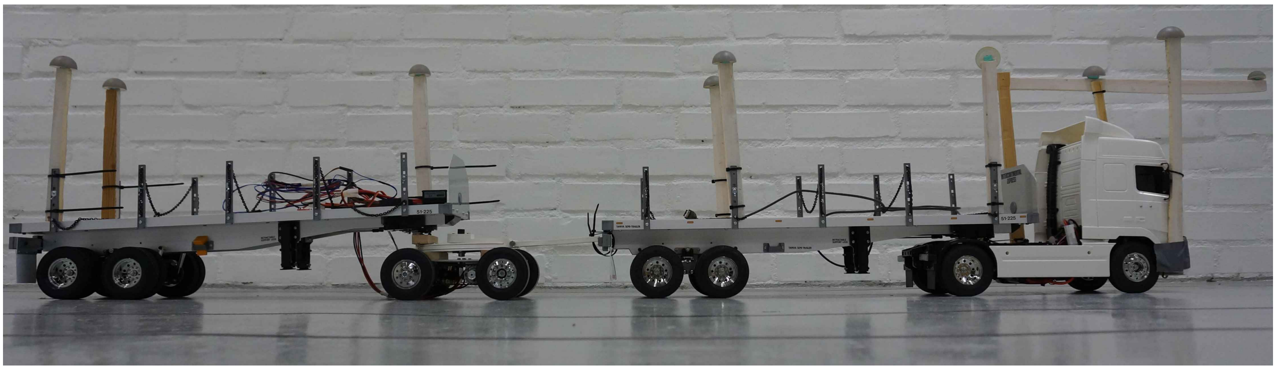

Scaled test track: Investigation of active steering for large heavy truck combinations and implementation of a demonstrator in 1:14 scale

Master's thesis in Systems, Control and Mechatronics

PASCAL A. M. WAMPRECHT

Department of Applied Mechanics
Vehicle engineering and autonomous systems
CHALMERS UNIVERSITY OF TECHNOLOGY
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Cover:
The cover shows the full road train consisting of one truck, two trailers and one dolly in the scale 1:14.

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Abstract

The recent trend in connection with heavy trucks is the aim of introducing long heavy vehicle (LHV) combinations which means for example a truck with two trailers. Therefore the powertrain and steering opportunities of the road trains have to be further developed. This can be done with a propelled and steered dolly unit between any two trailers. Thus, they are able to increase the maneuverability of the road train a lot.

In this report a complete new concept of dolly is shown. The model has four wheels, but it is track steered, which gives the opportunity to rotate the dolly on one position. On the top is a turn table, which allows the vehicle to go in a small outer laterally offset to the previous vehicles in smaller curves.

The physical model is constructed in the scale 1:14 and consists of one truck, two trailers and one of these new kind of dollies. The scaled model is built for the scaled test track of the intelligent vehicles and robots (IVRL) laboratory at Chalmers. Here are the projects for research about autonomous car driving, development, test and validation of active safety systems for cars and trucks in particular. For validating new functions it is cheaper to try it at first in the scaled size, than in the real size. The scaled test track is intended as a tool for seamless transition between computer simulations and full scale proving ground testing.

In the end the dolly proves as a useful tool and it confirms the required tasks of the beginning of this Master's thesis project. After a further development of the software to a closed loop system, it should be possible to test some more advanced algorithm.

Keywords: Road train, scaled real model, steered dolly, propulsion dolly, innovative dolly concept

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Nomenclature

β_2	Angle between the truck and the trailer 1.	5.
β_3	Angle between the truck and the dolly.	6.
β_4	Angle between the truck and the trailer 2.	6.
δ_1	Steering angle of the front wheels of the truck.	5.
δ_3	Steering angle. Position of the dolly in relation to the x-axle of the trailer 2.	6.
a_1	Distance between front axle and the center of gravity of the truck.	5.
a_2	Distance between front axle and the center of gravity of the trailer 1.	5.
a_3	Distance between front axle and the center of gravity of the dolly.	6.
a_4	Distance between front axle and the center of gravity of the trailer 2.	6.
b_1	Distance between rear axle and the center of gravity of the truck.	5.
b_2	Distance between rear axle and the center of gravity of the trailer 1.	5.
b_3	Distance between rear axle and the center of gravity of the dolly.	6.
b_4	Distance between rear axle and the center of gravity of the trailer 2.	6.
c_1	Distance between rear axle and the coupling point between truck and trailer 1.	5.
c_3	Distance between rear axle and the coupling point between dolly and trailer 2.	6.
R	Radius to the center of gravity of the truck (given radius).	5.
R_1	Radius to the front axle of the truck. Parallel to the rolling axis of the wheel.	5.
R_2	Radius to the rear axle of the truck. Parallel to the rolling axis of the wheel.	5.
R_3	Radius to the rear axle of the trailer 1. Parallel to the rolling axis of the wheel.	5.
R_4	Radius to the front axle of the dolly. Parallel to the rolling axis of the wheel.	6.
R_5	Radius to the rear axle of the dolly. Parallel to the rolling axis of the wheel.	6.
R_6	Radius to the rear axle of the trailer 2. Parallel to the rolling axis of the wheel.	6.
$R_{4,5}$	Radius to the center of the dolly. Perpendicular to the driving direction.	6.
R_{C1}	Radius to the coupling point between truck and trailer 1.	5.
R_{C2}	Radius to the coupling point between dolly and trailer 2.	6.

