner, without human intervention in traffic. It decides for itself what to do and how to react in which situation. On the other side “automated driving” means that the vehicle follows the processes and procedures without any human interaction, but without self-determination. (17) So the extent to which the vehicle can take over the tasks of the driver when needed and the way people and machines interact on the road nowadays and in the future takes place in the various stages of development. The SAE J3016 standard describes five levels of vehicle automation, defined in succeeding steps from “no automation” to “fully autonomously” (see figure 1.10, followed by a brief explanation of the certain steps).

[11] Last mile delivery is defined as the movement of good from a transportation hub to the final delivery destination. (124)

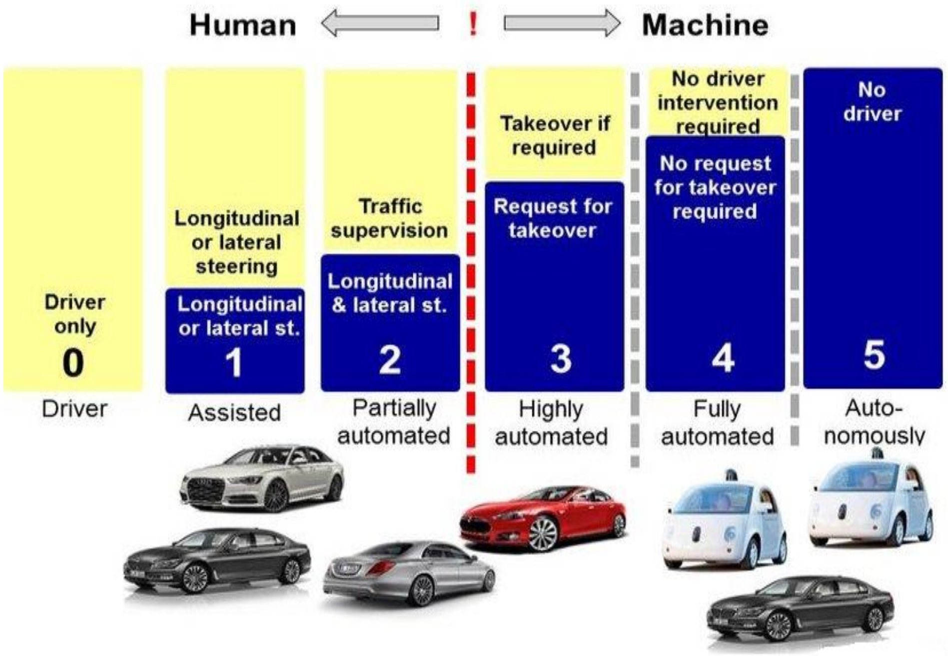


Figure 1.10 Levels of autonomous driving according to SAE J3016 (18)

1. Stage, assisted driving: Is already in use in most vehicles. The driver permanently executes the longitudinal or lateral force guidance. (19) These are functions such as active cruise control, stop & go functions, which independently regulate the distance to the vehicle in front, and collision warning devices, which avoid collisions by means of an independent braking process.
2. Stage, semi-automated driving: The driver must monitor the longitudinal and transverse guidance as well as the traffic permanently. The system takes over in exceptional cases. (19) For example, in the event of unintentional leaving the lane, the lane departure warning system can counteract on this.
3. Stage, highly-automated driving: The driver no longer has to monitor traffic and vehicle movement permanently. However, in potentially dangerous situations, he/she must be able to take over the control of the vehicle. (19)
4. Stage, fully automated driving: Only in special situations, a driver is required. (19) The vehicle can even autonomously move around complex traffic situations (e.g. at road works).
5. Stage, driverless driving: The system takes completely over the control, there is no driver necessary. (19)

In order to guarantee the correct function of automated or autonomous driving, the environment must be recorded accurately. For this purpose, various sensors are used in order to provide information about locations (coordinates, distance, angle), dimensions (length, width, height) and velocity (longitudinal, lateral, relative). With this information a central vehicle controller sends commands to the actuators. After that these actuators have to perform the movement.

In order to provide a better understanding, a closer look is given to the technology behind sensors and actuators.

1.4.1 Sensors

A sensor is a component that converts a measured physical or chemical quantity Φ into an analog electrical quantity E. Examples for physical quantities can be pressure, weight, acceleration, light intensity, temperature, radiation, sound, magnetic flux, speed and many more. The sensor measures the physical quantities and converts them with inductive, capacitive, piezoelectric, magnetic, field strength, radioactive, charging or photoelectric converters into an electrical quantity, which is set by the sensor in a pre-defined relation to the input variable. A sensor scales the signals so that they can be interpreted for further processing (see figure 1.11). (20)

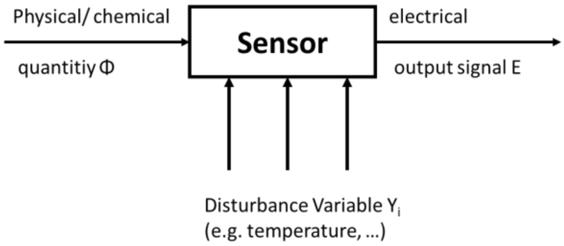


Figure 1.11 Basic function of a sensor (20)

This can be described with the following equations:

$$E = f(\Phi, Y_1, Y_2 \dots) \tag{1}$$

$$\Phi = \mathrm{g}(\mathrm{E}, Y_1, Y_2 \dots) \tag{2}$$

If the functions f and g are known, they represent a sensor model. With the aid of the sensor model, the desired quantity can be calculated mathematically from the output signal E and the disturbance variables Y_i virtually. (20) Since the topic of sensors is very extensive, in the further course only sensors, which are specifically relevant for autonomous driving are explained.

In order to make autonomous driving possible, the environment must be accurately recorded. This requires a number of sensors. As can be seen in figure 1.12, the different sensors cover a certain area of the environment; in this area they can perceive what happens.

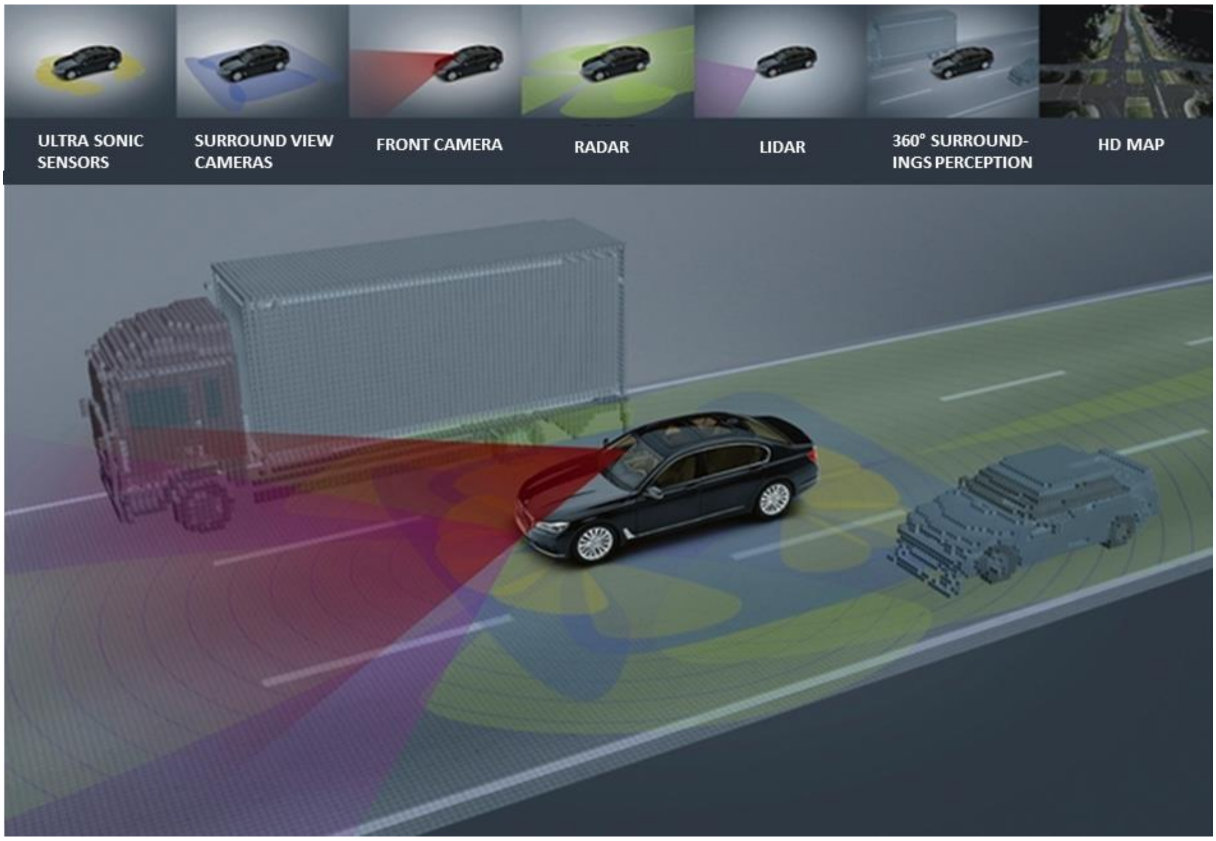
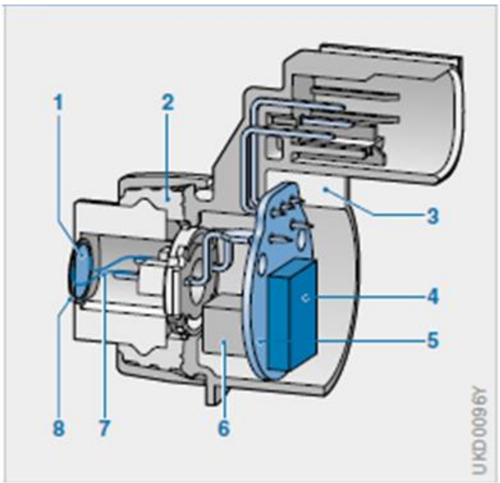


Figure 1.12 Overview of various sensors for autonomous driving (21)

For near and middle distances, ultrasonic sensors, short-/ medium range RADAR, cameras and LIDARs[12] are used. For long distances long range RADARs are used.

Ultrasonic sensors: These are able to detect objects without contact and to measure the distance to them within a short distance. Ultrasonic sensors work according to the pulse-echo principle in conjunction with triangulation. In this case, an electronic circuit stimulates an aluminum membrane (see figure 1.13 on the left side) with rectangular impulses for oscillating or emitting ultrasound at a frequency of about 43.5 kHz. (20)

[12] Light Detection and Ranging



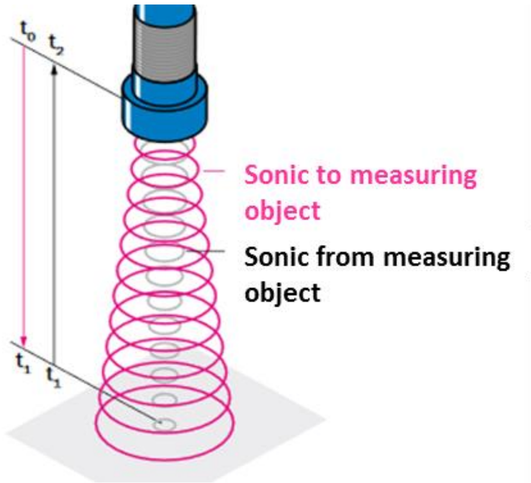


Figure 1.13 left: Sectional drawing of ultrasonic sensor (20); right: principle function of ultrasonic sensor (22)

1…piezoceramic

2…decoupling ring

3…housing with plug connector

4…ASIC (Application Specific Integrated Circuit)

5…circuit board with sender and evaluation unit

6…transformer

7…bonding wire

8…membrane

The sound reflected by the obstacle causes the now calmed membrane to vibrate again. These vibrations are converted to an output signal by the piezoceramic element as an analog electrical signal, amplified by the transmitter and converted into a digital signal. The distance is measured over time, which takes momentum from the sensor to the object and back again (see figure 1.13 on the right side), considering following equation:

$$a = c_s * \frac{t_2}{2} \qquad (3)$$

a…distance

c_s…sonic speed

t_2…entire duration of sonic speed

The exact distance from one object to the sensor can be obtained by means of the triangulation method. The measurement results of two sensors are used in order to get the distance and the position of the object (see figure 1.14).

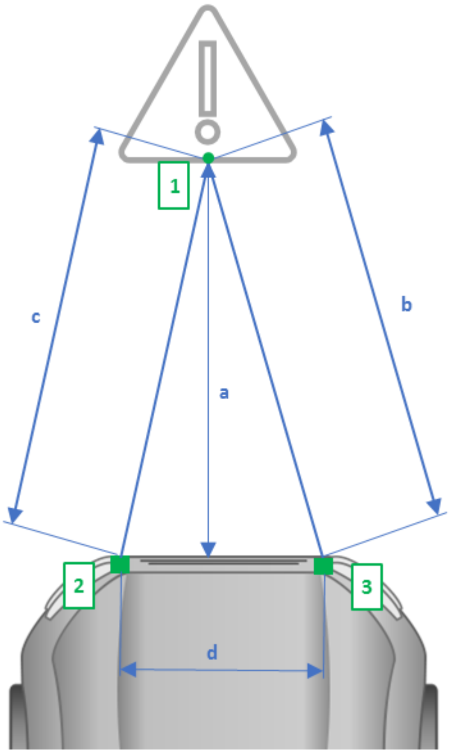


Figure 1.14 Principle of the triangulation method (20)

Distance from the object to the vehicle:

$$a = \sqrt{c^2 - \frac{(d^2 + c^2 - b^2)^2}{4d^2}} \tag{4}$$

By using several ultrasonic sensors, a large detection angle is produced. The range depends on the measured object. The less sound the object absorbs, the higher is the possible range.

RADAR[13]: For the environment sensing in "medium" and "long-range", (from 1 m up to 200 m) (23) RADAR is used. These devices emit electromagnetic waves that reflect on metallic objects. The RADAR device

[13] Radio Detection and Ranging

receives these signals, compares the time and / or frequency in order to determine the distance and relative speed. A distinction is made between direct transit time measurement and indirect transit time measurement (FMCW[14]). In direct transit time measurement, the time duration τ of the signal to the object and back again is measured. This results from:

$$\tau = \frac{2R}{c} \tag{5}$$

In this formula R is the distance [m] to the object and c is the speed of light [m/s]. The disadvantage here is that only one measurand can be determined, e.g. distance. If a determination of several measurands (e.g. distance and relative velocity) is required, the indirect propagation time measurement (FMCW method) is used. Here, the transmission signal is modulated in frequency. This method no longer measures the time between the transmitted and the received signal, but it compares their frequencies. In figure 1.15 the difference between constant speed and relative speed is shown by a phase shift. If there is a relative speed between two objects in addition to the distance, the received frequency increases by the amount f_d due to the Doppler effect. This gives f_1 and f_2. Add the two difference frequencies to get the distance, subtract f_2 and f_1 to get the relative velocity. (24)

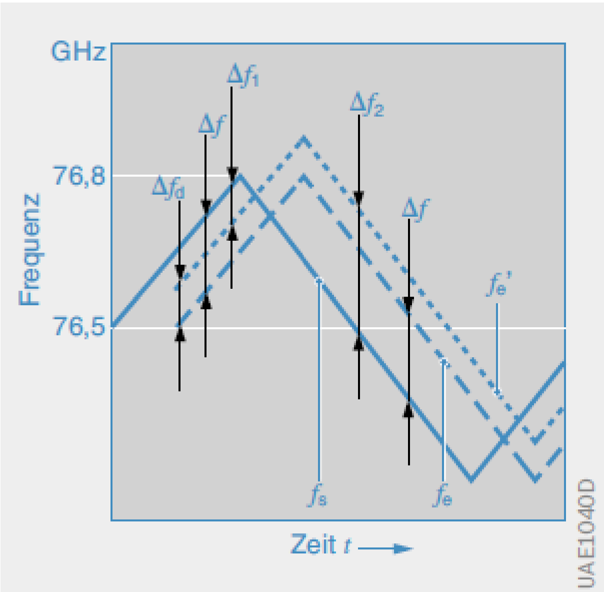


Figure 1.15 FMCW method (20)

f_s…transmit signal

[14] Frequency Modulated Continuous Wave

f_e…receive signal at constant speed

f_e'…receive signal at relative speed

The distance R to the reflecting object results from:

$$R = \frac{C * |\Delta t|}{2} = \frac{C * |\Delta f|}{2 * (\frac{df}{dt})} \tag{6}$$

c…sonic speed [m/s]

Δt…transit time [s]

Δf… measured frequency difference [Hz]

R… distance antenna to the object [m]

$\frac{df}{dt}$… frequency deviation per unit time

The big advantage of RADAR devices is that they are reliable even in bad weather conditions like fog or rain. (18) The difference between a short range RADAR and a long range RADAR is the operating frequency. The short range RADAR uses 24 GHz and makes high accuracy in a much wider radiation angle possible, but only in short range. The long range RADAR uses a 77 GHz works in a smaller angle, but with higher accuracy of long distances. (25)

Cameras: With the help of cameras detailed information can be obtained. For cameras image sensors are used. Image sensors are light-sensitive sensors that convert brightness into voltage. Image sensors are areal sensors that consist of many small, light-sensitive photocells that are arranged in rows and columns in a matrix. The two most common technologies are the CCD sensor or CMOS sensor. At the CCD-Sensor (Charge-coupled device) the electrical generated charge passes in many small steps the horizontal and vertical register by using the "bucket chain principle" [15] (see figure 1.16 right side). At the CMOS-Sensor (Complementary metal oxide semiconductor) the pixels are not read out serially, but can be controlled individually. For this purpose, every pixel has its own active electronic (amplifier), so the pixels can be read out more quickly (faster response) (see figure 1.16 left side). (20) (26)

[15] Bucket chain principle: Like a bucket chain, the loads of the individual components are passed on from one to the other. (125)

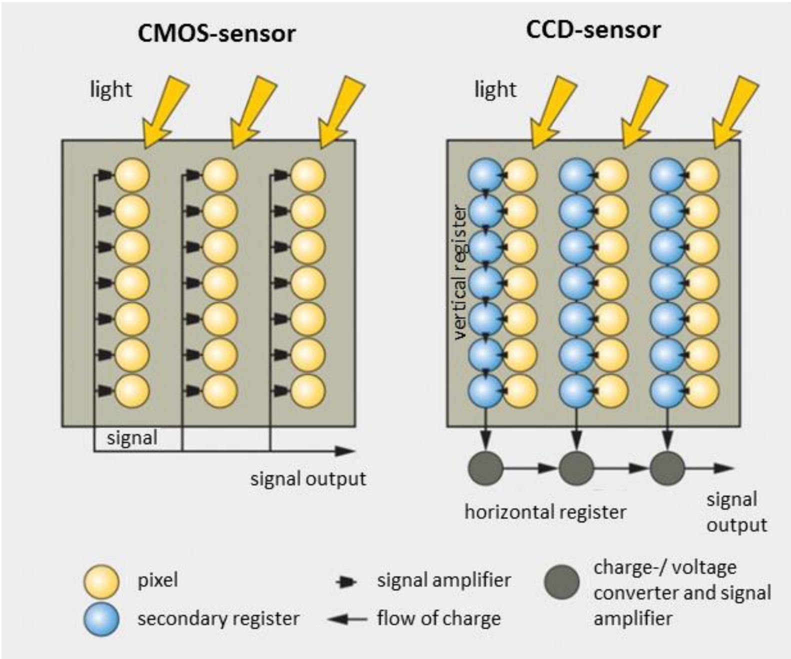


Figure 1.16 Function of image sensors: CCD- versus CMOS sensor (26)

In vehicles from automation level 1, cameras are already in use for driving assistant systems. Two basic camera types can be distinguished. The mono camera and the stereo camera (see figure 1.17). The mono camera is a monocular system that consists of a camera lens and an image sensor. It works on the basic of object classification and calculates distances using algorithms. For the object identification the mono camera uses a pattern recognition, which is trained by means of mechanized learning methods. Specific features of edge-based image segmentation allow the determination of special object types such as cars, trucks, motorcycles, cyclists and pedestrians, as well as road markings, traffic signs, construction sites and traffic lights (see figure 1.18 left side). The algorithms analyze the captured image and look for positive matches. In order to determine distances from the two-dimensional image sequence, conventional mono cameras use the object size and its position relative to the horizon. Therefore, the algorithms measure the angle of striking objects to a defined vanishing point. For example, the information about the relative angle of the feet of a pedestrian or the tires of a vehicle in front allows to draw conclusions about the respective distance. For driving at night cameras in conjunction with infrared-sensitive image sensors are in use. They allow object detection at night. (see figure 1.18 right side) (27)

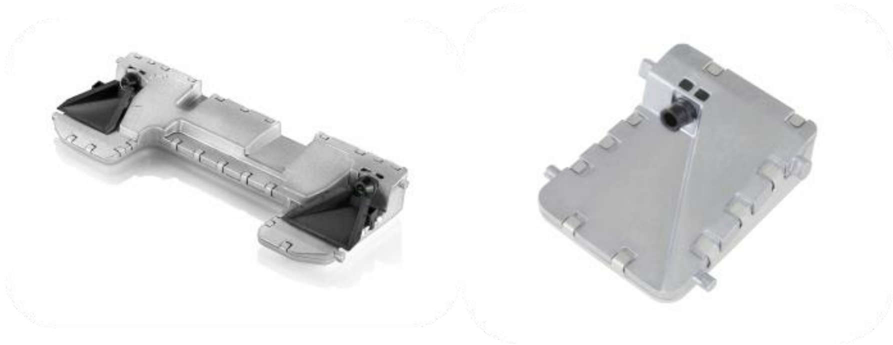


Figure 1.17 Camera systems: left stereo camera; right: mono camera (28)

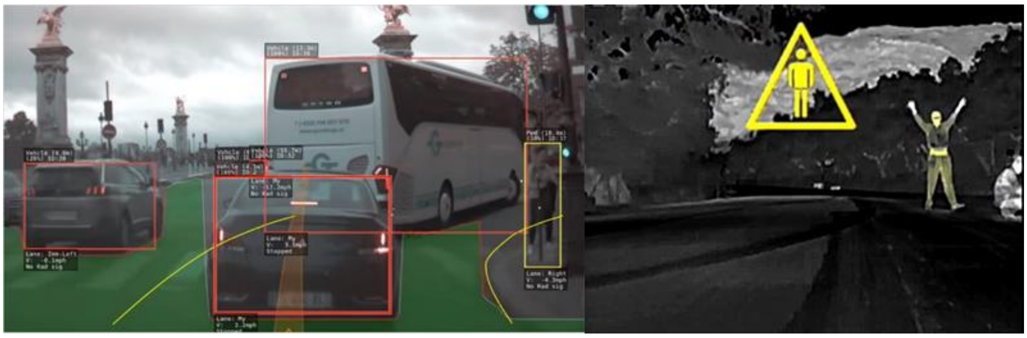


Figure 1.18 Left: Contour recognition of objects (29); right: objects recognition at night (21)

The stereo camera, on the other hand, consists of two camera lenses and two image sensors. It takes two pictures simultaneously and generates with the pictures a three dimensional image by comparing them. The perspective differences between the two images make it possible to measure the distance to the object in front, its actual size and direction of movement directly and precisely. "Spatial vision" also makes it easier for the stereo camera to better recognize partially hidden or closely spaced objects. However, due to the physical limits (the distance between the two camera lenses), it is limited with the range of the 3D image generation. (27) (30)

These two explained camera systems are the basic types. There are also further developments that combine the properties of the two systems and have hardly any technical losses (e.g. range of object detection). (30)

LIDAR: For distance and speed measurement, as well as for the classification of objects, LIDAR sensor systems are used in the mid-range view. This is an optical measuring method. The principle of the LIDAR system is similar to the RADAR system, but instead of microwaves, LIDAR uses ultraviolet, infrared or rays from the visible light range. There are various measuring methods for determining the distance. The most common method is the “Time-of-Flight” measurement (ToF). The duration from emitting the laser pulse to reception of the backscattered rays is proportional to the distance of the measuring device from the object, which can be described with the following formula:

$$d = \frac{c_0 * t}{2} \tag{7}$$

d…distance

c_0…light speed

t…time

Where t must be seen twice the time; The duration from the measuring device to the object and back again. With the ToF measurement a plurality of light pulses can be sequentially emitted (see figure 1.19).