Contents

1 Introduction

1.1 Background

The adaptive systems group at Chalmers is currently developing a scaled test track (STT) lab for research about autonomous car driving in general, for development, test and validation of active safety systems for cars and trucks in particular. For validating new functions it is cheaper to try it at first in the scaled size, than in the real size. The scaled test track is intended as a tool for transition between computer simulations and full scale proving ground testing [1].

The trend leads more and more to individualization. The cargo transportation should be faster, cheaper and more flexible. The transportation way by railway is a nice model, but the rails are not flexible. If the cargo should be delivered to a new area, one has to be built the rails before. Furthermore there are almost no ways to avoid on the rails. If there is trouble at the current part of the rails, the train has to wait or the transportation way will increase a lot. [2]

This leads to more traffic on the road. All this cargos should be transported by a truck trailer combination. In this case it would cost much more money, because each truck needs a driver and a lot of service. So the recent trend in connection with heavy trucks is the aim of introducing long heavy vehicle (LHV) combinations that means for example a truck with two trailers. [3]

The biggest problem with such road trains is the maneuverability. The recent roads are not made for such long trucks. The roundabouts and the curves are too small. Furthermore the acceleration should be better distributed for a better driving performance uphill. [3]

For improving of all this problems a new kind of dolly should be developed. In general "'Converter dolly' means an auxiliary axle assembly equipped with a fifth wheel hitch and used to convert a semitrailer to a full trailer. [1991 c.284 §2]" [4]. The conventional dollies are not steered or propelled at the moment. In the picture below, such a dolly of a Scania Streamline is shown.

Figure 1.1: *Dolly of Scania Streamline Road Train [5]*

In addition the development of this kind of dolly is much cheaper than adapting all older trailers to steerable axles. The old trailers keep the same. This leads to a new concept development in the road train area.

1.2 Purpose

The purpose with the suggested thesis project is to further develop the scaled test track lab at Chalmers by investigating the concept of LHVs with active steering and propulsion on trailer or dolly units.

1.3 Objective

After developing of one concept, a real model should be built in the scale 1:14. The model should be actively steered and propelled. Mainly already existing parts should be used. Also it should be possible to change the semitrailers which means the constructed dolly should be a self-contained system.

1.4 Limitations

The work includes a literature study for developing a good concept. The focus of this project is building the real model with down scaled in length geometry (not detailed analyses of behavior in different situations). That includes the design work of the dolly including the electrical part. For testing the functionality of the new model a simple controller should be implemented. This part should be implemented in the already existing software of the scaled test track.

2 Development of concepts

In this chapter two different concepts are presented. The first concept is a complete new one, and based on own ideas, and the second one is more conservative one. Before the two different concepts will be presented, a small proof is shown. The proof explains, why an active steering dolly is much better than a passive dolly.
In addition with the ability to accelerate and brake is guaranteed an uniform distribution of propulsion. So it is much easier to drive on slippery roads or a hill upwards.
With such a dolly it could be possible that the vehicle and the trailer can be driven autonomously or controlled by a remote control unit in low speed range for parking or coupling situations. This could be expected to save time for the operator in shunting tasks.

2.1 Proof of non-increasing radius

In this chapter it should be proofed, that with increasing of the number of trailers the turning radius will keep the same.
For proofing this statement, one has to calculate the off tracking distance of the vehicle. Off tracking is "when a vehicle goes around a corner, the rear wheels follow a different path than the front wheels." [6]. The figure 2.1 "shows how offtracking causes the path followed by a tractor and semitrailer to be wider than the rig itself." [6].

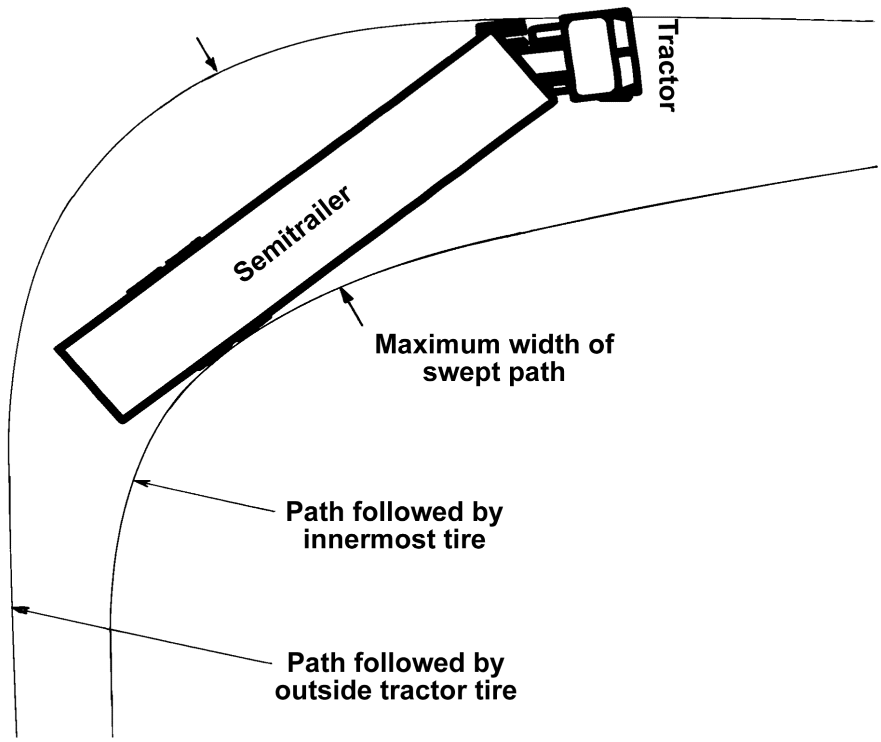

Figure 2.1: *Offtracking in a 90 degree turn with a tractor and a semitrailer [6]*

This is done by comparing all differences of radius in the following pictures 2.2, 2.3, 2.4 and 2.5. To simplify the calculation one uses a one track model. This is also referred to as the single track model.

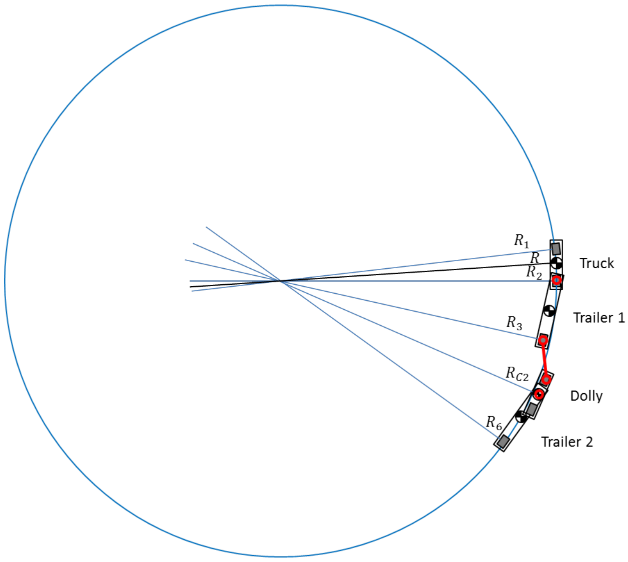

Figure 2.2: *Sketch overview of a concept 1 vehicle*

"The most basic intuitive relation between the wheels steering angles is probably that all wheels rotation axes always intersect in one point. This is called Ackermann geometry" [7]. Before the calculations starts, some assumptions have to be made:

- The wheels or couple points are the limitations of the vehicle sizes
- Ackermann steering is used
- The numbered radii $R_1, ...R_6$ are perpendicular to the tires

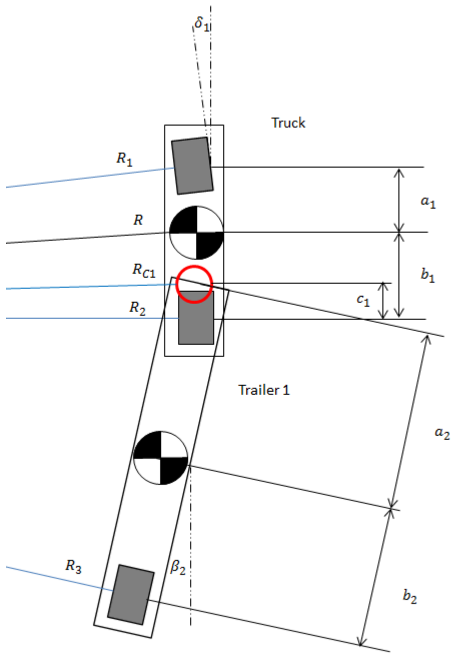

Figure 2.3: *Detailed sketch of truck and trailer 1*

The center of gravity of the truck is the main distance and the given radius from the center point.