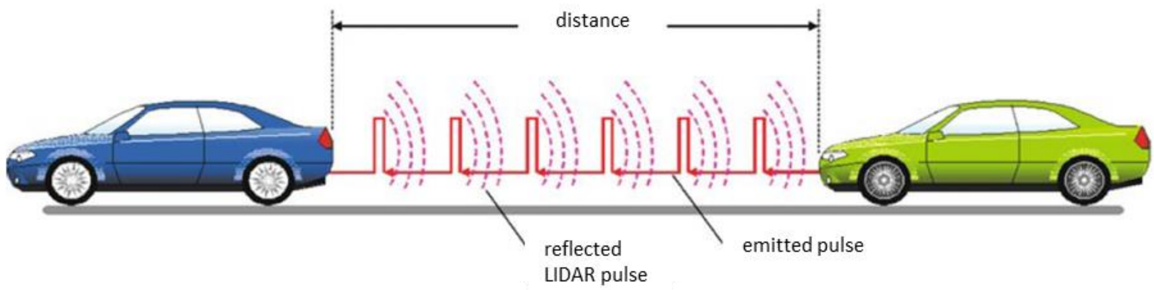


Figure 1.19 Time-of-Flight method for determing the distance (31)

The functionality is as follows: Through a laser diode (see figure 1.20 on the left side), a laser beam is emitted, which hits a 90° deflection mirror and enters the room. There an object in a certain distance reflects the light rays and these are received again from the LIDAR sensor. The reflected light rays are detected by the photodiode. The elapsed time from the emission of light to the reception by the photodiode is measured and used to calculate the distance. Through the spinning mirror it is theoretically possible for the LIDAR sensor system to obtain a 360 ° all-round view. In figure 1.20 on the right side the scan of a LIDAR sensor system can be seen with a 60° front view. (31) (32) (33)

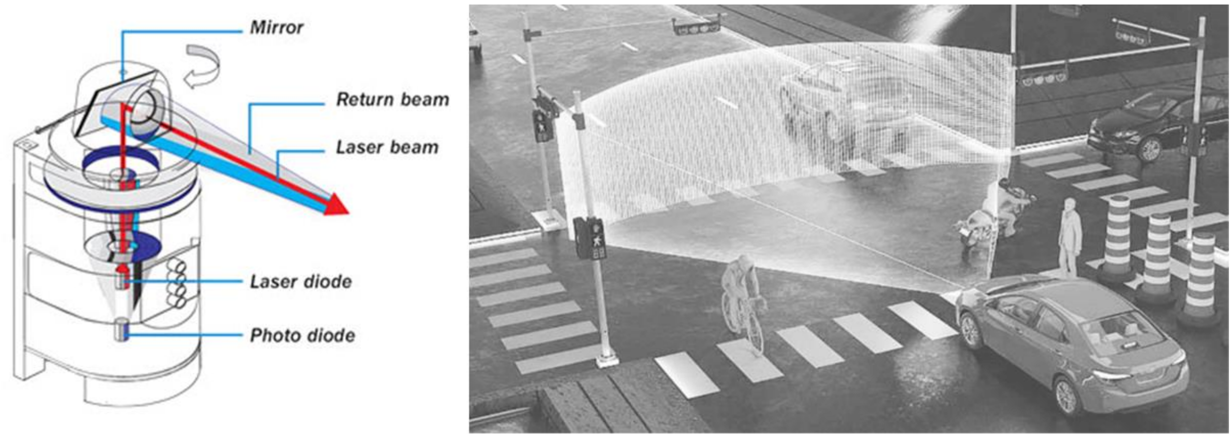


Figure 1.20 Left: Structure of LIDAR sensor (32); right: LIDAR 3D scan of traffic (33)

In addition to the environmental detection, an exact position determination is necessary for the autonomous driving operation. This allows conclusions to be drawn about the exact location. This is done with the help of the following sensor systems:

GPS[16] /GNSS[17]: It is a global positioning system based on satellites. These satellites orbit the earth and transmit permanently encoded radio signals, which provide information about their position and the transmission time. With an appropriate receiver (GNSS antenna), information about the current location can be given. This requires signals from four satellites. The exact position is determined via the trilateration method, which means the determination of a position via distance measurement of three points (satellites). The fourth satellite is for elimination of failures. As can be seen in figure 1.21, two positions (position A and B) can be determined via an intersection of the two running times t_1 and t_2 . As only one of the positions is at the surface of the earth, the correct position of the receiving object is A. (20)

[16] Global Positioning System
[17] Global Navigation Satellite System

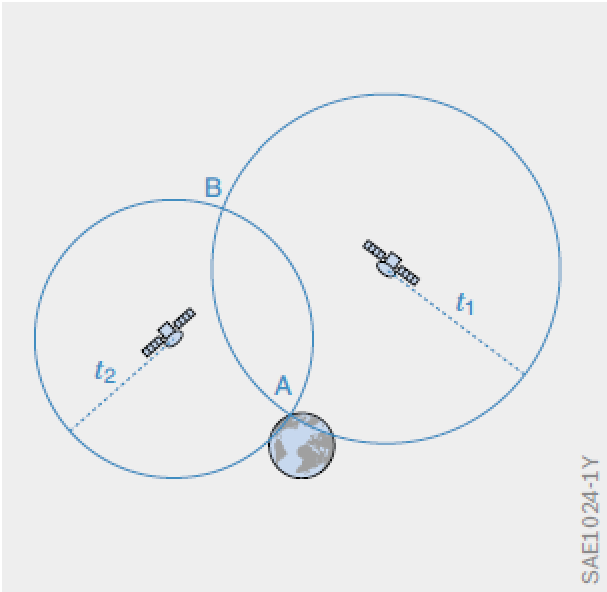


Figure 1.21 Position determining via GPS (20)

Odometry: Odometry is a method for estimating the position and orientation of a ground-based vehicle by the sensor data of its wheels. For this, the data from rotational wheel speed and steering angle measurement is used, often supported by GPS tracking. Odometry is a relative position determination, which is used in order to define the position and direction of a vehicle in a given reference coordinate system. The current position is calculated from the previously known position plus the traveled distance. figure 1.22 shows a vehicle in an absolute coordinate system. The values ΔL and ΔR are measured directly by the wheel sensors. Thus, information about the rotational angle α of the vehicle and the distance Δs of the vehicle can be obtained. (34)

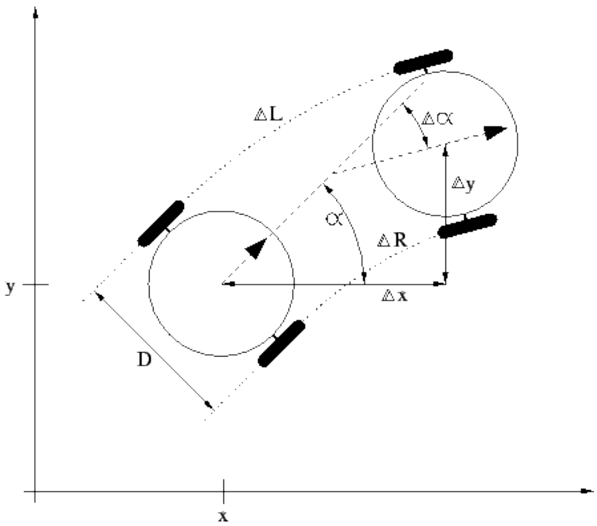


Figure 1.22 Odometry (34)

As already mentioned, mainly active Hall-effect based wheel speed sensors are used for odometry estimation. The advantage in comparison to passive inductive sensors is that even at standstill of the wheel the active sensor provides usable sensor signals. The measurement is usually carried out by scanning a multipole ring or incremental wheel (encoder ring), which can exemplarily be connected with the inner ring of the wheel bearing (see figure 1.23). If the multipole ring now moves in relation to the sensor of the wheel, magnetic fields are passed through. The polarity and frequency of the generated pulses pass on the direction of motion and speed of the wheel to the controller. (20) (34) (35) (36)

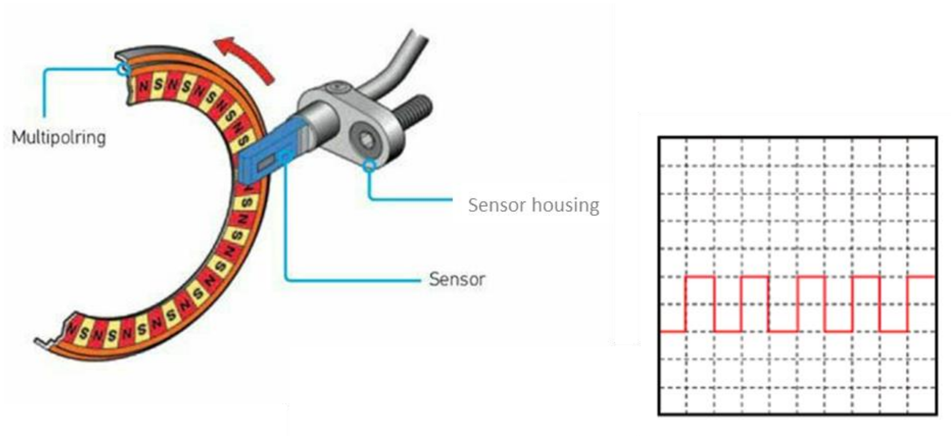


Figure 1.23 Left: Wheel sensor; right: schematic sensor signal representation (36)

1.4.2 Actuators

Actuators are the last part of a control circuit, receiving an electrical input signal (command) and transforming electric power into a certain kinematic movement. Therefore, they convert electrical signals into other physical quantities. For example, these can be sound, temperature, pressure, movement, or light. A schematic classification of actuators can be seen in table 2.

Actuator energy	Actuator type	Principle	Application
Electrical energy	electromagnetic	force acting on the body in the magnetic field	lifting-, rotating- and oscillating magnet
	electrodynamic	lorentz force on electrical conductor in the magnetic field	DC-, AC-motor, plunger coil, linear motor
	piezoelectric	piezo crystal thickness change due to electrical voltage	piezo motor, ink printer, injector
	magneto-strictive	ferromagnetic volume change in the magnetic field	adjusting unit, Translator
	magn./electr./rheol.	viscosity change in the electr./magnet. field	clutch, shock absorber, pump drive
Flow energy	pneumatic	fluidic pressure difference; displacement flow	thrust motor, diaphragm drive
	hydraulic	fluidic pressure difference; displacement flow	translation-, rotation motor
Thermal energy	thermostatic bimetal	thermal expansion difference of a material composite	thermal switch
	shape memory	temperature-induced microstructural transformation	adjusting and securing element
	expansion material	temperature-induced volume change	adjusting unit, thermostat
Chemical energy	electrochemically	pressure change due to electrochemical reaction	gas doser, expansion element

Table 2 Classification of actuators (37)

For the present conversion of a manually driven vehicle into an autonomous driving operation, mostly electrical actuator types (electric motors) are used. Electric motors are the classic actuators of electromechanics. They are based on electrodynamic and electromagnetic principles and convert electrical energy into mechanical work. The conversion is based on the forces or torques that a magnetic field exerts on a current-carrying conductor. Electric motors are classified according to the type of mechatronic motion exercise in linear motors and rotary motors as well as the type of power supply in DC and AC motors (see figure 1.24). (37)

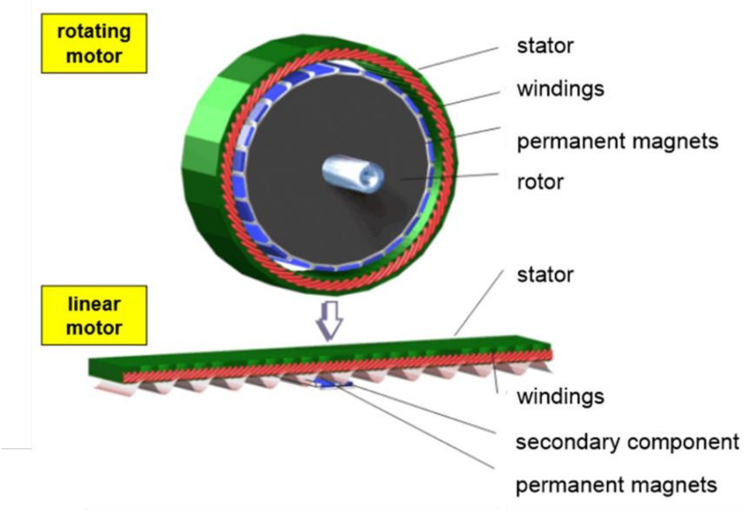


Figure 1.24 Principle of a rotating motor vs. linear motor (38)

Electric motors are available in a wide range of sizes with a wide range of speeds and torques, from large electric motors used as drives in cars to actuators used in microelectronics. The book "mechatronic" by Czichos Horst gives a good overview of different versions of electric motors (see figure 1.25)

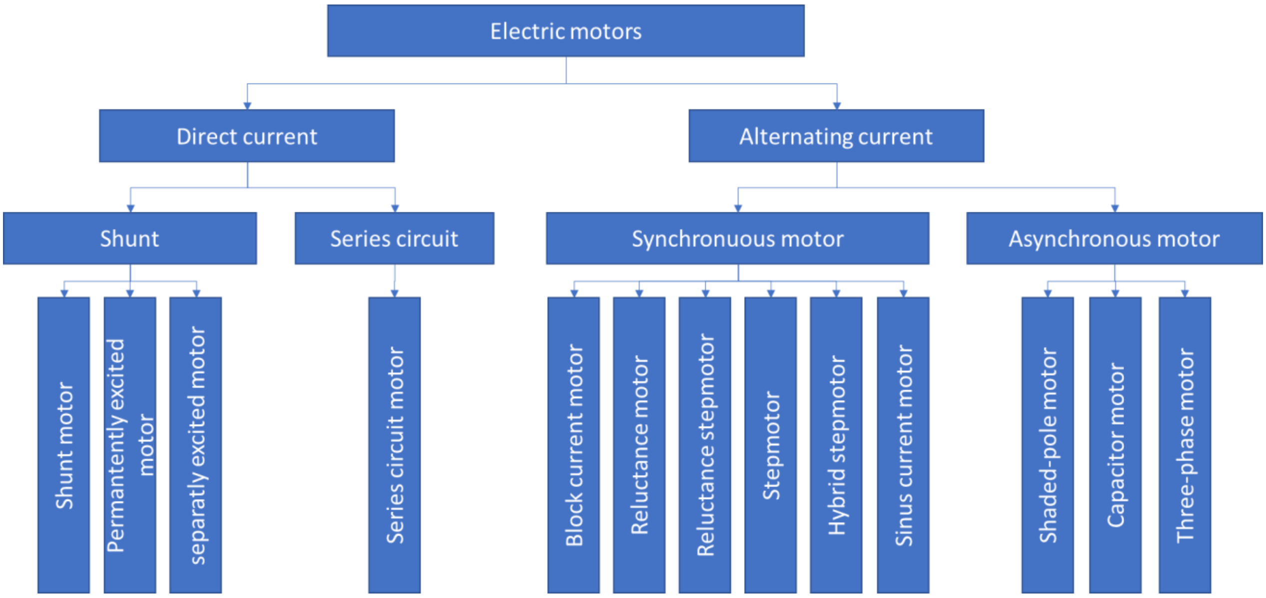


Figure 1.25 Overview of electric motors (39)

1.4.3 Interaction of sensors and actuators

The correct interaction of actuators and sensors is assured by a control system. Figure 1.26 shows a general sensor/actuator-application in a vehicle.

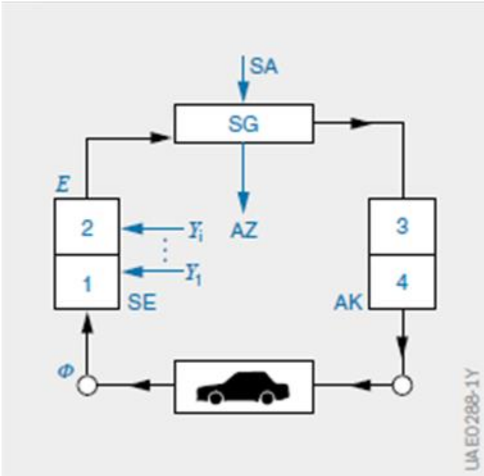


Figure 1.26 Interaction between sensors and actuators (20)

Φ…physical quantity

SE…sensors

E…electrical quantity

Yi…disturbances

SG… control unit

SA… control switch

AK…actuators

A physical quantity is detected by the sensors and passed on as electrical quantity to the control unit. The control unit can be influenced via an operating switch so that the actuator then reacts to that effect. It can be distinguished between open-loop control and closed-loop control. At the open loop control the input does not depends on the output (see figure 1.27 left side). No matter how the system behaves, the input is independent to the reaction of the output. An example is a vehicle driving along a road. The engine torque is the input, the vehicle speed is the output. The torque is dosed by the throttle (the driver). The disturbance is the gradient. The vehicle will drive slower when driving uphill then when driving straight ahead. On the other hand, the vehicle will drive faster when driving downhill then when straight ahead or uphill. At the closed loop control the output gives a feedback to the input (see figure 1.27 right side). So if there is a deviation the input can be adjusted. As example the cruise control of a vehicle. There a speed is set and measured by a speed sensor. If it comes to a deviation the input (engine torque) is adjusted. (20) (37) (40)

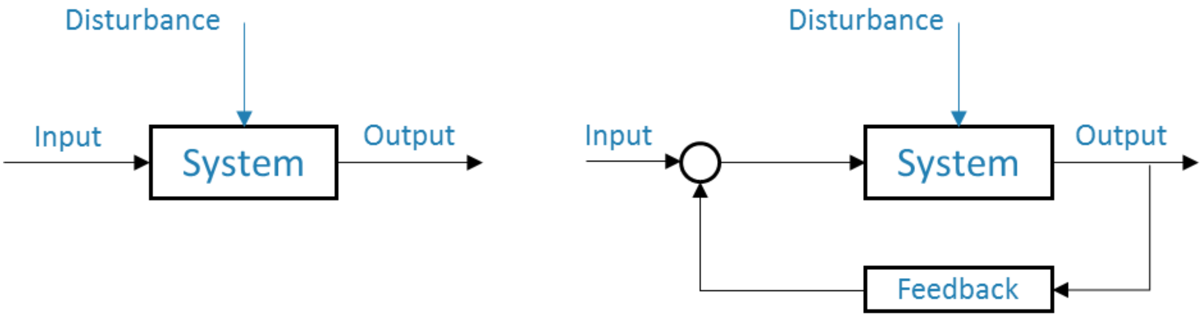


Figure 1.27 Left: open-loop control; right: closed-loop control (40)

As mentioned before, the environmental sensors are subdivided according to the principle into electromagnetic, optical and acoustic sensors. Electromagnetic sensors include RADAR sensors, the optical sensors include mono and stereo video, infrared and LIDAR. Acoustic sensors comprise ultrasonic sensors. In order to be able to drive automatically, the various environmental sensors must interact with each other. For that sensor fusion is used, which combines the independent sensors RADAR, LIDAR, camera, infrared and ultrasound to obtain information of better quality. For example, cameras can easily detect contours and classify objects. RADAR sensors, on the other hand, are capable of providing both distance and angle information, but cannot detect any contours. By merging the camera data with the data of the radar sensor, it is possible to detect an object and its distance from the vehicle. Alternatively, LIDAR sensors also provide information about distances, angles and object contours.

To ensure functional reliability, redundancies and plausibility checks are necessary. This intrasystem control prevents misinterpretations of the system. In order to determine the type of object and distance to the object, for example, data is fused not only by two sensor systems, but by multiple systems to control also the obtained data. Therefore, to name an example, merged camera and RADAR sensor data can be checked by the LIDAR sensors. (41) (31) (42) Figure 1.28 shows the sensors used in autonomous operations.

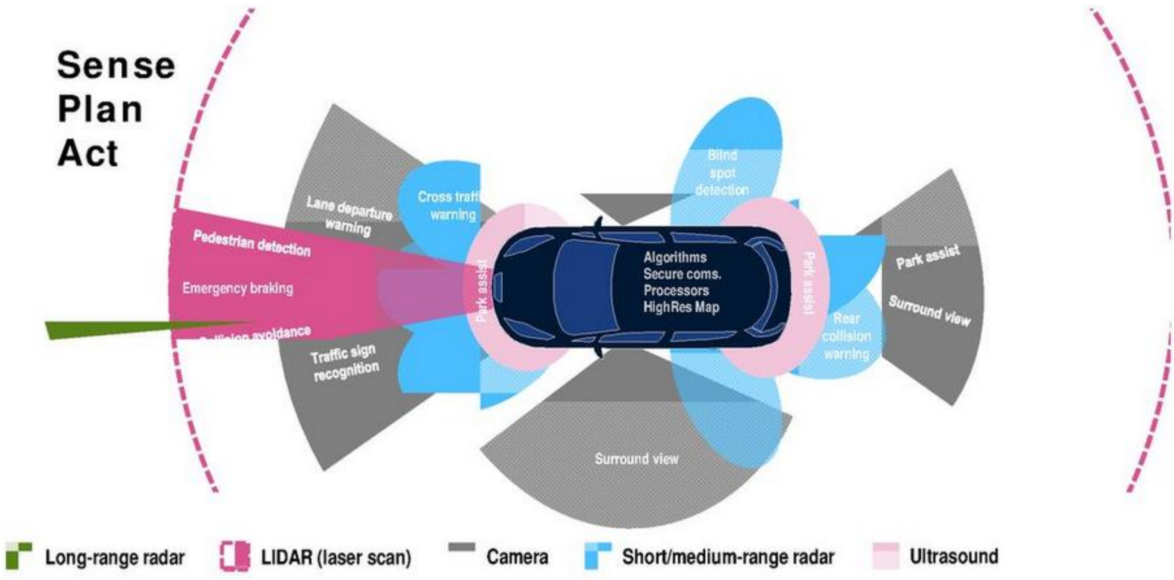


Figure 1.28 Sensors for autonomous driving (43)

1.4.4 Current automated and autonomous delivery vehicles

Actually, there are already many prototypes, which are autonomous or automated on the road, but only a few are ready for series production. In the following, projects that have already been implemented are named and clustered according to their use. Here, a distinction is made between passenger transport and freight transport. However, in order to better understand the following featured vehicles and their technologies, the most important terms are explained beforehand:

DC motors: Is a *direct current motor*, which is used to drive electric vehicles, actuators, etc.

BLDC: Are *brushless DC motors (brushless direct current*). In contrast to brushed DC motors, they have a longer service life, a higher torque and a higher speed level. Disadvantage: Additional communication technology is required for control. (44)

Encoders: Also known as *rotary encoder*. A rotation angle sensor that converts a mechanical motion into an electrical/digital output signal. Such encoders are used, for example, in autonomous vehicles for monitoring the steering angle. (45)

IMU: An Inertial Measurement Unit (IMU) is the combination of several inertial sensors. A triaxial structure of acceleration (accelerometer) and angular rate sensors (gyros) are common. The IMU is the inertial navigation system sensor unit, which detects changes in position and orientation. (46)

Accelerometer: Is an acceleration sensor that measures the speed increase or decrease and vibration of objects. They are used together with gyroscopes for position control and stabilization of (air) vehicles. (47)

Gyrosensor: Are angular rate sensors, which measure the rotation and speed of rotation. (48)

V2x Communication: Traffic networking (V2X) is the electronic communication of the participants in traffic in the forms vehicle-to-vehicle (V2V), vehicle-to-road (V2R), vehicle-to-infrastructure (V2I), vehicle-to-network (V2N) and vehicle-to-person (V2P). This networking makes it possible to identify changes in traffic early on, which contributes to increasing traffic safety, efficiency of traffic and energy saving. Applications include Collision Warning and Lane Departure Warning. (49)

SLAM: SLAM stands for *Simultaneous Localization and Mapping*. It is a technique used in robotics in which a mobile robot simultaneously creates a map of its environment and determines its position within that map. (50)

Pressure sensor: Converts the physical quantity pressure (force per area) into an electrical signal. Pressure sensors are used for example to monitor the air pressure in tires.

An autonomous good transporting robot that is already suitable for series production is on its way in the United States for a well-known catering company (see figure 1.29). It is equipped with 4 separately controlled wheels and has a cooling and a heating box. This makes it possible for it to drive from the store to the customers' front doors by using Google Map data, while keeping the food warm and the drinks cold. It is able to recognize objects by built-in LIDAR sensors and to find the sidewalk independently up to its customers, without endangering pedestrians or cyclists. (51) In addition to the LIDAR, an ultrasonic sensor similar as those in vacuum cleaner robots warns of direct collisions. With its 190 kg and a size of 1.20 m, the drone can deliver up to 5 km around the food store. (52) When the robot is on its final destination, the customer gets a passkey via mobile phone, which allows to open the boxes and take the food out. This passkey-system is also used in the project Jetflyer: When customers receive their package, they can open the boxes with a passkey.

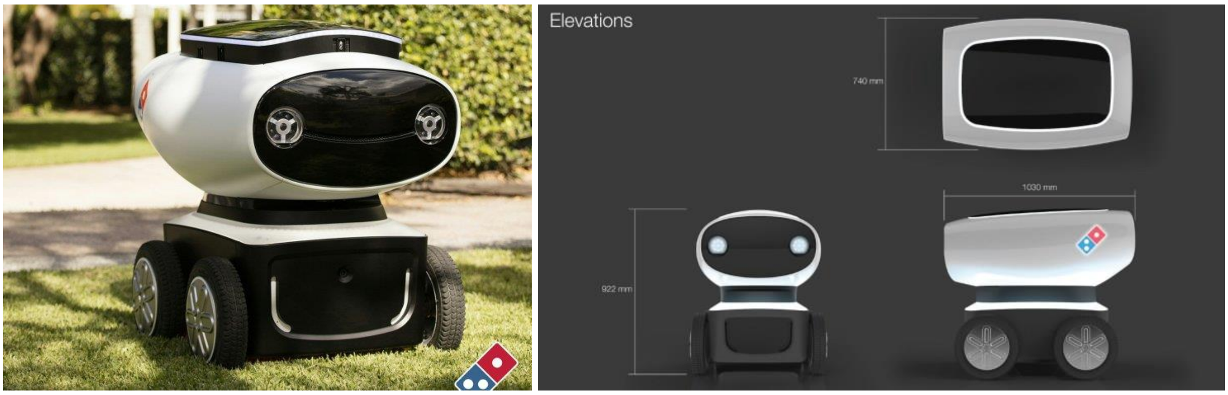


Figure 1.29 DOM delivery vehicle (53) and vehicle dimensions (52)

Technical data	
Drive	4 separately controlled wheels (BLDC)
Dimensions (length x width x height)	1000 mm x 740 mm x 922 mm
Weight	190 kg
Sensors	LIDAR and ultrasonic

Communication/ Orientation	GPS tracking
Camera	Only for detection of vandalism and thieves
Max. speed	20 km/h
Max. range	Up to 5 km

Table 3 DOM delivery vehicle technical data (52)

Another autonomous transporting vehicle, respectively -system is used indoors for logistics aid by a large online mail order company. The system consists of many small robots, which independently move racks, on which the ordered goods are located through the large warehouses. Fixed shelves are replaced by movable shelves under which the robots can drive and lift (see figure 1.30). The advantage of this system is that the shelf with the goods comes to the logistics worker and not vice versa. This saves time and effort because the worker don't have to pick up the required goods from the warehouse. One robot consists only of a Drive Unit that has two BLDC motors with encoders and a linear mechanism for lifting the shelves. In addition, two cameras are used to read the barcodes (or QR-codes) on the shelves and on the floor. Infrared and pressure sensors are used to detect obstacles. The communication between the robots, the shelves and the central computer, which contains the storage database, takes place wireless. (54) The central computer plans the tasks and paths and passes them on as motion commands to the Drive Units. The Drive Units then navigate based on a grid, whereby rotary and translatory movements are not executed simultaneously. Figure 1.31 shows a schematic representation of the field of application of Drive Units (orange dots). These bring the goods from the shelves (green dots) and finally bring the packages to the employees. The Drive Unit is oriented by means of a camera, which scans QR codes recorded on the ground (see figure 1.30). Once a robot has reached the storage location of an item, it scans the item and updates the inventory database. A small Drive Unit can thus cover distances of up to 16 km with one battery charging.

Figure 1.30 Kiva storage robot (55)

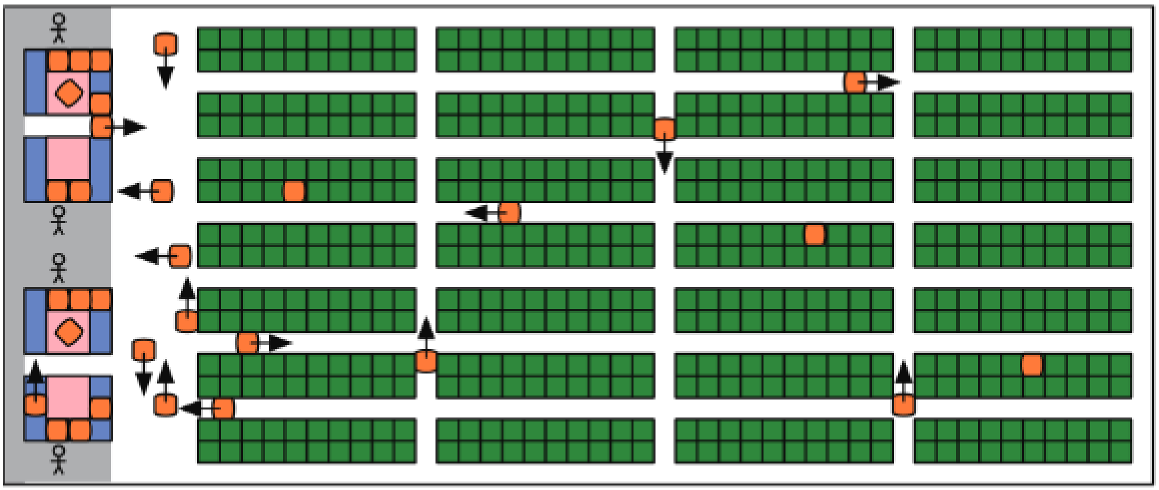


Figure 1.31 Paths (white) of a drive unit (orange), shelves (green), picking station with worker (blue); (54)

Technical data (of one robot)	
Drive	2 BLDC motors, 1 for the lifter
Dimension	406 mm (height)
Weight	145 kg
Sensors	Infrared + pressure sensors

Communication/ Orientation	Wireless to a central computer/ grid based
Camera	1 camera for orientation, 1 detecting the shelves
Max. speed	1.3 m/s
Max. load/ Capacity	1200 kg
Max. range	Up to 16 km
Power system	Four 12 V lead-acid batteries connected to 48 V DC

Table 4 Kiva logistic robot technical data (56)

At the project Jetflyer, the 1st stage of development will find a similar approach. In this case an employee goes from door to door and delivers the parcels. If the boxes of the Jetflyer are empty, it returns autonomously to the main warehouse and is refilled there. At the same time, another Jetflyer can supply the employee again.

Another application focuses on so-called "First Miles" / "Last Miles"- activities. There is often a gap between the place of residence and the nearest train station or between the train station and the actual destination. This gap can be closed with self-driving buses. This makes public transport accessible and attractive to those who might otherwise take the car. Such an autonomous bus for local passenger transport is in use in Salzburg. The vehicle offers place for 15 people and has got 11 seats at disposal. The bus runs electrically with 15 kW power distributed on two wheels. Due to the 2x2 steering system (steerable front and rear axle), the turning circle is only 4.5 m in diameter. This is only about half the space needed of conventional cars. (57) This allows turning maneuvers even in narrow streets. The battery package consists of $LiFePO_4$ with a capacity of 33 kWh and theoretically allows 9 hours of autonomous driving. In order to make autonomous operations possible, the shuttle is equipped with several cameras and sensors (see figure 1.32). Point 1 of figure 1.32 shows the cameras. These are installed on the front as well as on the rear of the shuttle. The cameras analyze the surroundings of the vehicle, especially traffic signs and traffic lights. They also contribute to the detection and identification of obstacles. Point 2 shows LIDAR sensors, which are installed at the front and at the rear side of the vehicle. The upper sensors are multi-layer LIDARS with a 360° all-round view and the lower sensors are mono-layer LIDARS with 180° view. Point 3 shows an IMU. This unit calculates the movement of the shuttle to estimate its sense of direction, its linear speed and its position. Point 4 is the GNSS[18] antenna (already described in chapter 1.4.1). The GNSS antenna is a global positioning system that communicates between the GPS sensor and a base station. It calculates the exact vehicle position in any moment. Point 5 is the odometry sensor, which is situated behind the wheels. This sensor estimates and confirms the vehicle's location and speed while it is moving. Traffic networking is also enabled by V2x communication.

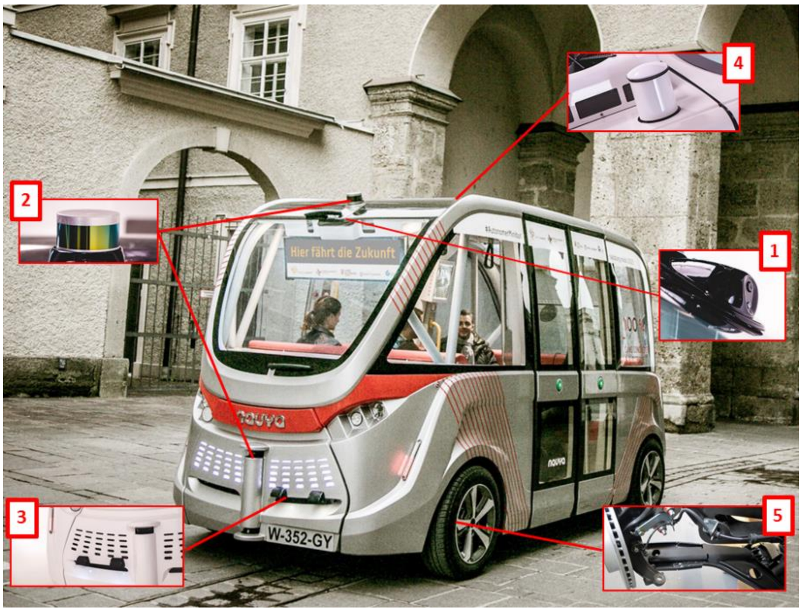


Figure 1.32 Autonomous shuttle (58)

Technical data	
Drive	2WD
Dimension (length x width x height)	4,75 x 2,11 x 2,65 m
Weight	2400 kg
Sensors	2x 360° LIDARS, 6x 180° LIDARS
Communication/ Orientation	GNSS Antenna + Odometry
Camera	Front and rear camera
Max. speed	25 km/h

[18] Global Navigation Satellite System

Max. load/ Capacity	15 passengers
Power system	Battery pack LiFePO4
Max. range	Not mentioned

Table 5 Navya shuttle technical data (58)

Due to the Jetflyer's size and also due to the movement, especially in pedestrian areas, similar types and numbers of sensors are required for protection, as with the Navya Shuttle. Especially the double version (sensors on the front and on the back of the vehicle) is often necessary for Jetflyers due to their size.

1.5 Future (in research) applications of automated and autonomous delivery vehicles

Actually, there are many autonomous delivery vehicles in research. Research is carried out in every conceivable economic sector. Almost every large company that wants to stand for innovation and progress, invests in the development and research of autonomous vehicles. In the next chapter, some of the autonomous vehicles in research from different sectors are briefly presented. According to their purpose; they are divided in passenger- and freight transport:

<u>Freight transport:</u>

- **CargoPod:** The food industry is already conducting research in autonomous delivery. A British online supermarket is testing autonomous food delivery together with a technology company in the Greenwich district of London. They have developed an autonomous delivery robot called CargoPod for the "last mile" (see figure 1.33). It delivers food from the supermarket, which the customer has previously ordered via app. It can be loaded with up to 128 kg, distributed on 8 separate boxes. This means it can supply goods for up to 8 different customers in one trip. The vehicle is equipped with several sensors and controllers that allow autonomous driving. Two stereo-vision cameras at the front and at the back side enable the generation of three-dimensional images. A special computer software generates a virtual map especially for the CargoPod. In order to better recognize pedestrians and other objects, two LIDAR sensors are mounted at the front (see figure 1.33). (59)

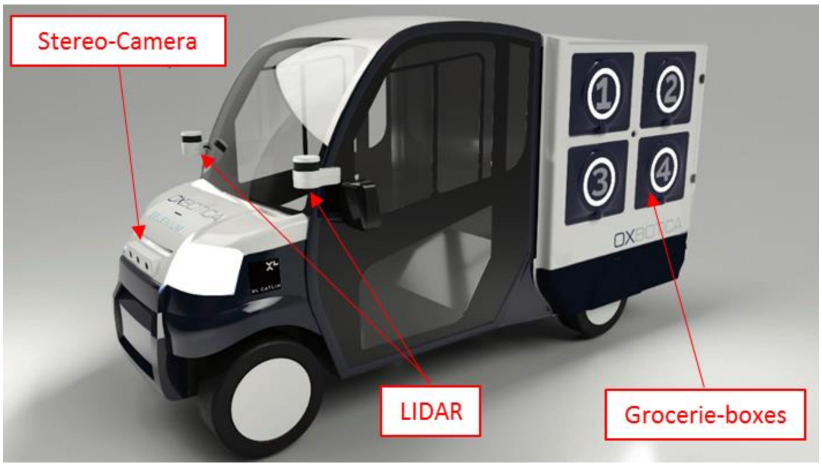


Figure 1.33 CargoPod (59)

At present, 2 trained employees still travel with the vehicle in order to be able to intervene in emergency situations, but in future they will be able to monitor an entire fleet of cargo pods from a control center. (59)

- **Streetscooter:** The German Post has been driving electric box vans called Streetscooter for some time now (see figure 1.34). Now they have started an autonomous delivery project with a large technology company by equipping this vehicle with cameras, RADAR and LIDAR systems that transmit the data to a ZF[19] ProAI Box. The ZF ProAI Box contains a supercomputer that acts as a central control unit. The supercomputer acts as a data processor that analyzes and processes the information from the cameras, RADAR and the LIDAR sensors in real time. (60) The vehicles perceive their surroundings and plan or change their route while driving without stopping. This company is already equipped with supercomputers, which record the daily routes of the Streetscooter in order to learn and to improve the driving algorithm. (61)

[19] Zahnradfabrik Friedrichshafen AG

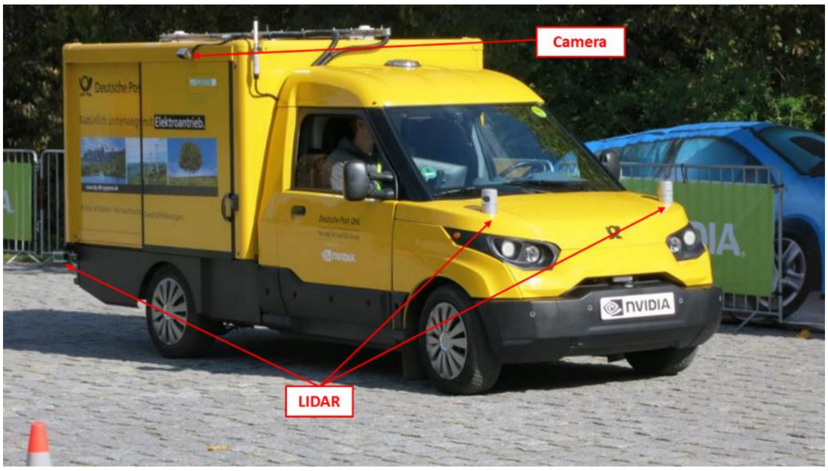


Figure 1.34 Streetscooter (62)

- **Truck distributor with integrated autonomous containers:**
  Another rather early stage concept is a distributor truck with autonomously moving containers for delivery on the so-called "last mile" (see figure 1.35). The truck is driven by a driver on long distances, such as highways or country roads. At target locations (e.g. in defined areas in larger cities), carried containers autonomously leave the truck, heading to the respective destinations, where they can then be unloaded by a worker. This project mainly focuses on B2B[20] markets. (63)

Figure 1.35 Truck with autonomous containers (63)

- **Autonomous luggage suitcase Gita:** An Italian motorcycle manufacturer introduced autonomous locomotion to completely contradict its traditional business model. They do not use this

[20] B2B Business-to-Business is a business relationship between at least two companies.

technology on their two-wheelers, but on self-driven luggage cases. These vehicles are designed to support people. They can be loaded up to 18 kg and it is possible for them to follow people or to simply drive to a given destination address at a maximum speed of up to 35 km/h. (64) The robot navigates by simultaneous localization and mapping (SLAM). In addition, it is equipped with several cameras, including a stereo camera (see figure 1.36). Through these 360° views, the mobile suitcase creates an environment map on which it can locate itself. The route itself is defined by a camera belt, which is carried by the person. The pictures of the camera are transferred to the luggage case. These are compared by the robot and made plausible. If the person gets out of sight, it still finds its way. (65)

Figure 1.36 Autonomous luggage case Gita (64) and implemented sensor technologies (65)

- **Delivery robot with stair climbing function Cassie:** Up to now, it was only possible to deliver autonomously up to the ground level front door. A new invention is a walking robot, which is also able to climb stairs. The robot, developed in USA (see figure 1.37), having no torso but only legs, now manages the last meters of the independent delivery. The robot has human-inspired hips that allow a movement along 3 degrees of freedom; the legs can be moved forwards and backwards, but they are also rotatable. In addition, the motorized ankle can stand in place without moving the feet. (66) Arms and additional sensors are still being planned to allow the robot to stand up independently if it falls. Further technical details were not explained by manufacturers and developers yet. But one can roughly say which sensors would have to be installed to enable the robot to do its job. For the balance IMU sensors would have to be used. Likewise, the legs must be equipped with torque sensors in the joints and force-moment sensors in the feet. (67) As in the previously described projects in chapter 1.3 and chapter 1.4, LIDAR systems, stereo cameras, ultrasonic sensors etc. can be used for orientation.

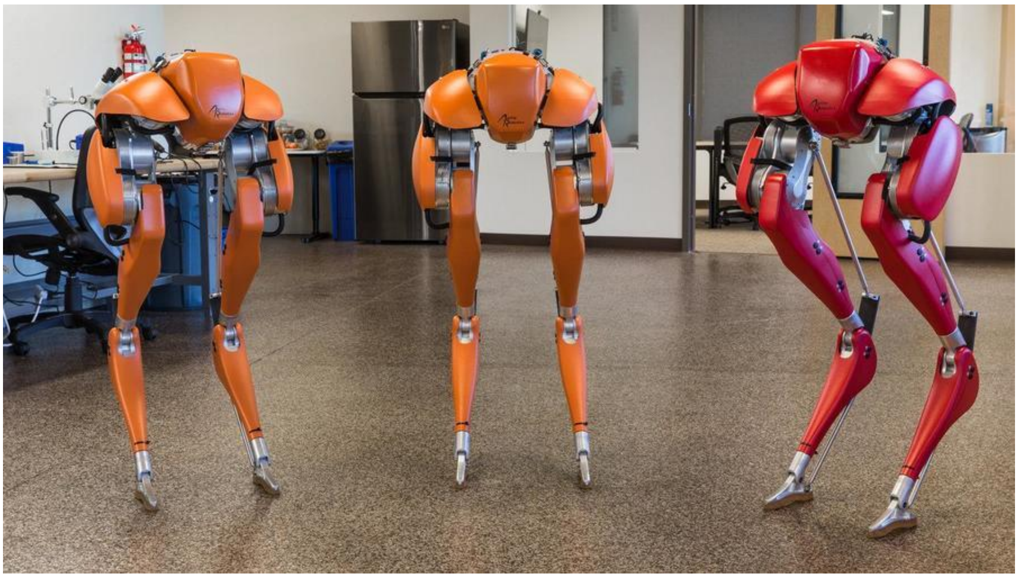


Figure 1.37 Delivery robot Cassie with stair climbing function (68)

- **Nuro**: A vehicle, which is very similar to the Jetflyer is the Nuro R2 (see figure 1.38). The all-wheel drive vehicle is as long and high as a conventional car, but only 1,3 m wide. This should make it easier to pass by for example a pedestrian or a bicycle. The electric vehicle weighs 1150 kg and is able to carry a payload of 190 kg. The Nuro should only use the road and not like many other autonomous delivery vehicles the sidewalk. The maximum velocity of the Nuro is 30 km/h. In order to be able to capture the environment in the best possible way, the vehicle is equipped with 12 high definition cameras, which enable a constant 360° panoramic view. On the roof of the Nuro a LIDAR sensor is mounted, which precisely detects other road users and their movements. RADAR sensors are installed for object detection and speed estimation, even over a longer distance. In order to collect more detailed data from the short range environment, ultrasonic sensors are installed, which work redundant with the other systems. In order to increase pedestrian protection, the front and rear bumpers – contrary to conventional vehicles – are made of soft material and serve as a “crumple zone”. In addition, the brakes are dimensioned for twice the weight of the Nuro. All drive- and safety systems are redundant. If a system failure occurs, the Nuro still has a “fallback strategy”. This strategy instructs the Nuro what to do if a certain error happens or a certain component fails. (69) (70)

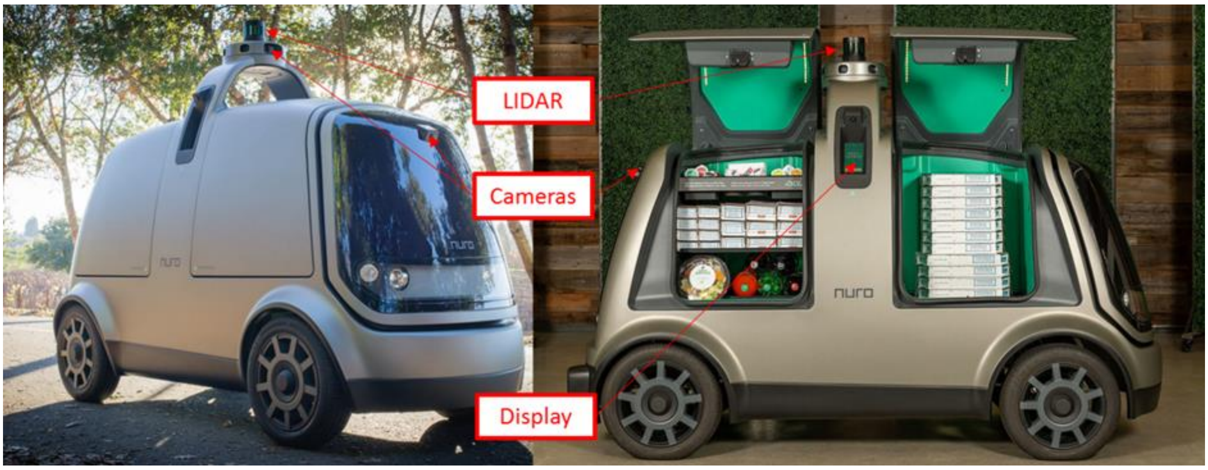


Figure 1.38 Nuro R2 (69)

The Nuro should be used for delivery food. After the order has been placed, the customer can track the vehicle and at the same time he/she receives a pin code, which he/she enters in the touch screen of the Nuro and can thus take his/her order. The technical data of the Nuro is listed in table 6.