$$R_2 = \sqrt{R^2 - b_1^2}$$
$$\delta_1 = \arctan(\frac{a_1 + b_1}{R_2})$$
$$R_1 = \frac{R_2}{\cos(\delta_1)}$$
$$R_{C1} = \sqrt{R_2^2 + c_1^2}$$
$$R_3 = \sqrt{R_{C1}^2 - (a_2 + b_2)^2}$$
$$\beta_2 = \arccos(\frac{R_3}{R_{C1}})$$

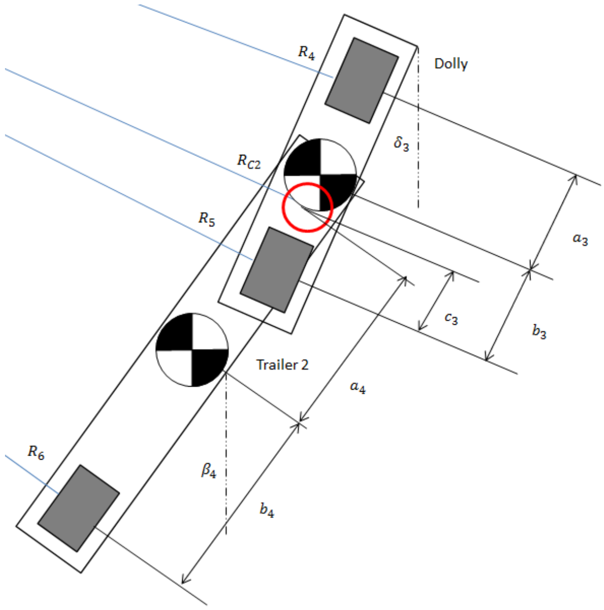

Figure 2.4: *Detailed sketch of dolly and trailer 2*

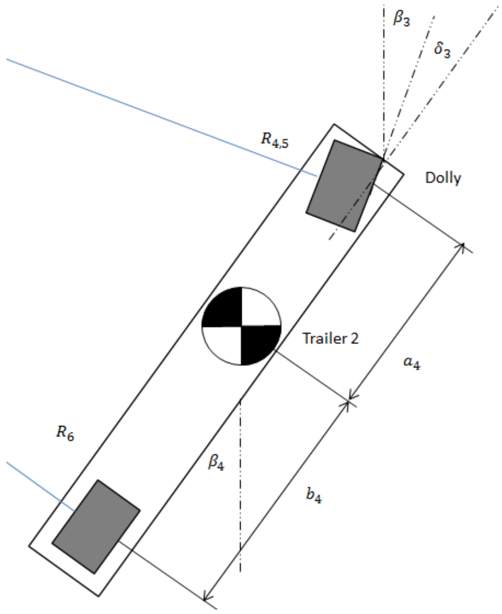

Figure 2.5: *Simplified sketch of dolly and trailer 2*

Due to the track steering of the dolly should be $R_4 \approx R_5 \approx R_{C2}$ and one can simplify the sketch (see Figure 2.5).

Because R_1 is the largest radius, the $R_{4,5}$ should be equal to R_1

$$R_{4,5} = R_1$$
$$R_6 = \sqrt{R_{4,5}^2 - (a_4 + b_4)^2}$$
$$\delta_3 = \arctan(\frac{a_4 + b_4}{R_6})$$
$$\beta_3 \approx \beta_2$$
$$\beta_4 = \beta_3 + \delta_3$$

Now one can try the calculation with some numbers:

Radius:	$R = 100m$		
Truck:	$a_1 = 1m,$	$b_1 = 3m,$	$c_1 = 0.5m$
Trailer 1 und 2:	$a_2 = a_4 = 4m,$	$b_2 = b_4 = 4m$	

And one gets:

truck+trailer 1:	$R_1 = 100.0350m$	$R_2 = 99.9550m$	$R_3 = 99.6356m$
	$R_{C1} = 99.9563m$	$\delta_1 = 0.0400 = 2.2916°$	$\beta_2 = 0.0801 = 4.5906°$
dolly+trailer 2:	$R_{4,5} = 100.0350m$	$R_6 = 99.7146m$	$\delta_3 = 0.0801 = 4.5870°$
	$\beta_3 = 0.0801 = 4.5906°$	$\beta_4 = 0.1602 = 9.1775°$	

The off tracking distance from truck and trailer 1 is $R_1 - R_3 = 0.3994$ m and from the dolly with the trailer 2 $R_{4,5} - R_6 = 0.3204$ m. So it is proved, that the full combination of road train is not worse than a normal truck with one trailer.