Technical data	
Drive	Not mentioned
Dimension (length x width x height)	2,74 x 1,3 x 1,86 m
Weight	1150 kg
Sensors	LIDAR, RADAR, ultrasonic sensors
Communication/ Orientation	Not mentioned
Camera	12 cameras
Max. speed	40 km/h
Max. load/ Capacity	190 kg
Power system	Battery 31 kWh
Max. range	Not mentioned

Table 6 Nuro R2 technical data (70)

Starship: Another vehicle that is similar in construction to the Jetflyer is the autonomous delivery robot from Starship (see figure 1.39). The 6-wheel drive vehicle is – in contrast to the Nuro- smaller and uses sidewalks. It has 8 ultrasonic sensors and a RADAR sensor. A total amount of 12 cameras are integrated, with 3 on the front, 4 on the side and 2 on the rear. With a maximum payload of 10 kg, the robot can travel up to 6 km without charging the battery. To date, it has been tested on university campuses. For this purpose, 3D maps of the campuses were created, in order to be able to orientate themselves more quickly. The small robots are supposed to deliver on demand. For this a order can be placed via app. Once the vehicle has reached its destination, a pin code has to be entered, which was previously sent to the mobile phone, to get access to the delivered order. As anti-theft protection an alarm system is integrated. If the robot is blocked by humans, it uses its speech function by asking to be allowed to pass. A similar access system via code is used in the Jetflyer project, but still without an alarm system. The technical data of the robot from starship is listed in table 7. (71) (72) (73)

Figure 1.39 Starship delivery robot (74)

Technical data	
Drive	6 WD (BLDC motors)
Dimension (length x width x height)	0,68 x 0,57 x 1,25 m
Weight	23 kg
Sensors	8 ultrasonic sensors, + RADAR
Communication/ Orientation	GPS
Camera	3 front, 4 side, 2 rear cameras
Max. speed	6 km/h
Max. load/ Capacity	10 kg
Power system	Lithium-Polymer-battery
Max. range	6 km

Table 7 Starship delivery robot (75)

Table 8 shows an evaluation of the autonomous vehicle presented so far, which transport goods.

Good transport	Drive	Weight [kg]	Sensor	Communicat-ion	Max. speed [km/h]	Max. range [km]	Max. payload [kg]	Power system
DOM robot	4 WD (BLDC motors)	190	LIDAR, ultrasonic, camera (only for vandalism)	GPS	20	5	n.m.	battery
Kiva-storage robot	BLDC motor	145	Infrared, ultrasonic, 2 camera	wireless to a central computer	1,3	16	1200	4x 12 V acid batteries
Cargo pod	2 WD	n.m.[21]	LIDAR, stereo camera	not ready yet	8	30	128	n.m.
Street scooter	2 WD	n.m.	RADAR, LIDAR, 2 cameras	n.m.	n.m.	80	n.m.	33 kWh lithium ion battery system
Autonomous luggage suitcase Gita	2 WD	25	Stereo camera,	camera belt (follows a person)	10	35	18	battery
Climbing robot Cassie	bipedal (BLDC motors)	31	IMU sensors, not more are mentioned	n.m.	5	5 hours operating time	n.m.	20,5 Ah battery
Nuro	n.m.	1150	LIDAR, RADAR, ultrasonic, 12 cameras	n.m.	40	n.m.	190	31 kWh battery
Starship	6WD (BLDC motors)	23	Cameras, ultrasonic sensors, RADAR	GPS	6	6	10	Lithium polymer battery

Table 8 Evaluation of autonomous vehicle, which transport goods

Passenger transport:

- **Autonomous air taxi:** An interesting concept of a German company is the Volocopter (see figure 1.40). The lightweight helicopter-like vehicle, which is developed in Bruchsal, flies completely autonomously and exclusively with electric drive thanks to its redundant computer systems. 18 rotors (BLDC motors) are distributed over six arms and fed by nine lithium-ion batteries (one battery for 2 motors). The flight control system consists of several completely independent units, which communicate with each other via Mesh Networks[22]. Each flight control unit includes a complete set of position sensors, consisting of a gyroscope and an accelerometer for all three spatial axes. Each flight control unit is able to fully control the Volocopter. In the event of failure of a control computer unit, the remaining computers can continue to communicate with each other. (76) The Volocopter offers space for two passengers or a maximum payload of 160 kg. The maximum range is 27 km (at 70 km/h) or 27 min (at 50 km/h) flight time. The maximum speed is 100 km/h and the maximum climb rate is 3 m/s. Despite its 18 rotors, the noise level of the vehicle is only 65 dB(A). If the batteries are empty, there are two possibilities: You either recharge the

[21] n.m. = not mentioned
[22] In a mesh network, each network node (control computer) is connected to one or more other computers. (78)

battery system completely (duration <120 min.) or you simply change it to a fully loaded system thanks to a Quick-Change system. (77) (78) In order to make autonomous flight operations possible, the Volocopter must be equipped with a number of additional sensors and communication systems, which the manufacturer does not explain in more detail. In contrast to land-based autonomous vehicles, flying autonomous drones must increasingly focus on communication. That means that sensors are necessary when starting, landing or with tight flight routes, but if the flying object is in the air for the first time, wireless high-speed communication is essential. Here, GNSS antennas can be used in urban areas.

Figure 1.40 Autonomous Air Taxi, Volocopter (77)

- **Combination of self-driving car and passenger drone:** A futuristic mobility concept shows what happens when a design company, a car manufacturer and an aircraft manufacturer work together. It is a combined vehicle-drone system, which should contribute to solve future traffic problems. The system consists of a self-driven car and a drone and will be used as a means of transport for road and air. The modular concept is an ultra-light, two-seater passenger cabin that can be coupled to either a car or a flight module (see figure 1.41 and figure 1.42). The flight module should achieve a maximum speed of 120 km/h and 2 passengers should be able to fly 50 km. At a speed of 100 km/h, the self-driven car has a range of 130 kilometers. Both modules should be fully charged within 15 minutes. In the capsule, a plurality of cameras and sensors is used. By face recognition, the authorized driver or pilot can be detected and unlocked, the viewing direction is recognized for an optimized display of adverts and hints. In addition, a voice control or a control via a touch display should be possible. (79) Since this is a first concept, no details about sensors and systems for autonomous operation are known. This dual autonomous application could be used for goods delivery in the future, too. Parcels could be sent for long distances by truck (see “Truck distributer” page 50). On the “last mile” they could be distributed either via an autonomous drone or an autonomous vehicle. Depending on the urgency of the parcel content. For example, if it is an urgent parcel with essential medication, the drone could be used. This would be especially during the rush hour in cities of advantage. If the urgency of the parcel is secondary, autonomous ground delivery could be used. So the parcel would be distributed with other parcels and not individually. This is a personal assessment, which could certainly be researched in more detail in a separate study, but not in the course of this master's thesis.

Figure 1.41 Combined autonomous locomotion (80)

Figure 1.42 Combined autonomous locomotion; flight module (80)

- **Robot taxi Waymo:** An autonomous taxi is already being test in numerous US cities. It is a Chrysler Pacifica which was retrofitted in cooperation of two companies. (see figure 1.43). The vehicle has a hybrid drive and manages 53 km purely electrically. It can be ordered via app and can accommodate up to 8 people. The operational area of the taxis currently cover about 260 km² and can be used by a few hundred people. For environmental detection LIDAR, RADAR and cameras are installed. A total of three types of LIDAR sensors are mounted, which were developed and adapted to the vehicle by Waymo itself. With these LIDARs, even more objects can be captured in a higher resolution. In contrast to conventional LIDAR sensors, the direction of view of the pedestrian can also be recorded, which is extremely important to predict where someone is going in the next step. In addition a new type of long range LIDAR is installed which also has a zoom function and can detect a football helmet from a distance of two football fields. With the built-in LIDAR sensors a 360° surround view can already be generated. In addition, a vision system is built in, which consists of 8 vision modules. These modules together enable the detection of traffic signs, traffic lights, have a “face forwarding” function and a super HD resolution with 360° panoramic view. In addition, they can produce an image in all lighting conditions. The RADAR system also generates a 360° all-round view and is highly effective in rain, fog or snow thanks to the own development of Waymo. Taken as a whole, the sensor suite crates a safety cycle with the software. (81) (82)

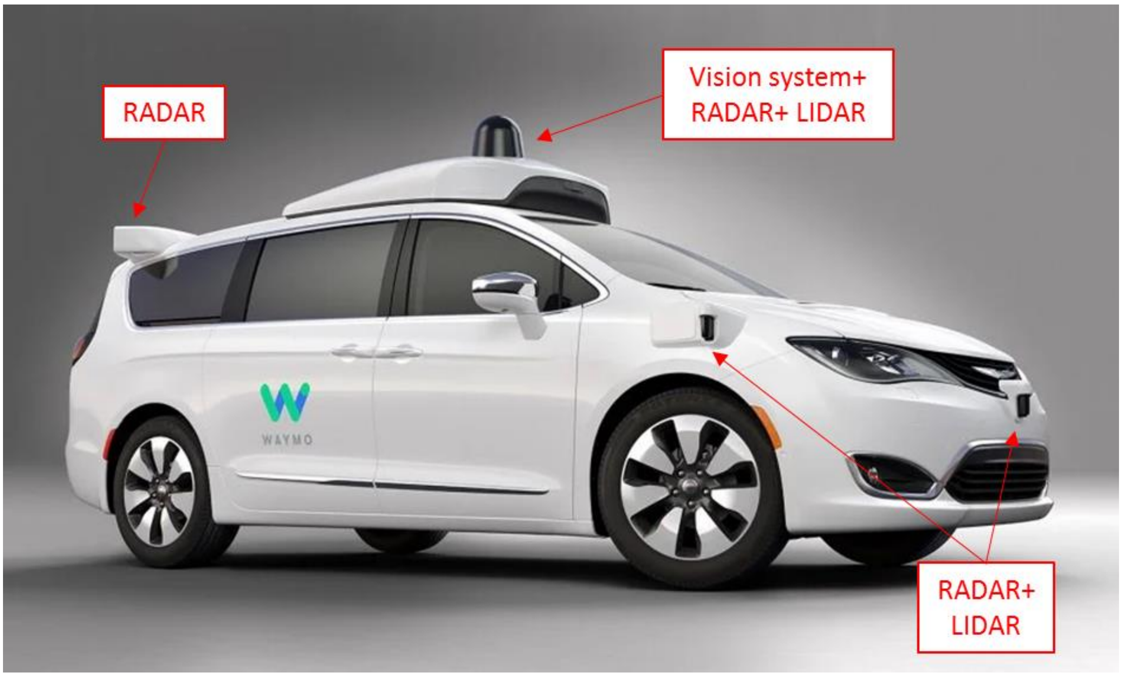


Figure 1.43 Robot taxi Waymo (83)

Technical data	
Drive	Hybrid (2 WD)
Dimension (length x width x height)	5,18 x 2,02 x 1,78 m
Weight	2262 kg
Sensors	LIDAR, RADAR, camera
Communication/ Orientation	GPS
Camera	3 cameras (generating a 360° view)
Max. speed	72 km/h
Max. load/ Capacity	Up to 8 persons
Power system	Gasoline/ 16 kWh lithium ion battery
Max. range	53 km (electrically)

Table 9 Waymo technical data (84) (85) (86)

Robot taxi Zoox: A company which does not want to offer the autonomous car for private buyer but want to offer it on-demand is already testing with a car fleet in California. What is special here is the development of the autonomous vehicle: The aim is not to convert an existing vehicle and adapt the autonomous technology to it, but to develop a new vehicle from ground. So first the sensor suit including the software should be developed and then the associated vehicle. A fleet of Toyota Highlander and Prius was initially retrofitted to test and validate the sensor packages including the software. With this vehicle fleet the development of the sensor suit is taken place. In figure 1.44 a such a prototype can be seen.

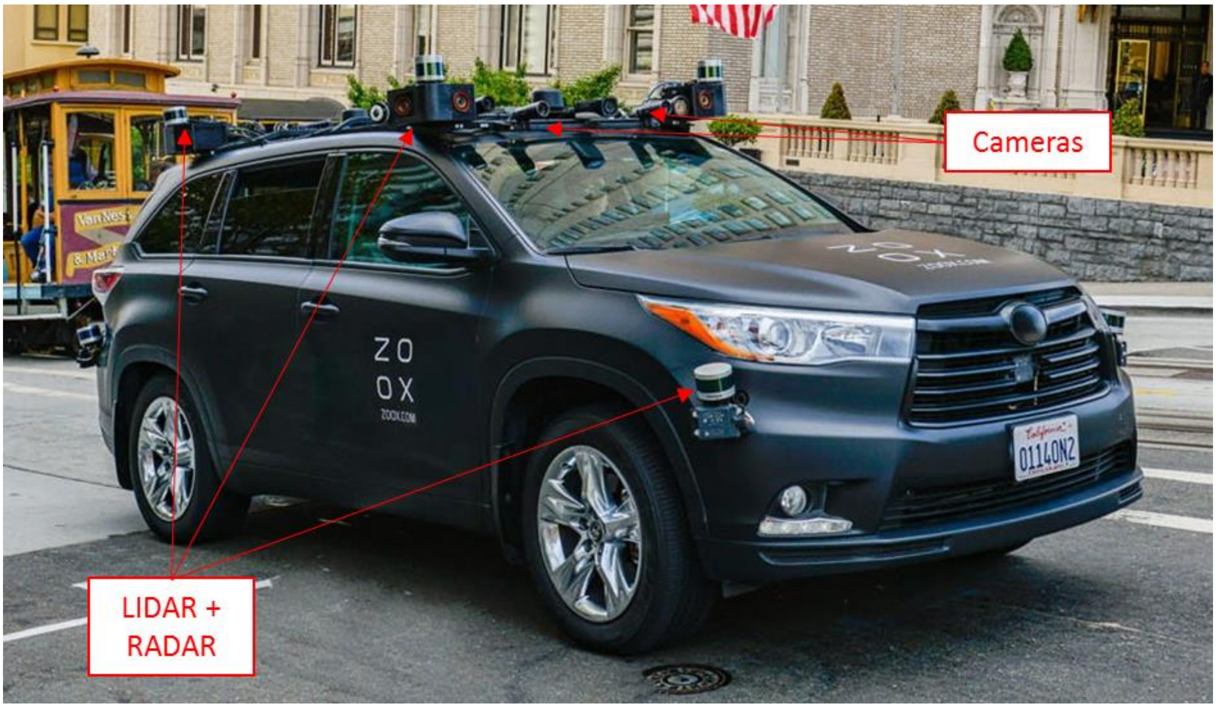


Figure 1.44 Retrofitted Toyota for testing the senor suit (87)

This is equipped with cameras, LIDAR, RADAR and proprietary sensors. The vehicle is localized using localization software. This accesses the data from the initial sensors, GPS and LIDAR and can therefore exactly say where the vehicle currently is (accurate to the centimeter). For testing as a taxi, the Zoox company has the authorization to transport passengers in some districts of San Francisco. The customers can order the vehicle via app. If the sensor suite has a sufficiently mature level of development, the concept vehicle can be built for it (see figure 1.45). This first concept offers space for 4 people and is bi-directional. That means the symmetrical and can drive in both directions. Based on the active spoiler and the colors of the LEDs, a passerby can see in which direction it will move. The bi-directional design means that all 4 wheels are steered, which provides the vehicle with innovative ways to navigate city driving safely. Due to the confidentiality of the company and the state of development, no further details about the maximum range, cruising speed or battery system are known. (88) (89) (90)

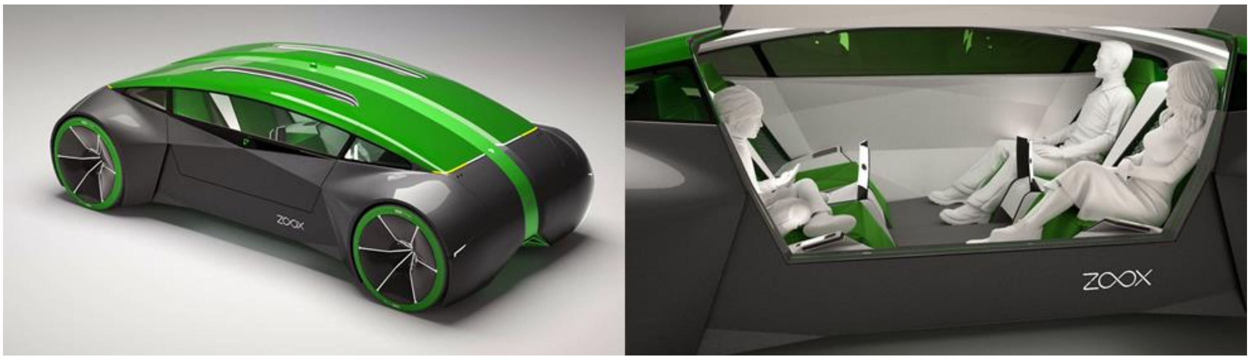


Figure 1.45 Autonomous prototype Zoox (88)

1.6 Potential assessment of autonomous delivery vehicles

More and more institutions, companies and start-ups are investing in the automation of delivery vehicles. The aim is to be a pioneer and therefore one of the best in this branch. With the integration of autonomous vehicles in traffic systems, economic, safety or social aspects need to be taken into account as well.

As an example, the Fraunhofer Institute for Material Flow Technology and Logistics sees great opportunities for autonomous "parcel delivery on demand". They are based on a concept according to which the transport vehicles only start moving when they are told to by the customer via SMS. In addition to that, transport robots can also support autonomous vehicles. *"We see a potential of up to 400 million deliveries per year for delivery by transport robots,"* says the Fraunhofer IML institute director. (91) "*That would correspond to one in ten parcels in Germany."*

A study by ARK Investing Group sees great cost potential: This study shows that delivery by means of drones could cost on average less than 1 US dollar. Comparing these costs with the average cost per shipment in 2016 would result in an average saving of $4.75 per shipment. (92) According to BI Intelligence, there would be benefits shown in figure 1.46.

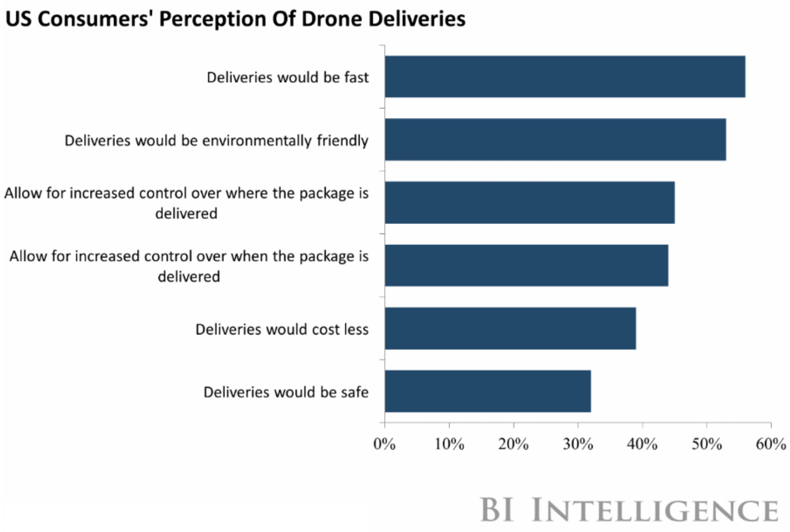


Figure 1.46 Advantages of drone delivery (92)

However, BI Intelligence does not see an increased potential for drone delivery until 2020, as there are still some important aspects to be clarified, such as legal obstacles, technical problems and customer acceptance. Above all, customer acceptance still needs to be improved. As a survey of more than 1200 US consumers showed, only 32% believe that drone delivery will be safe. (92) Moreover, many technical questions are still open: Do the drones land for parcel delivery or do they drop the parcel by parachute? What does delivery to houses look like compared to apartments? These hurdles must be overcome step by step to enable delivery by drone in the next few years.

In a publishes study, McKinsey sees four clearly dominant delivery methods for the future: self-driven delivery vehicles on the ground, drones, bike couriers or droids and already today's conventional delivery.

Each of these delivery variants has its own special advantages and disadvantages and is therefore used in a different way (see figure 1.47).

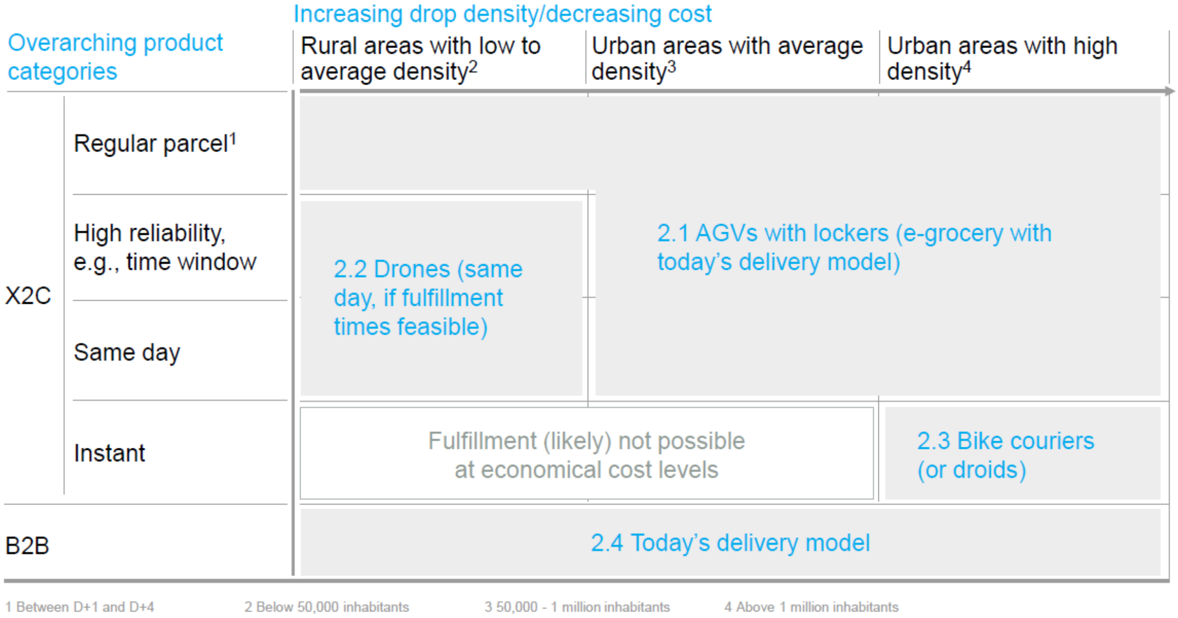


Figure 1.47 Delivery Models (93)

In this model, AGVs (Autonomous ground vehicles) in particular will replace the conventional method of delivery, which should bring cost advantages of up to 40%, especially in urban areas. A saving of 40 % in delivery costs would increase turnover by 20 %, taking into account the rising costs of vehicles and the reduction of costs by skilled workers. AGVs with combination locks will also be increasingly used for same-day deliveries and time-window deliveries. The AGVs can also be parked and customers can pick up parcels that could not be delivered during the day at night by means of access (e.g. by entering the correct payment combination in a combination lock). (93)

Drones, on the other hand, would find more use in rural areas, where criteria such as necessary delivery time or obstructive terrain could cause disadvantages for the use of AGVs. However, the cost of drone delivery is estimated at around 10% of the cost of traditional delivery. Nevertheless, 13% of X2C[23] packets can be used for same-day or time-window delivery. (93) They would be a great advantage, e.g. especially for deliveries out of conventional times, like during weekends or nights.

The 3rd variant of the autonomous delivery is by use of bike couriers or droids, which are dimensioned in a size and speed range so that they can move on sidewalks without disturbing. These would be monitored by staff via a central control point while delivering to a defined destination address. In this case, useful

[23] X2C- denotes a business relationship with the customer. X can stand here for Manufacturer, Business, Individuals.

action radii are distances from 1 to 10 km. Deliveries over longer distances are relatively inefficient due to the dimensioning and associated costs. For this reason, conventional delivery by postmen or bicycle couriers would be more cost efficient. (93)

2. Development of a prototype for automated delivery traffic in inner-city areas

Parcel deliveries and delivery traffic have been handled by classic trucks for a long time. Particularly in cities, this poses a major challenge for traffic optimization or the emission of pollutants, to name just two examples. The increasing digitalization and networking is also considered as an important development for optimization in delivery traffic, which is one of the reasons why many companies are working on innovative solutions in this area. One field of research is the development of autonomous vehicles for delivery traffic. Österreichische Post AG and Energie Steiermark are therefore jointly pursuing the goal of taking a further step in this direction. Together with i-Tec Styria, which has developed the Jetflyer, and TU Graz, the aim is to develop and test parcel delivery in Graz city center with an autonomously guided electrically operated vehicle of the L6e class.

Therefore an existing ATV from the company Jetflyer should be retrofitted with an autonomous technology package, consisting of sensors, actuators and the appropriate software. Based on the sensors, the vehicle should be able to locate itself and be able to detect the surroundings. The sensors are intended to send the acquired data in the form of signals to the computer unit, where they are processed The computing unit should then send appropriate commands to the actuators. The actuators should execute the commands, which is reflected in steering, acceleration and braking. Finally the vehicle should find autonomously its destination through the city center of Graz, taking other road users into account. Arrived at the destination a secure package removal should be possible.

2.1 State of the art / initial situation

The basic vehicle, the Jetflyer (see figure 2.1), is already in use in cities such as Graz, Linz and Vienna for Post AG and Energie Steiermark, though not yet independently driving, but human driven. The Jetflyer's maximum speed is 45 km/h and the maximum range is about 100 km. The future solution as an autonomous vehicle makes new application scenarios for independent delivery as well as for the support of the parcel deliverer possible. The aim of this project is to guide the vehicle autonomously at walking speed to a defined destination address in the inner-city area. This scenario is shown in figure 2.2. Employees of the delivery company load the parcels into separate lockers, which are attached to the Jetflyer. The Jetflyer travels autonomously to the defined destination address. At the destination, the customer receives a notification that his parcel is ready to be picked up at the door. The customer opens the locker using the code of the notification. After removing the goods, the vehicle drives to the next customer. In the present prototype status, it allows four deliveries at the same time. If the box with the lockers is empty, the Jetflyer returns to the distribution center in order to be loaded again by the employees.

Figure 2.1 Jetflyer (94)

The basic vehicle is a class L6e vehicle developed by i-Tec Styria and produced by E-volution Elektromobilitätskonzepte GmbH (95) (96) (see Figure 2.1). The total weight is 222 kg (incl. battery package) and the maximum payload is 180 kg, whereby 2 powerful wheel hub motors, with 2 kW each, drive the vehicle. The sporty two-seater with a length of 1909 mm and a width of 1150 mm is very maneuverable and due to its low construction (1064 mm) it is very stable on the road. The range is indicated by its battery pack (16 pcs. $LiFePo_4$ with 3.2 V each and 60 Ah) with up to 70 km. Also the charging time is worth seeing with 70 % after 90 min and 90 % after 3h. (97) A summary of the data is shown in table 10:

Power	4.0 kW (5.4 PS)
Battery type	lithium iron phosphate
Battery charge	60 Ah
Drive voltage	56 volts
Drive	2x wheel hub motors (rear)
Dimensions (length x width x height)	1909x1150x1064 mm
Max. Speed	45 km/h

Vehicle weight	222 kg
Max. total weight	520 kg
Bench	2 persons
Range	50-70 km
charging time	90 min for 70 %; approx. 3h for 100
Consumption	approx. 3 kWh/ 100 km
Climb rate	up to max. 20% up or down

Table 10 Technical Data Jeflyer (95)

Figure 2.2 Sequence of autonomous delivery (98)

The implementation took place in the development and integration of two technology packages: Sensors/navigation and actuators. The development was carried out in cooperation between the Institute of Software Technology (99) and the Institute of Automotive Engineering (100) at Graz University of Technology. The aim of this master project was the development of actuators for the implementation of steering motion as well as braking and acceleration. At the start of the work, a benchmark was carried out and possible concepts were evaluated. After component selection and virtual design (CAD), the prototypes were designed and integrated on the target vehicle. The first milestone was to convert the Jetflyer into a remote controlled vehicle, in order to get test data and information about the driving behavior in advance and to create the interactive map for the autonomous operation. In the second step, sensor technology was used to enable independent driving operations. According to defined SAE levels for autonomous driving, the 4th level should be reached in the first stage of the present project, and after several iteration loops level 5 should be possible.

2.2 Mechanical conversion

The mechanical conversion includes the actuators for the steering, the brake, as well as the handle/lever for acceleration. The vehicle should be able to change direction to the left and to the right, accelerate and brake from a distance using the actuators. There should also be the possibility of remote emergency braking in order to be able to intervene at any time in critical situations.

2.2.1 Evaluation of existing designs on solutions

In order to find a suitable concept for the Jetflyer, existing autonomous conversions of the vehicle classes L6e and L7e were first analyzed and evaluated from trade journals, studies and textbooks. The following section provides an overview of gathered results.

Steering: Since the steering speed was not specified, this was determined on the basis of tests. Evasive maneuvers were carried out with the Jetflyer and the steering speed was set at 15 rpm. For a full steering angle from left to right, this corresponds to a duration of 1 second. The steering should be fast, robust and reliable in order to make spontaneous evasive maneuver possible for the Jetflyer and in order to avoid collisions. Linear actuators are one possibility for steering control. The steering knuckle would have to be rebuilt and the linear motor would have to be installed parallel to the drawbar of the steering (see figure 2.3). (101) This type of steering is space-saving and easy to implement. However, the linear motor would have to be mounted below the double wishbone at the Jetflyer. As a result, the actuator would be the lowest component on the vehicle. In that case, the Jetflyer's ground clearance would be less than 7 cm and there would be a risk for the actuator to get damaged, if the street or the ground was uneven. Because of that this design is insufficient for road use.

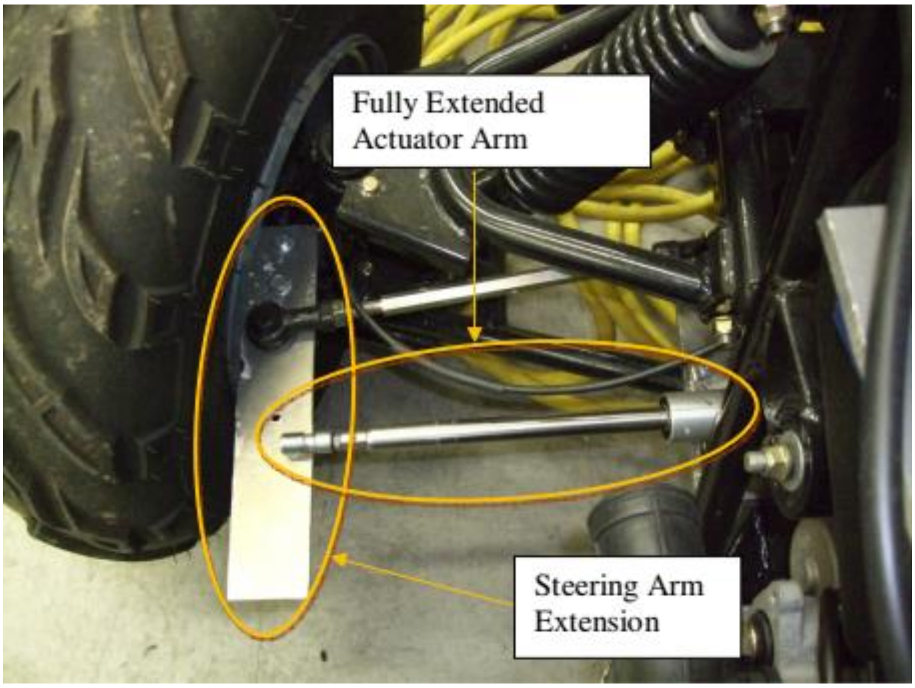


Figure 2.3 Version with linear actuator (101)

Another option for executing the steering movement would be a rotary actuator. This would have to be connected to the steering column in order to transfer the steering movements to the wheels. One possibility would be by gear wheels and a chain (see figure 2.4). In the present embodiment, a DC motor was used, which is slightly space saving because of its size. One drawback is the occurring play in combination with a chain for transmitting the force. In addition, a chain underlies an elongation over its lifetime, which would result in an increasing inaccuracy in the advancing age of the chain. Instead of the chain, a pair of gears could be used. The gears are more robust against wear. However, high manufacturing accuracies would be necessary in order to guarantee the exact center distance of the gears. A variable adjustment of the axis distance would be possible, but here an increased space requirement and a precise manufacturing accuracy would be necessary.

Figure 2.4 Version with rotary actuator (102)

Another approach is to use a three-phase current motor in combination with a pair of bevel gears. These would be compact and easy to install. A major disadvantage is the axial force generated by the bevel gears (see figure 2.5). Due to this axial force, the shaft-hub connection would additionally have to be designed for axial loading and the steering column, which consists of a simple tube made of an aluminum- alloy, would have to be replaced by a more solid steel tube. As a result, the weight of the vehicle would increase and there would also be an additional workload and further costs.

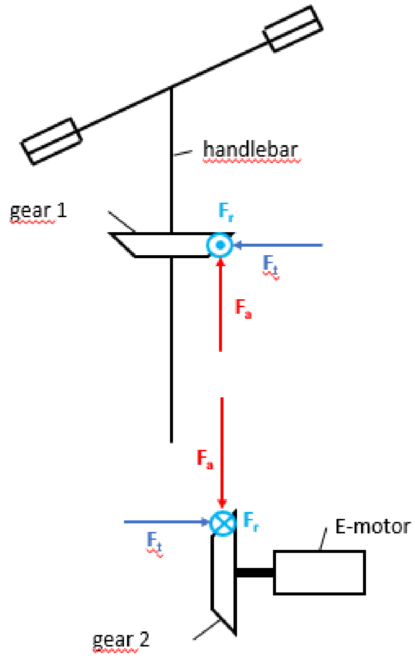


Figure 2.5 Effective forces on the bevel gear pair

Brake: The Jetflyer's brake mechanism must consist of two parts: A first, a dynamic brake that makes deceleration processes possible while the vehicle is in motion. These should be easy to dose and should not cause any stuttering on the vehicle. The second brake mechanism has to be available for emergency braking in order to be triggered via radio-control transmitted dead man switch in critical situations. In this case the vehicle must stop immediately. In existing researched publications, no emergency braking devices were installed. (101) (102) (103) (104) For this reason, a completely new concept must be developed. As an exemplary modification for the service brake in existing publications, the existing foot pedals were modified, so that this was controlled, as can be seen in figure 2.7. There, a linear motor was used as actuator, which extends during a braking process, pushes the foot pedal downwards and thus initiates the deceleration. Another applied example is the use of hydraulic cylinders to intervene in the brake circuit. The cylinder is compressed during braking and brings the vehicle to a standstill. (103) At the project Jetflyer, the conversion of the service brake is not possible, since this has only one handbrake lever, which works by means of brake circuit on all 4 wheels alike. The foot brake that usually decelerates the rear wheels was omitted here. Instead, the brake lines of the rear wheels are closed in parallel with those of the front wheels. The right brake lever in figure 2.6 serves purely as a parking brake and acts on the rear wheels over mechanic pulling force via a cable and an additional brake cylinder. These parking brakes are installed at this vehicle category for legal reasons. Figure 2.6 shows the conversion process of the braking systems at the institute. Therefore, the Jetflyer was partly disassembled. In the yellow highlighted regions, the state of the art of the braking system is shown. On the left side there is the operational brake (hydraulic) and on the right side the mechanic parking brake can be seen.

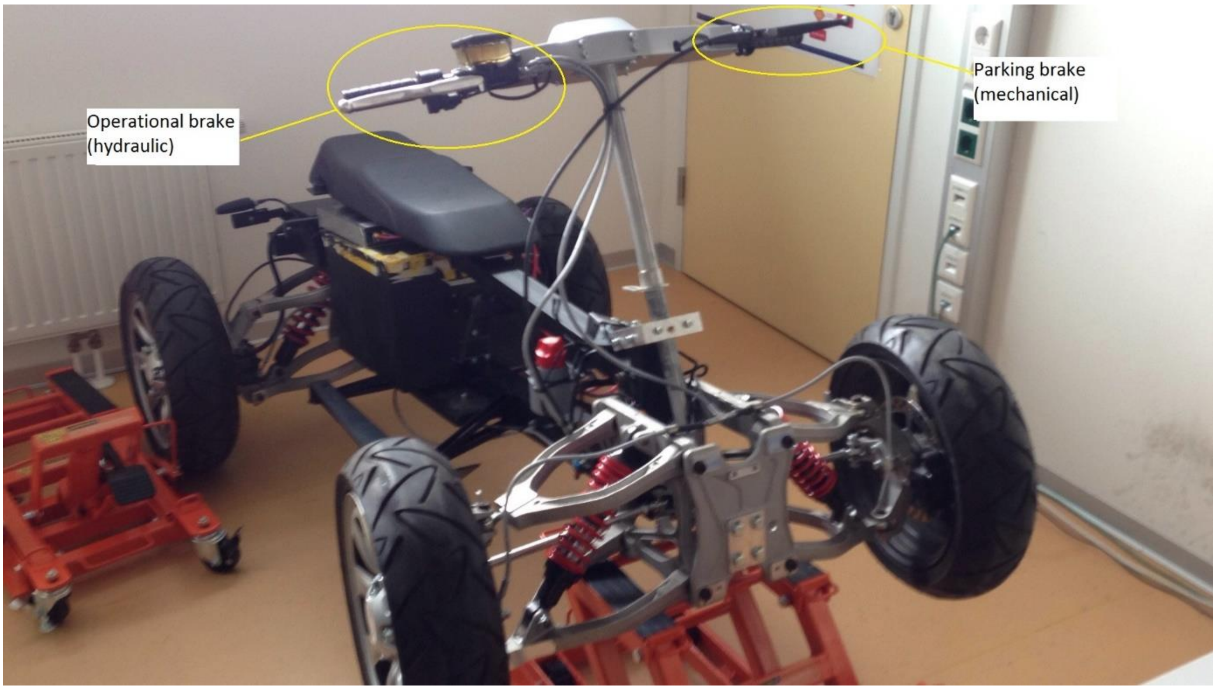


Figure 2.6 Braking mechanisms

However, this mechanical braking device can hardly be used as a dynamic brake, as it only activates the brake with a mechanic wire pull. The electric motor, triggering the parking brake, must be strong and fast ($F \geq 30$ N; more details in chapter 2.2.3). For the market-available post delivery vehicles, the company i-Tec Styria uses electric motors for fixing the rear brakes for parking situations, and it was considered to use these as service brake or emergency brake. One drawback is a missing possibility of a linear proportional control of this motor, leading to the fact that braking cannot be “dosed”. It is only possible to brake fully or not at all and. Brake tests with the vehicle showed that the electric motors are also unsuitable for emergency braking. At a speed of v= 6 km/h, the braking distance was 2 m. The motors trigger braking too slowly. For this reason, the original parking brake is neither suitable as an emergency brake.

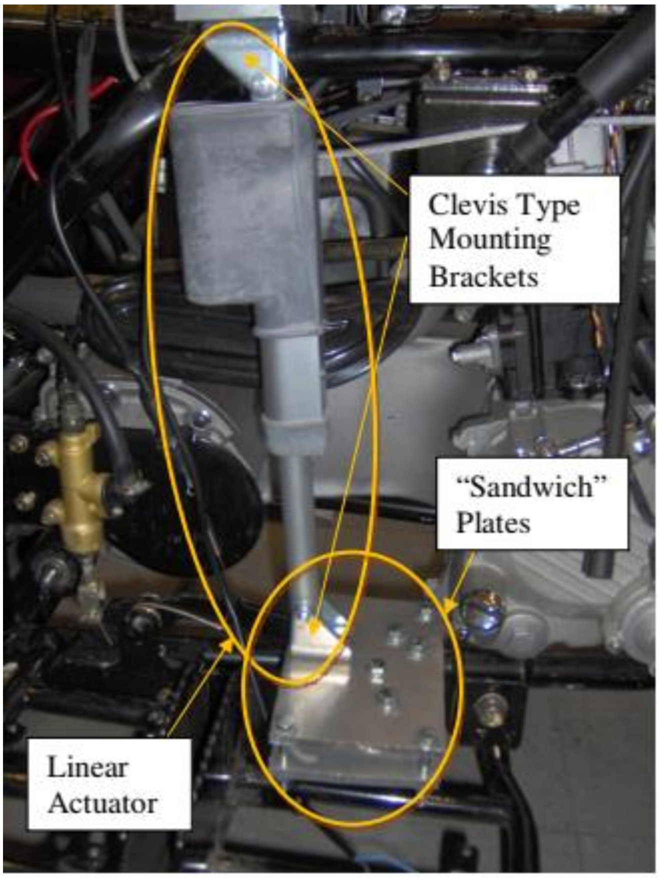


Figure 2.7 Linear actuator on foot pedal (existing solution for an emergency brake) (104)

2.2.2 Steering

In order to select the right steering system, the torque required by the engine to turn the handlebar had to be determined first. The measurement was carried out with a simple spring scale attached to the left end of the handlebar (see figure 2.8). For this purpose, the vehicle was placed on asphalt, which is a relatively rough surface, leading to a relatively high friction of the tires and thus requiring a high force for steering. (105) In addition, the vehicle was loaded with 90 kg to simulate the subsequent loading of the transport boxes of Österreichische Post AG. The maximum force from 5 measurements was 117.72 N (display according to balance: 12 kg load). According to calculation 5.1.1 with a distance between the spring balance and the handlebar center of 380 mm, this resulted in a torque required for turning the handlebar of 44.7 Nm (about 45 Nm).

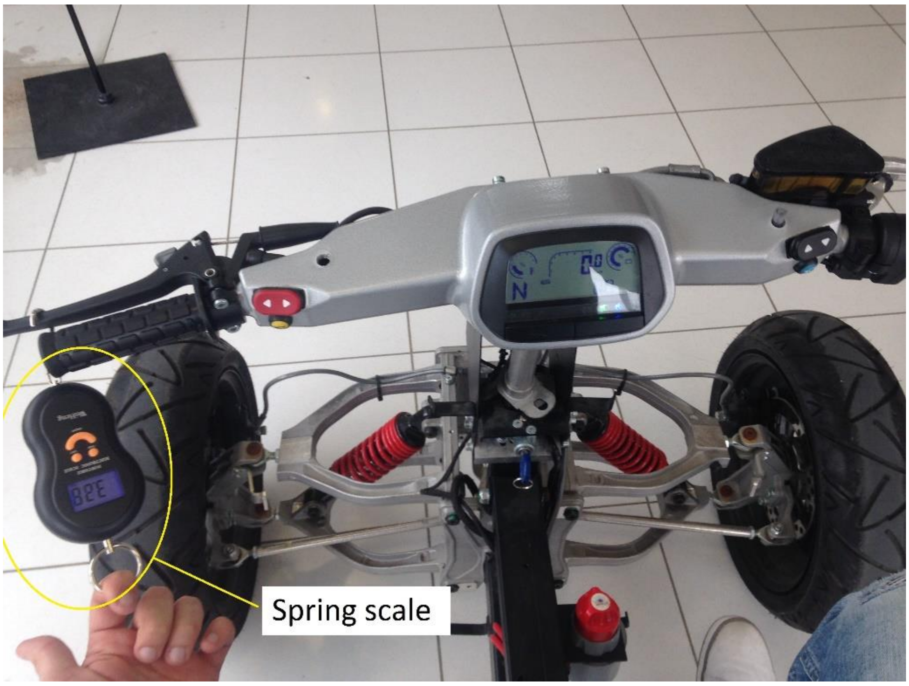


Figure 2.8 Determining the force to turn the handlebar

In order to further evaluate the steering actuators, five variants and their advantages and disadvantages are compared. These variants have already been used in various ATV conversions (see chapter 2.2.1) and were generated during brainstorming workshops. The 4 criteria for the selection were:

- The simple feasibility of steering actuators: This refers to how much effort (time and money) must be invested in the conversion of steering actuators. The aim is to construct a system with a relatively low complexity.
- Space-saving: The modified steering system should be space-efficient in order to have enough space for the sensors, which are installed at the front part of the vehicle, later on.
- Precise steering movement: The steering movement should be as precise as possible, including very low mechanical play between the handlebar and the electric motor (relative angle between handlebar and wheels < 0,5 °). The handlebar should also be able to be held at the actual steering position in order to prevent the wheels from swinging while driving.
- Appearance: The appearance of the system plays a subordinate role here. Nevertheless, it is important to make sure that the steering system is in line with the later bodywork or at least, as mentioned before, that it is not visible later on.

In order to determine a suitable actuator for the steering, an evaluation matrix was created (see table 11): This evaluation matrix allows the comparison of several solution alternatives for the steering actuator. In the 1st column, the target criteria are listed and in the 2nd column the respective weighting of these targets are shown, which add up to 100. Afterwards, grades are awarded according to the school grading system (1 ≤ n ≤ 5). Multiplied by the weighting of the objectives, this results in a weighted partial achievement of the objectives. The alternative with the highest sum of weighted partial goals appears in the 1st rank and is thus the best solution approach.

Goal criteria	Weight (g) Σ= 100	linear motor		DC motor with chain		DC motor with gear pair		DC with bevel gear		DC motor with toothed belt	
	g	n	n*g	n	n*g	n	n*g	n	n*g	n	n*g
Easy implementation	30	4	120	4	120	2	60	1	30	4	120
Save space	20	4	80	3	60	3	60	3	60	3	60
Precise steering movement	30	3	90	1	30	5	150	5	150	5	150
Optical look (design)	20	4	80	3	60	3	60	3	60	3	60
Sum	**100**	370		270		330		300		390	
Rank		2		5		3		4		1	

Table 11: Evaluation matrix steering actuator (106)

n...grades (assessment) of the respective goal criteria,

g...weighting of target criteria

Finally, the variant of the DC motor with toothed belt drive was chosen. It is easier to implement than the solution variants with gear pair and bevel gear pair, as high manufacturing accuracies are not required as it is the case with the rest of the variants. Although the timing belt drive is not as space-saving as the linear motors, but in contrast to this it is not as close to the underbody (see chapter 2.2.1) of the vehicle and does not run the risk of damages by road unevenness. The precise steering control, which is not given by the solution approach with the chain, is also fulfilled by the toothed belt, since the tension of the belt results in less play than with the chain. The only two criteria that could be improved are space requirements and design (optical look). However, this can be remedied by replacing the DC motor by a DC geared motor. This variant integrates a gearbox with a given transmission ratio inside, it is therefore more compact and generates higher torques at the gearbox output with a smaller design. (107) As a DC geared motor, the DOGA 258 was chosen (see figure 2.9). The motor generates a tightening torque of 80 Nm at 24 volts and a transmission ratio of 52:1 thanks to the integrated worm gear. Power is transmitted over a feather key and the engine itself is firmly bolted to the vehicle with three M8 screws. (108) Since the rotational speed of the handlebar is also important for the steering movement, a suitable torque/speed ratio must be determined from the manufacturer's data sheets with which the motor is controlled.

Figure 2.9 DOGA 258 actuator (108)

The steering speed was defined as one second for ¼ revolution of the handlebar, which would mean one second at full impact from the left to the right. This results in a necessary rotational speed of the steering column of around 15 rpm.

Figure 2.10 shows the rotational speed and torque curves at the output of the DC geared motor. Here it is obvious that with the required torque of 45 Nm (green line) a turning speed of 15 rpm can be achieved. To ensure that the force is sufficient in order to change direction, an additional transmission ratio of 1:2 was selected for a pair of timing belts. Thus, a torque of 30 Nm (blue line) is achieved at a rotational speed of 30 rpm, which in turn means a rotational speed of 15 rpm and a torque of 60 Nm at the handlebar.

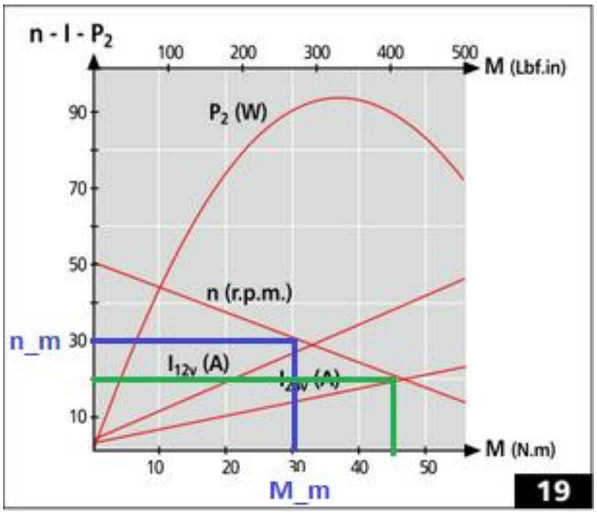


Figure 2.10 DOGA 258 DC Motor Torque/Number Curves (108)

Once the motor and toothed belt transmission ratio were selected, the geometry, number of teeth and center distance of the gear pair had to be determined. The focus here was on finding the most space-saving and the most reliable designs.

Using the calculation tool from a supplier (109), as well as independent iterative calculations (see chapter 5.1.2), the following results were obtained.

- Center distance: a= 193 mm
- Gear 1: z_1= 40
  b_1= 20 mm
  d_{p1}= 101.86 mm
- Gear 2 : z_2= 80
  b_2= 20 mm
  d_{p2}= 203.72 mm

The torque at gear 2 is 60 Nm and the space requirement for the toothed belt set is 345.0 x 203.7 x 20.0 mm.

Figure 2.11 shows the CAD design of the actuator for steering. The basis is a welded construction made of 5 mm thick structural steel, which is screwed to the main frame, using four M4 screws. The DC motor, shown here in brown, is connected to the welded construction by three M6 screws. Gear wheel no. 2 is equipped with a taper bush (green) and transfers the steering torque to the handlebar by friction. Gear wheel no. 1 is also equipped with a taper bush and clamped onto a shaft (yellow), which is supported on the top by a flange bearing unit and at the bottom by a shaft-hub connection (adjusting spring). A clearance fit was chosen as fit for the shaft-hub-connection. Following tolerances have been considered.

- Electric motor shaft: 14 g6 (specified by manufacturer)
- Hub milled into the connecting shaft: 14 H7.

As a reinforcement of the handlebar, an aluminum sleeve (yellow Figure 2.11) was welded at the seat of the gear wheel no. 2. Since the handlebar should be dismountable during an autonomous operation, the handlebar was cut apart and re-connected using a connecting sleeve, consisting of a bolt and aluminum sleeve, so that it can be mounted or dismounted at any time.

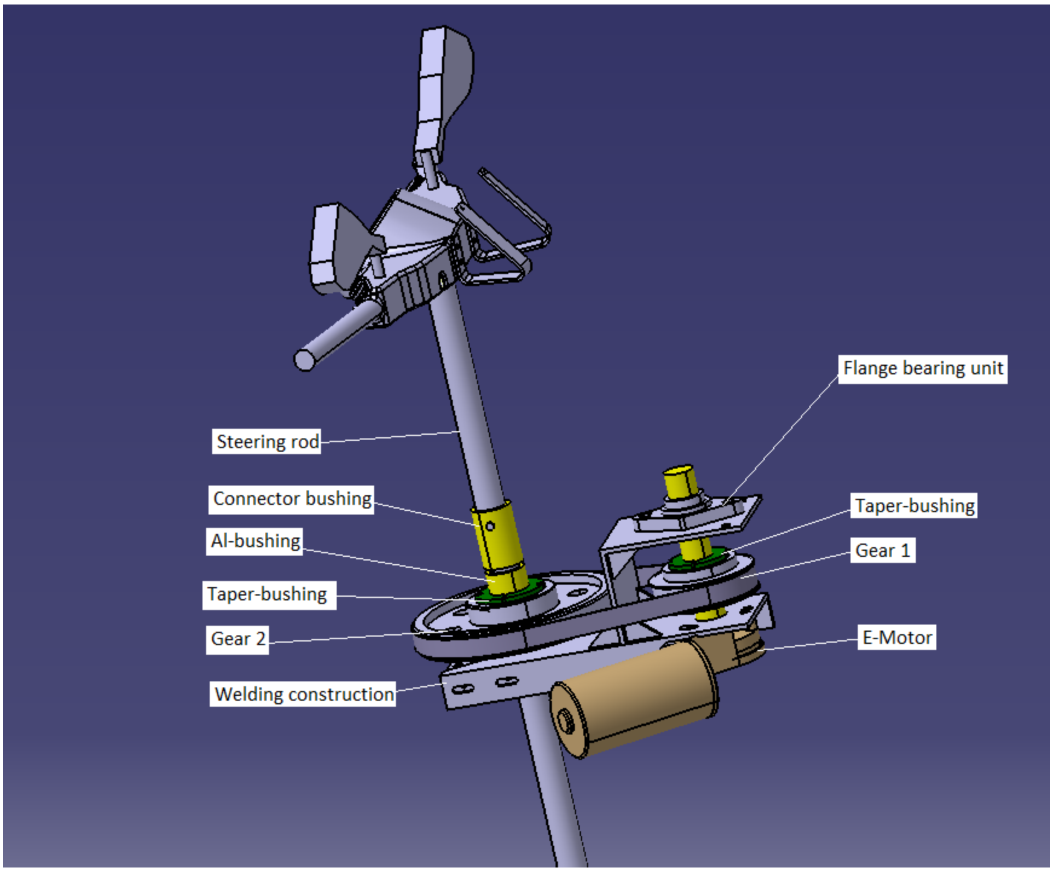


Figure 2.11 CAD design steering actuator

Since sensors had to be attached to the front and the rear of the vehicle, it was necessary to develop and apply a sensor carrier. Thus, an inclusion of the steering system was integrated into the intended mounting device for the laser sensors, which are needed for navigation (see figure 2.12). This was bolted to the front of the frame with six M12 bolts and connected to the welded construction of the steering actuator with M8 bolts. This provides additional stability for the steering unit.

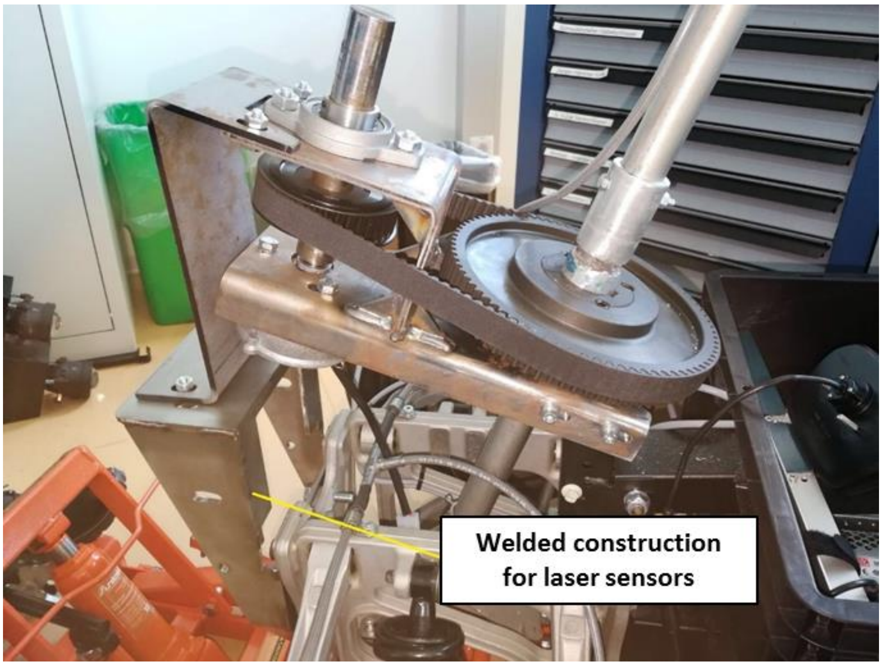


Figure 2.12 Welded construction for laser sensor

Since the vehicle always needs information on the actual rotation position of the steered wheels, a steering angle sensor was also required. A hall sensor was considered to be appropriate for this. The use of hall sensors is a common application in vehicles for vehicle dynamics control (110). For this reason, an attempt was made to use a suitable, already existing sensor from an automobile manufacturer. However, since the steering angle sensors are installed in the steering column of the cars and fastened by means of individual plastic clip fasteners, it was not possible to use an existing component of car manufacturers. The handlebar on the Jetflyer would have had to be equipped with a corresponding clip fastener, suitable for the respective manufacturer. Finally, Megatron singleturn encoders with Hall Effect were used. This device has a resolution of 12 bits (which corresponds to a value range from 0 to 4096 or an accuracy of 0,087 °) and a measuring range of one revolution (singleturn). (111) The transmission of the rotary motion from the handlebar to the sensor was realized with steel gears with a transmission ratio of 1:1. The encoder itself was screwed to the Jetflyer’s frame in order to prevent twisting (see figure 2.13).

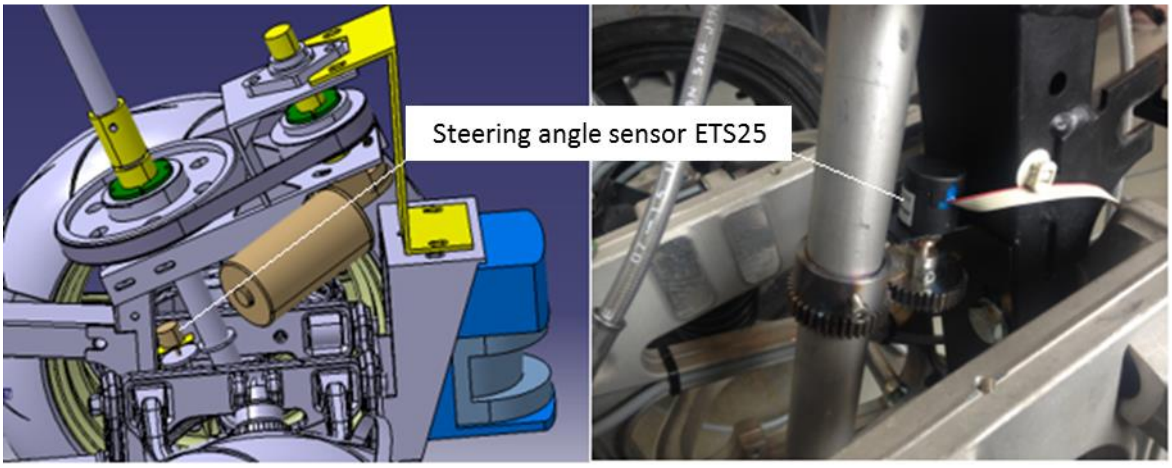


Figure 2.13 Steering angle sensor ETS25 (left in CAD, right in installed condition)

2.2.3 Operational brake

Before the specification and design of the operational brake, the maximum speed was defined and limited to 6km/h, ensuring a safe operation in the test area (pedestrian zone). Therefore, the responsible parameters in the motor controller were first changed using a software that was provided by the manufacturer (see figure 2.14, parameter: "Max. Forward Speed"). The deceleration (parameter: "deceleration") of the two drive motors has been changed to the maximum, so that when the throttle handle is released, the deceleration is instantaneous and the deceleration is at the maximum. Subsequently, brake tests were carried out in order to determine if this deceleration alone would be sufficient as a brake variant. The fact that the parameter "deceleration" was set to its maximum value "1.00e+02", resulted in a very strong stuttering of the motors during starting, which made the Jetflyer hard to drive. In addition, the deceleration only worked at speeds > 1 km/h. That means, if the vehicle was faster than 1 km/h, it would brake electrically. If it was slower than 1 km/h the deceleration would be deactivated and the vehicle would roll, which would lead to unsatisfactory braking distances. Finally, the delay value was reset to the factory setting. Figure 2.14 shows the software of the motor controller and its possible variable parameters and settings.

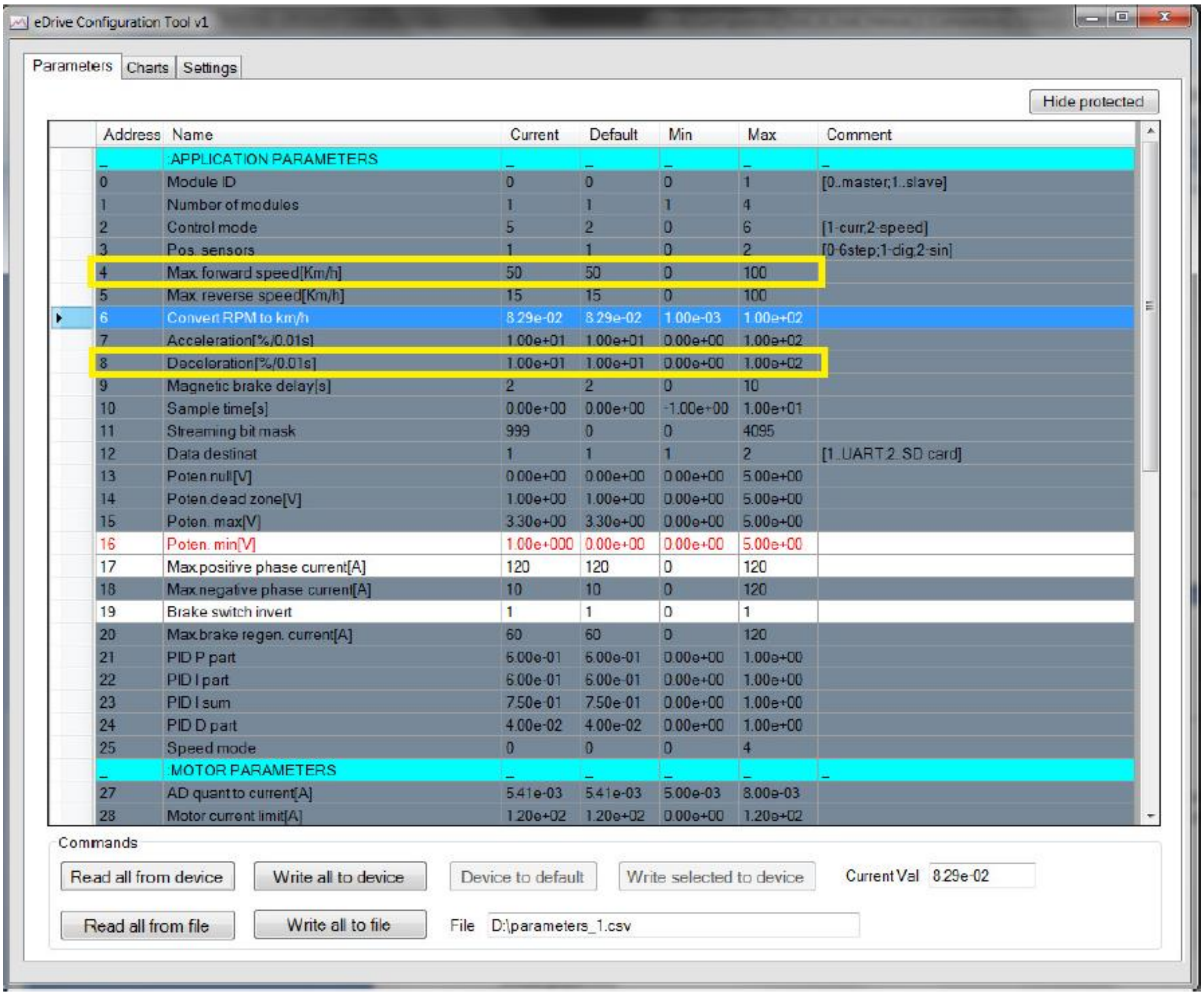


Figure 2.14 Software tool of the motor controller

In order to find a suitable concept for the brake actuator, brake tests were carried out again. The required force at the brake lever, which brings the vehicle to a standstill, was determined. For this purpose, the spring balance was used again, as already described in chapter 2.2.2. This was fixed to the brake lever and pulled when the vehicle was moving (v_{max}= 6 km/h), as well as when the vehicle was stationary and tried to push it away (see figure 2.15). Five measurements were carried out again – this time with a load of 90 kg. This resulted in a maximum value at the point of application of the brake lever of 3.03 kg, which in turn corresponds to a force of 29.72 N (about 30 N). Figure 2.16 shows the geometry of the brake lever.

Figure 2.15 Force measurement on the brake lever at standstill

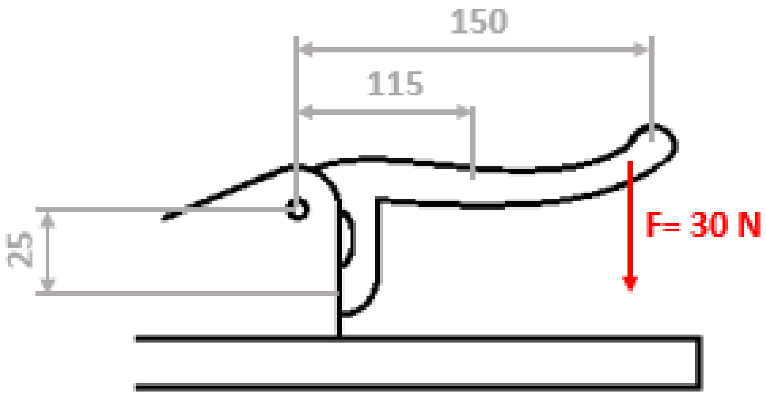


Figure 2.16 Sketch geometry of the brake Lever

Consequently, there were two possible dynamic brake system control variants to choose from:

1. **Variant:** Attaching a linear motor directly to the input of the expansion tank (see figure 2.17). The advantage would be that the electric motor could be mounted directly parallel to the handlebar grip and the movement would be 100% linear (no need for pivoting motor bearings). This would be easy to implement as the motor could easily be mounted on the handle without the need to build a special fixture. However, the disadvantage of this direct force application to the brake

reservoir would be that the linear motor would have to apply a larger force than with a motor that engages via the brake lever (see calculations 5.1.3. Here a force of at least F_1= 180 N would be necessary to initiate a sufficient deceleration. Motors with such an application of force exceed a reasonable amount of installation space on the handlebars in their design.

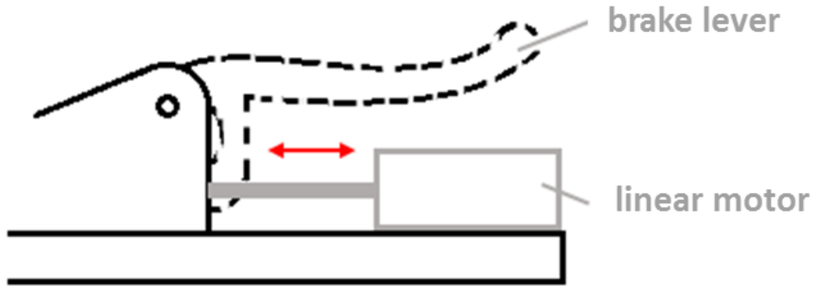


Figure 2.17 Sketch of electric motor in direct engagement

2. **Variant**: Attaching an electric motor in combination with a turning spindle to the brake lever (see figure 2.18). This requires less effort, as the brake pressure from the electric motor passes through the brake lever, which then compresses the volume in the brake circuit and builds up brake pressure. In this case some disadvantages would be a non-linear movement, which can lead to tensions in the area of the motor and its spindle, and a longer braking time, since the spindle needs some time to turn.

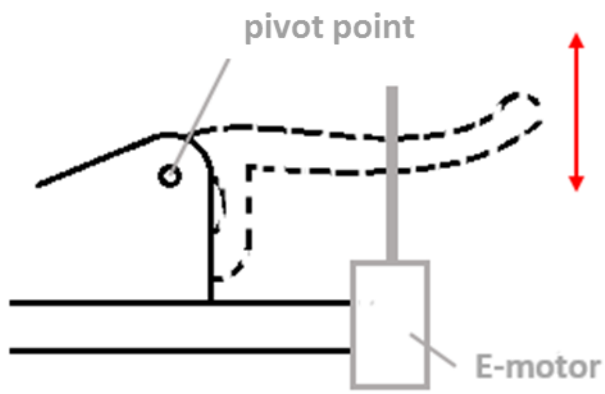


Figure 2.18 Sketch electric motor in indirect engagement via lever

Variant 2 was chosen because here the electric motor only has to apply a force of about 40 N with a travel distance of 10 mm (see calculations 5.1.3) in order to achieve full braking force. Thus, this force is smaller, easier to apply and easier to proportionally control.

The chosen motor was a NEMA Size 8 hybrid stepper motor with an external linear spindle (pitch G=2.0) from KOCO MOTION (112) (see figure 2.19). Such stepper motors are synchronous motors in which the rotor is rotated by a certain small angle (step) through a stepwise rotating electromagnetic field of the stator coil. (113) In the case of the NEMA 8, it manages to build up a braking force of 45 N within one second (see figure 2.20) as the travel of the brake lever is about 10 mm until the wheels lock.

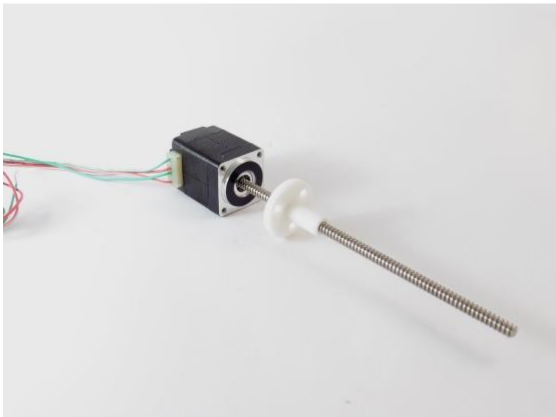


Figure 2.19 Linear Actuator Nema 8 Hybrid Stepper Motor (112)

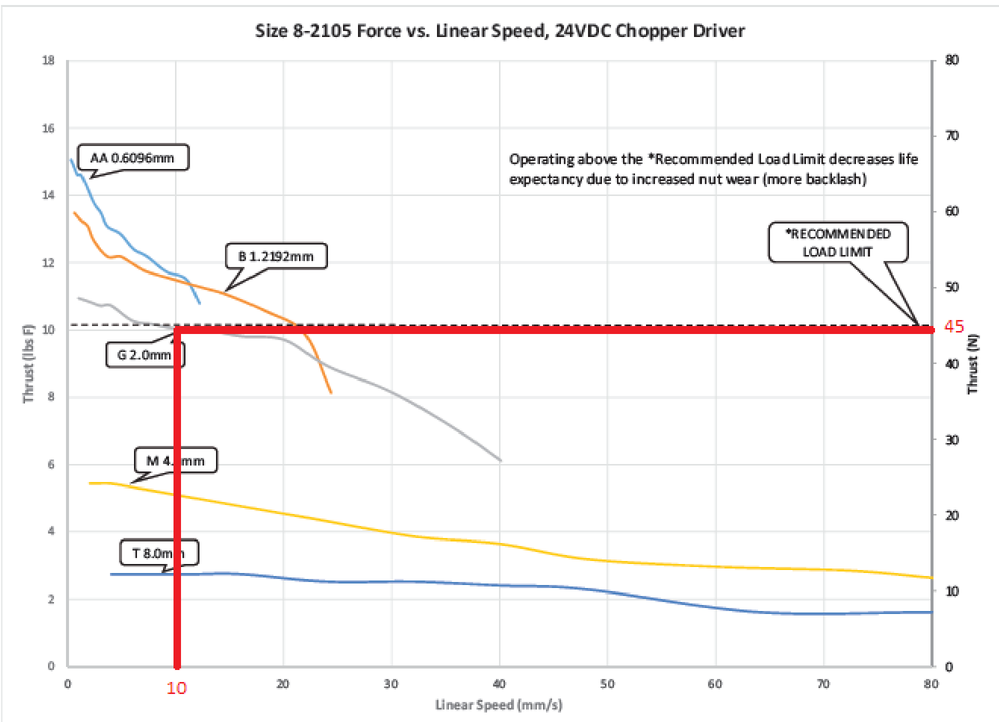


Figure 2.20 F-v Diagram Linear Actuator (112)

Figure 2.21 shows the converted operational brake device. As visible, the brake lever has been shortened and screwed at the end of a rotary joint. The stepper motor was rotatably mounted on the turning spindle and on the housing itself, since the movement, when the brake lever is tightened, is not purely linear, but circular. In the first modification this was neglected and it came to tensions of the spindle and as a result to an unsatisfactory braking process. An initial error, that the stepper motor always reports the correct position, did not allow the braking process to be carried out correctly. The problem: As the torque was applied too quickly, the rotor could not follow the electromagnetic rotating field correctly and step losses occurred, which in turn led to insufficient deceleration. This was remedied by means of a potentiometer, which monitored the movement. When the angle is changed by a movement, the electrical voltage value also changes and therefore a certain angle can be assigned to each voltage value. (114) Thus, despite of the step losses, which occur if the torque is applied too quickly, the correct conclusion about the current position of the rotor is obtained. In addition, the brake lever was pre-tensioned with two tension springs in order to support the stepper motor when the brake lever was tightened and in order to initiate the braking process even more quickly.

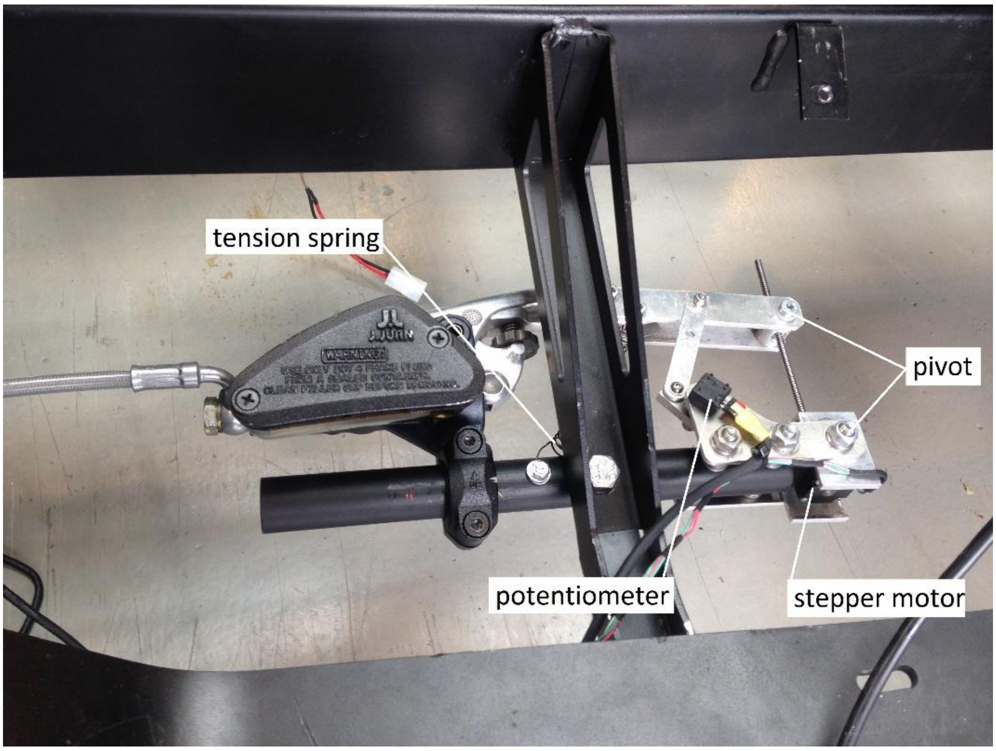


Figure 2.21 Brake actuator operation

As already mentioned in chapter 2.2.1, the brake circuit was separated into two independent systems. The operational brake acts on the two rear wheels and the two front wheels are blocked by the emergency brake, if necessary. The actuator for the service brake was moved from the handlebar to the frame below the basic vehicle. This makes it possible to remove the handlebars for an autonomous operation.

2.2.4 Safety concept and emergency stop brake

A fail-safe operational concept on the vehicle is provided for mastering critical situations. Critical situations can be, for example, a failure of an important component or a malfunction of the system (e.g. unexpected steering or deviation from the specified path). In this case, an emergency stop switch must be able to be triggered by radio control, interrupting the power supply for all driving functions. The Jetflyer should stop immediately in such a situation to avoid collisions of any kind with surrounding obstacles. However, this braking mechanism must still function even in the event of a voltage drop if the rest of the system doesn't work any longer or can't be controlled. The block diagram in figure 2.22 shows how the emergency brake system should work. An emergency kill switch, triggered remotely, was integrated between the original circuit. The magnetic actuator is linked to this emergency kill switch, which is triggered as soon it is not power-supplied. So, the emergency braking process will be initiated.

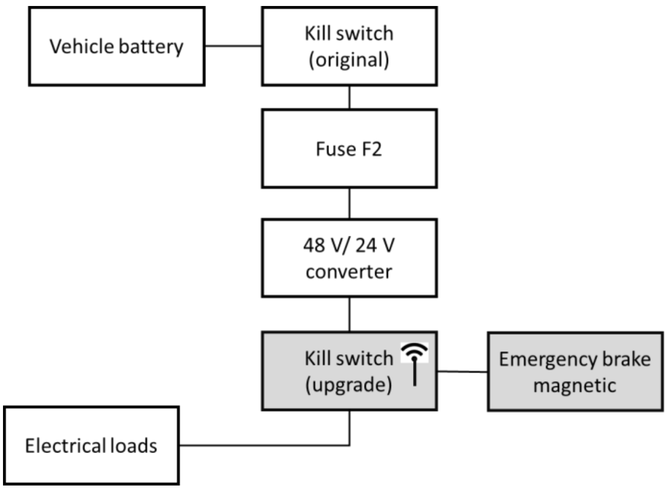


Figure 2.22 Function of the emergency brake system (98)

A system similar to an emergency locking system for fire doors was sought. In such systems, the usually self-closing door is held in place by a magnet, in case of fire these magnets are released and the door closes. This concept was transferred to a prototype with direct attack on the existing brake lever (see figure 2.23). Here a tension spring should be tensioned between the brake lever and the handlebar grip. The spring should be strong enough to fully tighten the brake lever and thus initiate maximum braking deceleration. When driving, the magnet should hold the brake lever in the position originally releasing the brake.

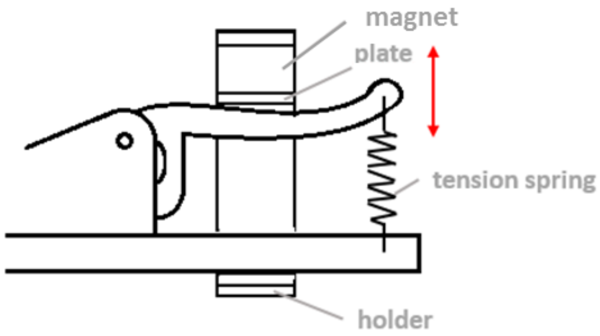


Figure 2.23 Emergency stop brake sketch

Established requirements for the tension spring to be installed are:

- F_{min} = 30 N
- L_2 = 80- 85 mm (length of spring loaded)
- S_2 = 30- 35 mm (distance of spring tensioned)

Figure 2.24 and figure 2.25 show the CAD design of the emergency stop brake. In the starting position (driving operation) the brake lever with ferromagnetic plates is shown transparent and the end position for braking is shown normal in figure 2.24. The holder of the magnet (yellow) is shown in this figure cut for comprehensibility. The holder is screwed to the handlebar grip and holds the magnet. The ferromagnetic plate is screwed through a hole in the brake lever.

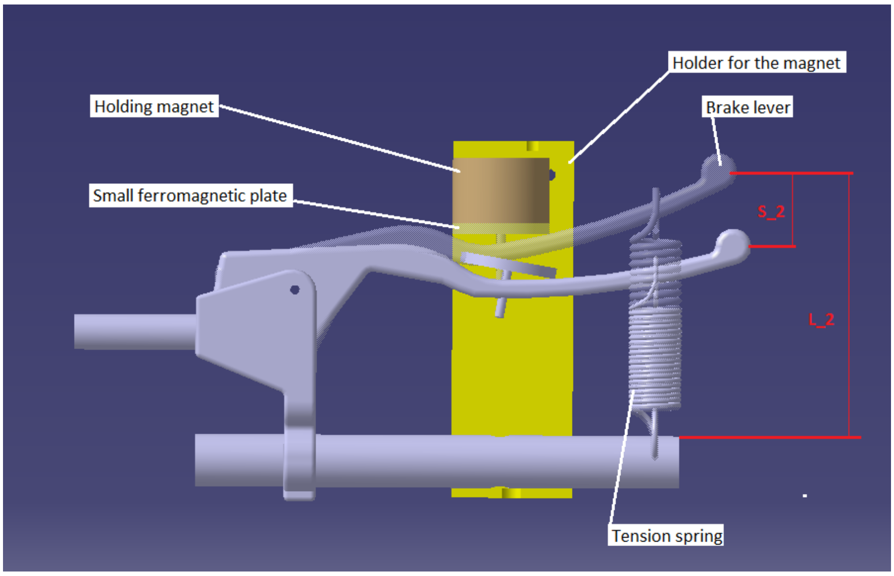


Figure 2.24 Emergency stop brake CAD

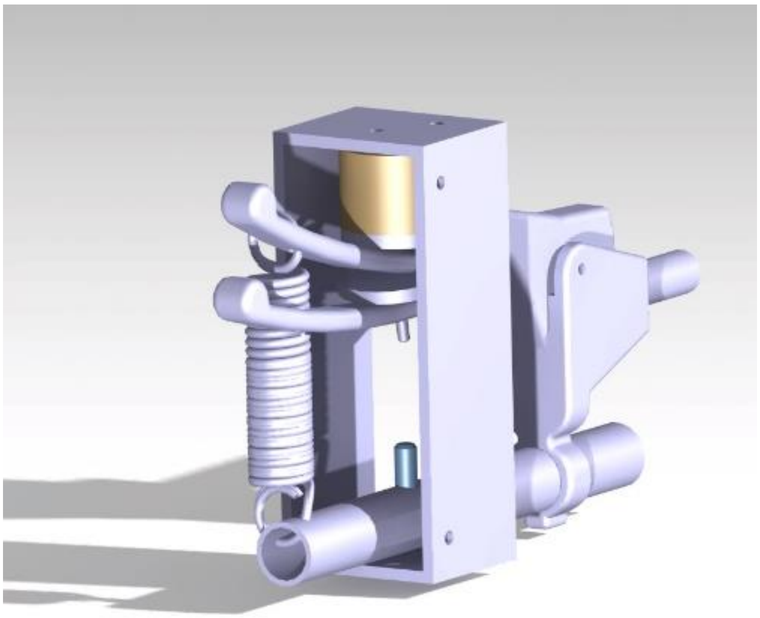


Figure 2.25 Emergency stop brake CAD 3D

Figure 2.26 and figure 2.27 show the final version of the emergency braking system, as installed on the vehicle. For the emergency brake actuator, a second brake lever set including compensating reservoir was provided by i-Tec Styria. The magnet used was a holding magnet made by Company Red Magnetics. (115) The magnet has a holding force of F = 200 N, at a power of P = 6 W. With a net weight of 230 g it is ideal for the brake actuator. The thickness of the ferromagnetic pull plate is at least 4.5 mm, as specified by the manufacturer. A grub screw was welded into the tightening plate in order to fix it to the brake lever with a nut. The magnet was screwed to the holder with three M3 screws. The holder itself was screwed with an M8 screw to the aluminum tube (handlebar set) and with two M6 screws to the Jetflyer's frame. The tension spring has a length of L_2= 85 mm with a force of F_2= 30 N and runs through the hole in the brake lever and through one in the aluminum tube.

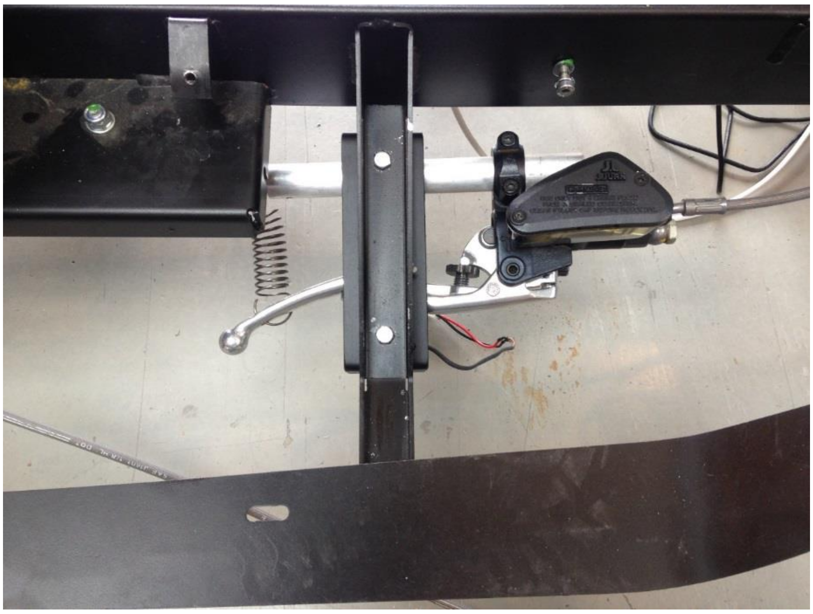


Figure 2.26 Emergency stop brake view 1

Figure 2.27 Emergency stop brake view 2

In figure 2.28, the two brake actuators are shown, as they are installed on the vehicle. They were mounted underneath the swingarms for the tread plates and are not the lowest point of the underbody of the Jetflyer due to their inclined position, so they are better protected.

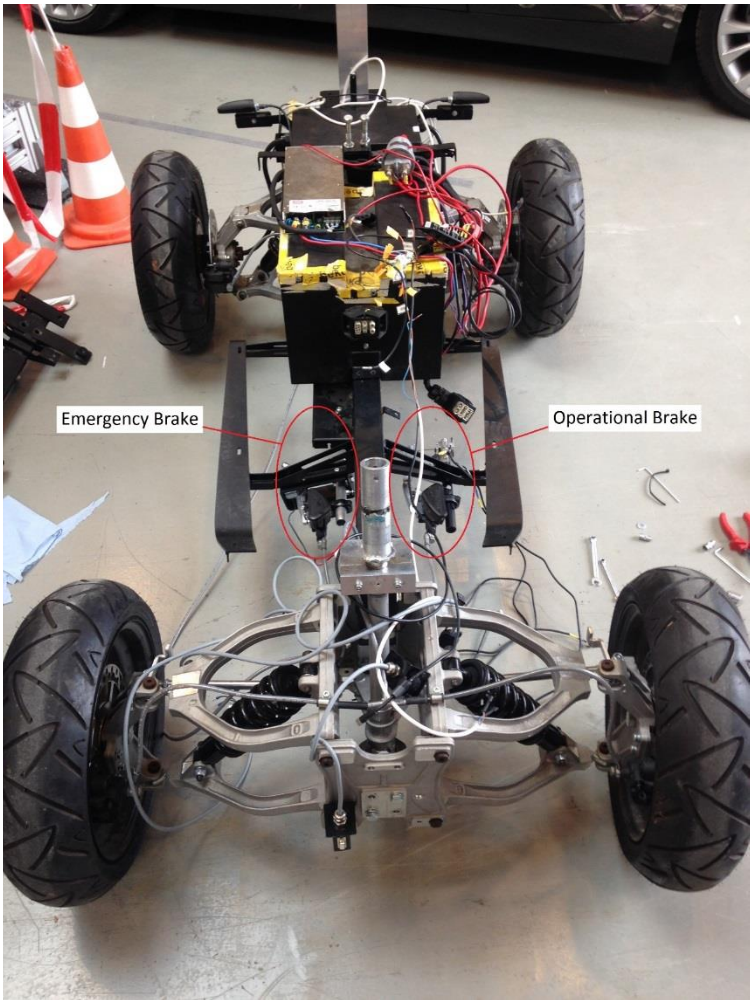


Figure 2.28 Brake actuators installed on the vehicle

2.2.5 Acceleration grip

The acceleration takes place via direct intervention of the controller responsible for autonomous driving functions into the ECU of the electric motors; it was not part of the present work. Here, as mentioned in chapter 2.2.3, the value of the maximum speed was reduced to v_{max} = 6 km/h. In addition, the maximum acceleration had also been reduced. The applied voltage in the range of 0.2 V and 3.3 V determined the speed (signal voltage from acceleration grip to the controller).

2.2.6 Packages of measures for the conversion to an autonomous operation

Signal control and electronic integration of present actuators was not task of the present work. Only the assembly of the sensors and the box of the hardware was carried out in cooperation. For the box of the hardware an original battery box was adapted (see figure 2.29). Here all voltage converters, laptop and switches are installed.

Figure 2.29 Hardware Components Box

The display, the emergency stop switch and the switch for activating the power supply have also been moved there and incorporated into the fairing parts (see figure 2.30).

Figure 2.30 Electronics integration and HMI

2.3 Body conversion

The conversion of the bodywork took place in two stages. In the 1st stage, the vehicle was modified to such an extent that remote-controlled driving was possible in the city center of Graz (see figure 2.31). In figure 2.32 it can be seen where the actuators and the sensors are located at the vehicle. The seat as well as the handlebars were still preserved in this stage. Thus, the vehicle was still maneuverable manually even without being activated. In this step, the interactive map of the alleys of the entire city center was created (for more details, see chapter 3.1)

Figure 2.31 Conversion body 1st stage

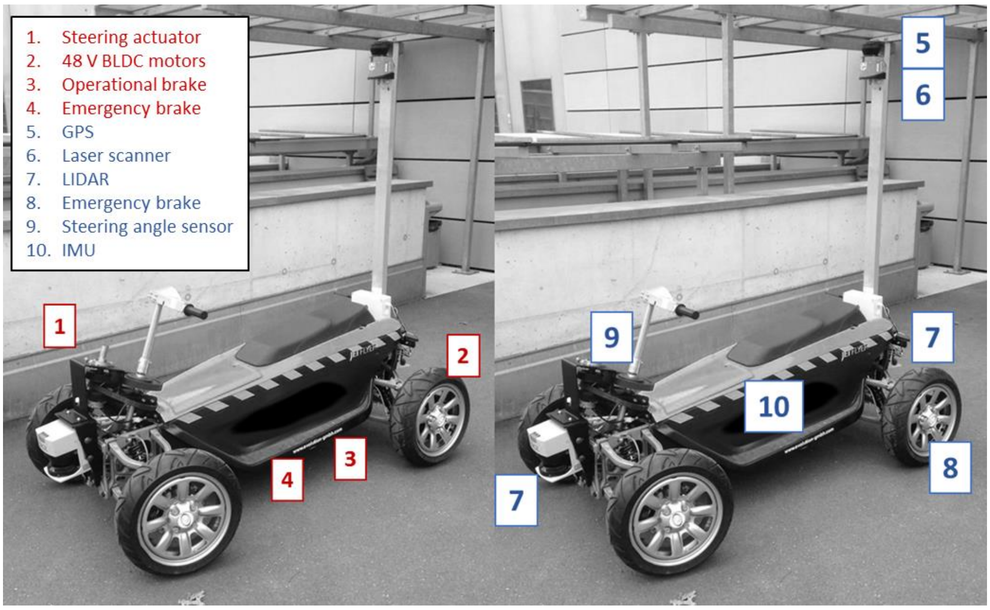


Figure 2.32 Location of the actuators (red) and sensors (blue)

In the 2nd stage, the transport boxes, which were provided by the Austrian Post AG, were fitted to the vehicle (see figure 2.33). These were welded to a specially manufactured frame part and then fitted to the vehicle. In order to compensate the optical disadvantage by the boxes, a suitable fairing was developed. The CAD design was done in Catia V5 Surface and Wireframe Design, based on given design data of the base vehicle. The resulting flat sheet metal blanks were bent and welded (see figure 2.34 and figure 2.35). The shape of the body was kept simple here. There are several reasons for this: Due to the short duration of the project, low production effort was required and in order to keep costs as low as possible, no external company was commissioned for production. The parts were manufactured in-house with the available machines and tools. Figure 2.36 shows the adapted front fairing. A window was left open on the left side in order to access the switches and electronics. This window should be lockable and held by means of magnets. Small bumpers were also mounted at the front and at the rear of the vehicle. The purpose of this is to protect the lower two LIDAR sensors.

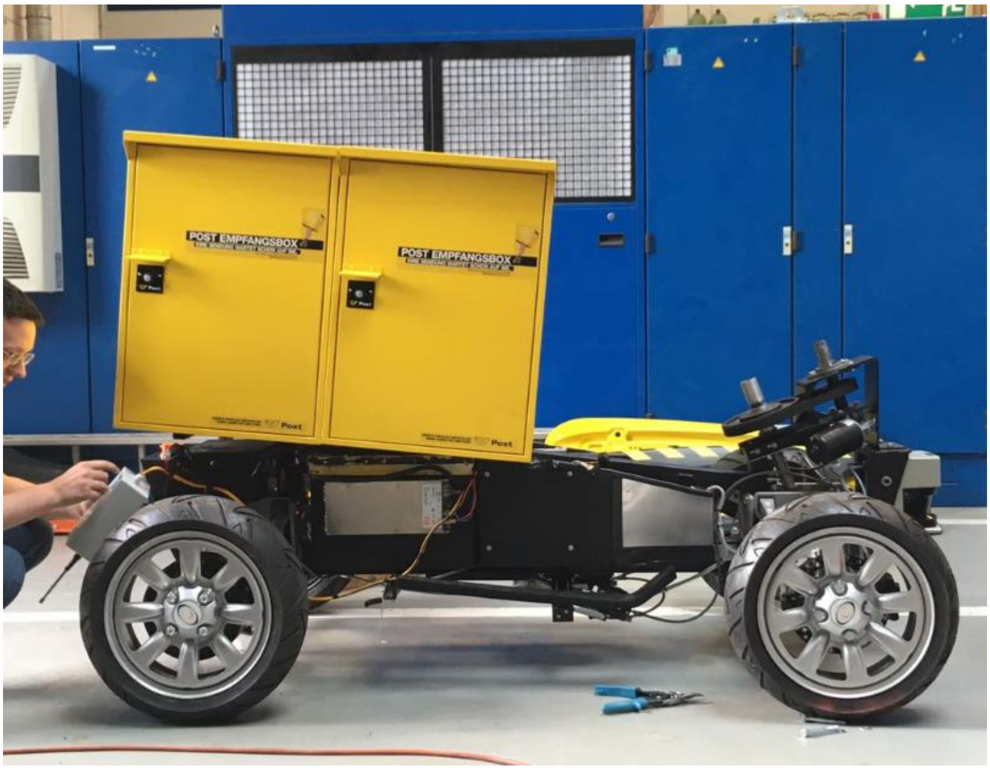


Figure 2.33 Transport boxes on the vehicle

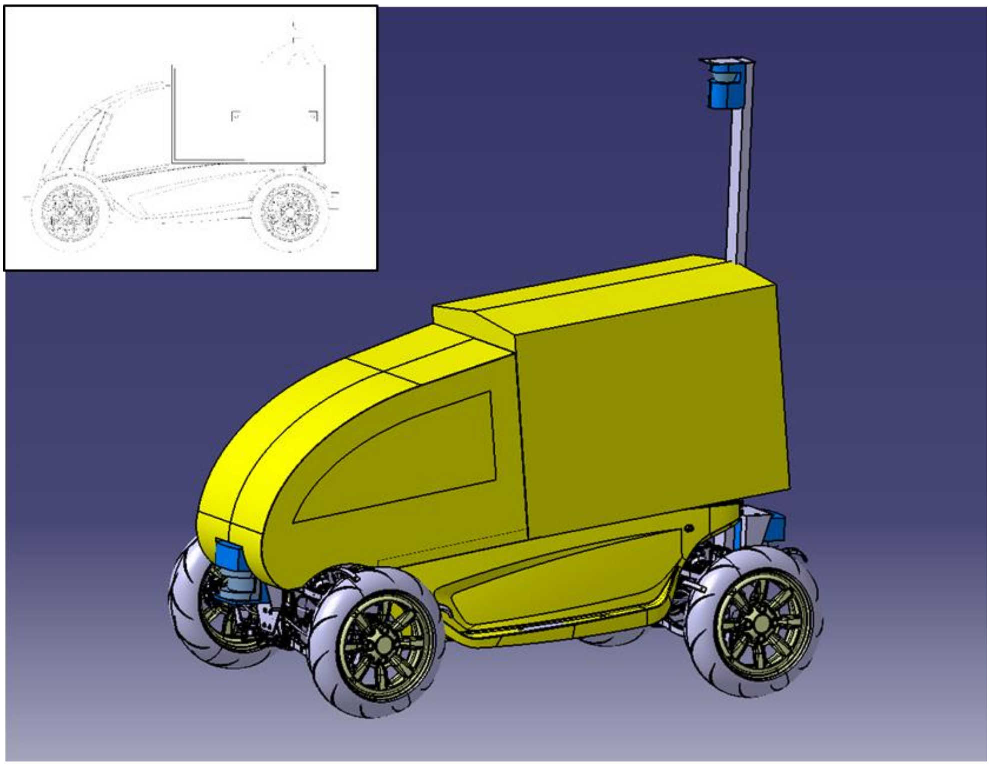


Figure 2.34 CAD design car body (1/2)

Figure 2.35 CAD design car body (2/2)

Figure 2.36 Adapted front fairing on the Jetflyer

The entire covering parts were foil-coated in the desired design. Figure 2.37 shows the finished vehicle at the end of the project.

Figure 2.37 Conversion body 2. stage

3. Testing phase

3.1 Functional tests of remote control and map recording

In order to make autonomous driving possible, maps of the target area must first be created. But before all of that some test cases at the campus were performed to make sure that all components and programs work the way they should. For the steering loops, slalom and hard steering maneuverers were done. By doing target braking to an object, the brakes were tuned to get a short braking distance. The emergency brake was checked by de-energizing the Jetflyer. In it was measured, how long it took the vehicle to come to standstill. Some software iterating loops were done for accelerating, too. After the function tests at the campus, the map was created at the inner city.

The principle of path planning consists of 4 phases:

1. Virtual recording of the environment: In order to create the interactive maps, the Jetflyer was remotely moved through selected and approved downtown streets (figure 3.1, blue lines). Figure 3.2 shows the distance traveled by the vehicle (green) and the data recorded by the laser scanner (white). In blue, the GPS points are shown as lines between GPS measurement and real position, making the deviations of the GPS clearly visible. Figure 3.3 shows the same information; in addition buildings from openStreetMap[24] are displayed. So, an adjustment of the two maps was possible. A 2-dimensional interactive raster map was captured by the environment using the laser scanners. From the data of the laser scanner partial maps were generated, which have a size of 50x50 meters, as can be seen in figure 3.4. The grid map provides information about the probability that a cell is free or part of a (permanent) structure. These sub-maps are subsequently used for localization in these maps; only the static obstacles are recorded, not the dynamic ones.
2. Location of the vehicle in the map: The localization of the vehicle on the map takes place by using odometry and LIDAR sensors. The position (distance to the surroundings) of the vehicle on the map is determined using LIDAR sensors. With the help of the data from wheel speed sensors, steering angle sensors and IMU, the further gained data from the LIDAR is refined (tracing of the distance covered). In this way, the exact position of the vehicle on the map is determined.

[24] Is a free geo information system (123)

3. Global Path Planning: The system automatically plans a collision-free path from the actual position to a given goal. This is done by searching a sequence of small movements so as not to collide with any obstacles from the map. However, without involving dynamic obstacles.
4. Local Planning: The system also takes into account the actual measurements of LIDAR sensors in order to respond to dynamic obstacles. It executes the path and finds a collision-free motion command for the next time step, taking into account the actual dynamics. In order to avoid a dynamic obstacle collision, the planner is allowed to deviate from the globally planned path within defined limits.

Figure 3.1 City center of Graz

Figure 3.2 Recorded map of the city center

Figure 3.3 Recording map of the city center with OpenStreetMap

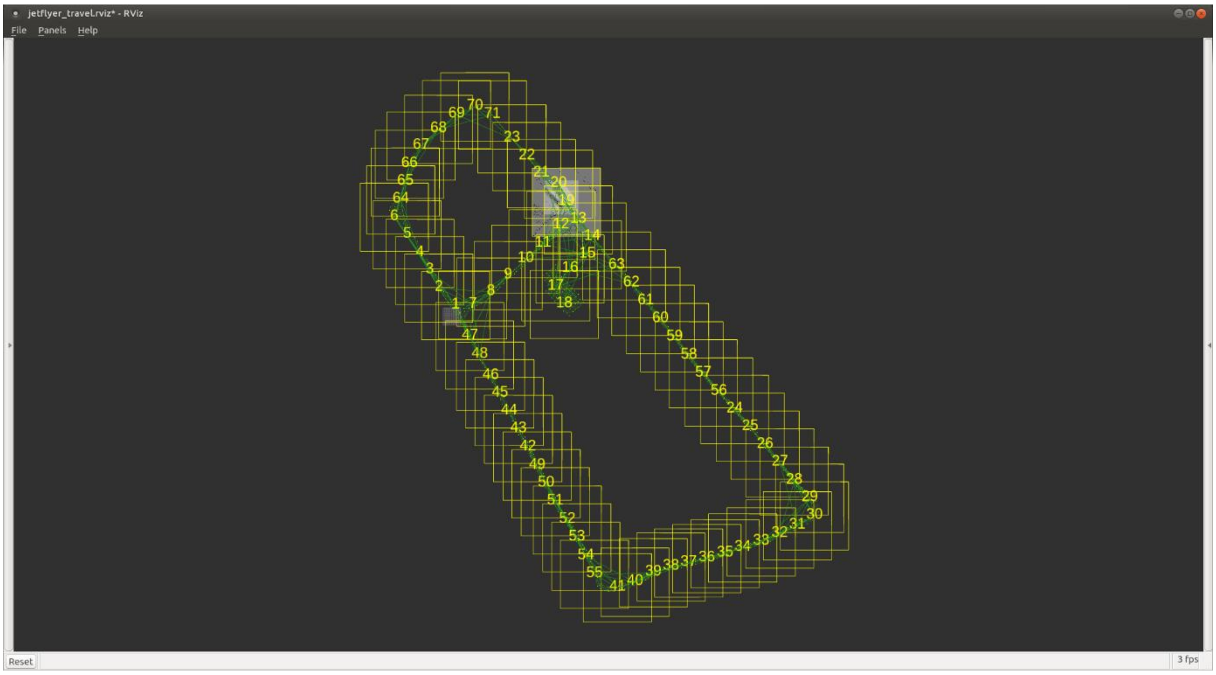


Figure 3.4 Recording sub maps

3.2 Autonomous test drives

The autonomous test drives were then carried out with a team of at least three people. A "supervisor" is the one, who has the remote control and the radio emergency at disposal. The remote control is used for safety reasons, in such a way that a certain button must always be kept pressed for an autonomous operation. The two other colleagues supervised the general events and drew passers-by' attention to dangers, if necessary. At the request of the client, the vehicle itself was wrapped during the test drives (see figure 3.5). During the test drive all actuators worked the way they should, without any errors.

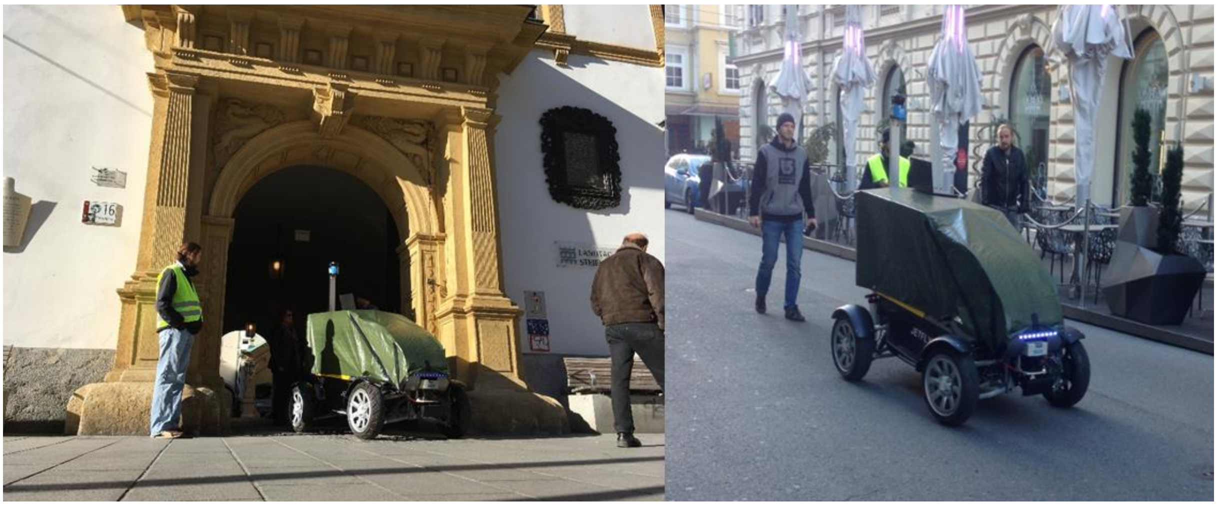


Figure 3.5 Autonomous test drives

4. Conclusion and Outlook

In the context of the present project, the potential of autonomous vehicle movement was illustrated. It was shown that the "last mile" delivery stands out here as a large potential for the near future. With the steady increase in online commerce as well as with the growth of cities, the automation of delivery vehicles and passenger transport will be an important and inevitable step towards reducing the environmental impact (noise, pollutants, etc.) in cities. Autonomous delivery combined with an effective traffic planning could also reduce traffic jams, if bottlenecks at the rush hours are eliminated. Delivery for individual consumer good could take place at times when there is little to no traffic. By use of automated driving vehicles, the working time of postmen could not be affected and the majority of customers could be at home.

In the present work, the delivery to the "last mile" was finally tackled. Here, a delivery vehicle of the class L6e was used, which is equipped with four separate transport boxes and delivers packages autonomously. The vehicle makes its own way through the city of Graz and arrives at its destination, the recipient is notified by SMS about the arrival of the shipment. An intense test phase was necessary to create the map of the inner city of Graz. First, the entire area has been recorded with the Jetflyer in remote mode and then switched by use of iterative steps of autonomous driving. Permissions from the city of Graz, which laid down the legal framework, were also necessary for that.

With a development time of 6 months, this prototype was rebuilt for Österreichische Post AG and Energie Graz for autonomous parcel delivery. Due to the short development time, the Jetflyer has still great potential for further improvement. The actuators for the steering could be integrated into the steering column. As actuators for the service brake, hydraulic system could be used. Overall, a design for higher speeds would be possible and also the design could be more compact with corresponding improvements. That would benefit the efficiency and the design.

Autonomous land vehicles are said to have great potential for a broad field of future use. For example, this technology could be used for firefighting, as transport vehicles, in road maintenance and in many other cases. They can not only make the work easier, but also safer for people. For example, an autonomous vehicle for firefighting omits the necessity of emergency services personnel being present on the site. In the long term, autonomous vehicles, whether on land or in the air, will certainly establish themselves in our everyday lives and relieve them considerably. Finally, they will no longer be indispensable.

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5. Appendix

5.1 Calculations

5.1.1 Calculation Torque Handlebar

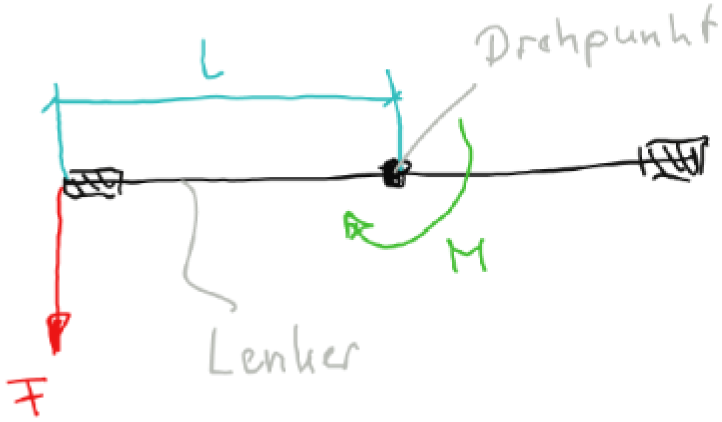

Figure 5.1 Calculation torque at the handlebars

$l := 0.38\ m$

$m := 12\ kg$

$F := m \cdot g$ $\qquad$ $F = 117.68\ N$

$M := F \cdot l$ $\qquad$ $M = 44.718\ N \cdot m$ $\qquad$ (rounded 45 Nm)

5.1.2 Calculation toothed belt set

- <u>Approach 1:</u>

  $z_1 := 22$ $\quad$ Number $\quad$ $z_2 := 90$ $\quad$ of teeth gear 1 and 2

Belt and gear width

$a := 197\ mm$

Centre distance according to calculation tool of the manufacturer[25]

$d_{p1} := 56.02\ mm$

Effective diameter of gear wheel 1

$d_{p2} := 229.19\ mm$

Effective diameter of gear wheel 2

$M_{E\_motor} := 30\ N \cdot m$

Torque DC motor

$$F_U := \frac{M_{E\_motor}}{\frac{d_{p1}}{2}}$$

$F_U = 1071.046\ N$

Circumferential force on toothed belt

$$M_2 := F_U \cdot \frac{d_{p2}}{2}$$

$M_2 = 122.737\ N \cdot m$

Moment to steering column, more than necessary. Circumferential force very high. In order to reduce circumferential force, increase z1.

[25] Calculationtool: http://duri.at//Riemenkalkulator/Technische-Zahnriemen-Berechnung.html [date of access 16.11.17]

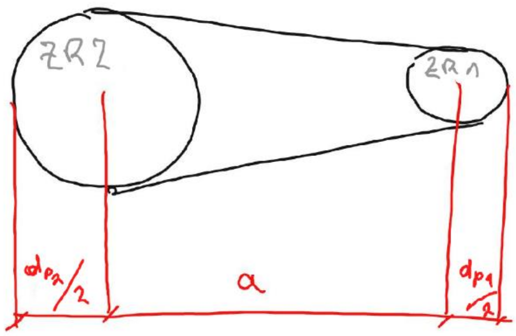

Figure 5.2 Geometric dimensions of toothed belt set

$$L := \frac{d_{p1}}{2} + a + \frac{d_{p2}}{2}$$

$$L = 339.605\ mm$$

Space requirement in longitudinal expansion of belt set

- **Approach 2:**

$z_1 := 30$; $z_2 := 90$

$b := 30\ mm$

$a := 202\ mm$

$d_{p1} := 76.4\ mm$

$d_{p2} := 229.19\ mm$

$M_{E\_motor} := 30\ N \cdot m$

$$F_U := \frac{M_{E\_motor}}{\frac{d_{p1}}{2}} \qquad F_U = 789.058\ N$$

$$M_2 := F_U \cdot \frac{d_{p2}}{2} \qquad M_2 = 90.422\ N \cdot m$$

$$L := \frac{d_{p1}}{2} + a + \frac{d_{p2}}{2} \qquad L = 354.795\ mm$$

Torque on gear 2 still more than necessary, further reduce by reducing z2.

- **Approach 3:**

$z_1 := 30$; $z_2 := 80$

$b := 30\ mm$

$a := 189\ mm$

$d_{p1} := 76.4\ mm$

$d_{p2} := 203.72\ mm$

$M_{E\_motor} := 30\ N \cdot m$

$$F_U := \frac{M_{E\_motor}}{\frac{d_{p1}}{2}} \qquad F_U = 789.058\ N$$

$$M_2 := F_U \cdot \frac{d_{p2}}{2} \qquad M_2 = 80.373\ N \cdot m$$

$$L := \frac{d_{p1}}{2} + a + \frac{d_{p2}}{2} \qquad L = 329.06\ mm$$

Moment still more than necessary, increase z1 again, and reduce toothed belt width.

- **Approach 4:**

$z_1 := 40$; $z_2 := 80$

$b := 20\ mm$

$a := 193\ mm$

$d_{p1} := 101.86\ mm$

$d_{p2} := 203.72\ mm$

$M_{E\_motor} := 30\ N \cdot m$

$F_U := \dfrac{M_{E\_motor}}{\dfrac{d_{p1}}{2}}$ $\qquad F_U = 589.044\ N$

$M_2 := F_U \cdot \dfrac{d_{p2}}{2}$ $\qquad M_2 = 60\ N \cdot m$ ALL RIGHT.

$L := \dfrac{d_{p1}}{2} + a + \dfrac{d_{p2}}{2}$ $\qquad L = 345.79\ mm$ ALL RIGHT.

5.1.3 Calculation of brake lever variants

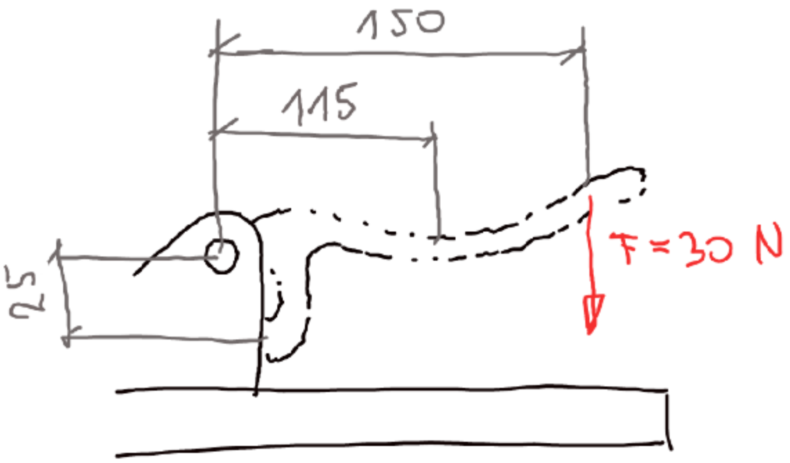

Figure 5.3 Brake lever geometry

- **Variant 1:** Required power for linear motor parallel to the handlebars

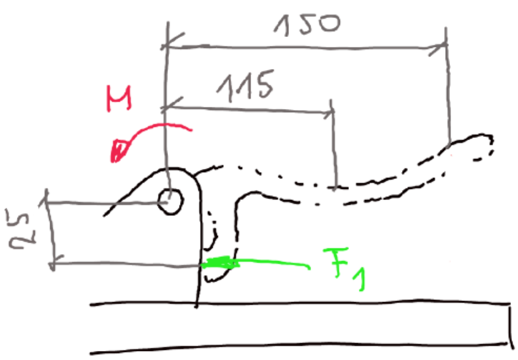

Figure 5.4 Brake variant 1

$F := 30\ N$

$l := 0.15\ m$

$M := F \cdot l$ $\qquad$ $M = 4.5\ N \cdot m$

$l_1 := 0.025\ m$

$$F_1 := \frac{M}{l_1}$$ $$F_1 = 180\ N$$

- **Variant 2:** Required power for electric motor that attacks the brake lever.

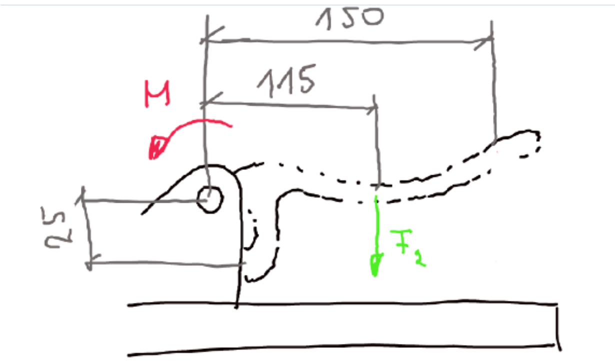

Figure 5.5 Brake variant 2

$$F := 30\ N$$

$$l := 0.15\ m$$

$$M := F \cdot l$$ $$M = 4.5\ N \cdot m$$

$$l_2 := 0.115\ m$$

$$F_2 := \frac{M}{l_2}$$ $$F_2 = 39.13\ N$$