2.2 Concept 1

The evolution of this concept based on some wishes of the maneuverability.

2.2.1 Steering

It is desirable, that the new model gets propulsion and is steerable until 90 degree. Since this is not feasible with normal steering modes of cars and trucks, some other possibilities have to be looked for.

There are two steering modes, that are used for construction site vehicles:

- Articulated steering (see figure 2.6)

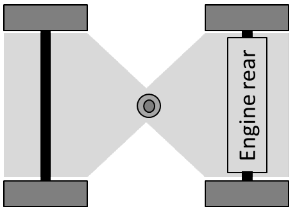

Figure 2.6: *Simplified representation of an articulated steering*

  - Advantage: The maneuverability is very good and the underbody is robust due keep off the steering mechanism of the front or rear axle.
  - Disadvantage: The vehicle has to consist of several parts. All hydraulic pipe lines, electrical wires and control cables have to be flexible and leaded through the articulated joint. Consequently there is large material stress at this point.

- Tracked steering with wheels (see figure 2.7)

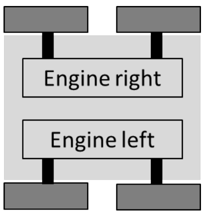

Figure 2.7: *Simplified representation of a tracked steering*

  - Advantage: The steerability is over 90 degree and it is possible to rotate on one position.
  - Disadvantage: The realization is commonly with brake bands, where high friction and high wear is included or with a cross-drive steering transmission, which is more expensive.

In both proposals the joining point, between the drawbar and the unsprung body, and the joining point, between the unsprung mass and the coupler, could be coinciding, which is easier to control. Due to the improved benefits of the track steering, the second steering possibility is used in the further.

2.2.2 Concept presentation

This concept (see figure 2.8) based on tracked steering, which is presented in the previous chapter. The most important advantage is the rotating on a fix position. Furthermore twin wheels can be used instead of single wheels. So the dolly could support a higher normal force.

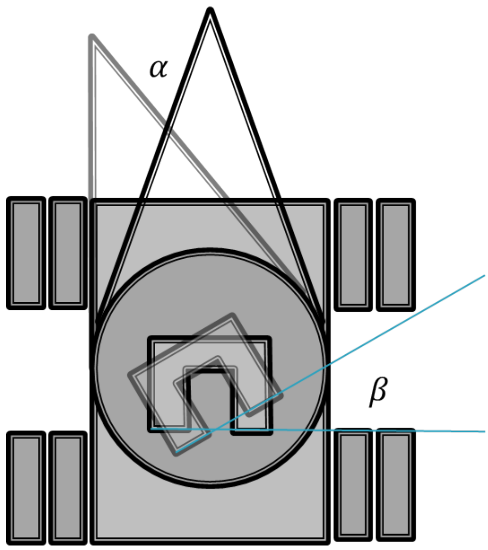

Figure 2.8: *Sketch of the concept 1*

On the top of the dolly is located a turntable for the trailer coupling between the previous trailer and the dolly. This represents one degree of freedom. This construction offers a further degree of freedom: The mounting point between the dolly and the second trailer.
This is an advantage on one side, because the dolly is able to drive a little bit next to the previous trailer (good for small arcs), but on the other side it is a disadvantage, because it is one more degree of freedom, which has to be controlled.
Thus between two trailers are 3 degrees of freedom:

- One in the rotation around the z-axis between the previous trailer and the connection point to the dolly,
- one in the rotation around the z-axis with the turntable on the top of the dolly and
- one in the rotation around the z-axis in the mounting point of the following trailer with the dolly.

With the possibility to "steer" with 90 degrees, it is possible to drive around really small arcs. This will be presented in the chapter 2.4.
Furthermore the practical implementation in the scaled model is much easier. Two motors are used for accelerate the left and the right side separately and the servo is dropped.

2.3 Concept 2

The idea of this concept (see figure 2.9) is more conservative. It is a development of the normal dollies today, because two axles are conventional steered. This concept has two degrees of freedom, that has to be measured: On one side the coupling point between the previous trailer and the dolly and on the other side the mounting point between the dolly and the following trailer.

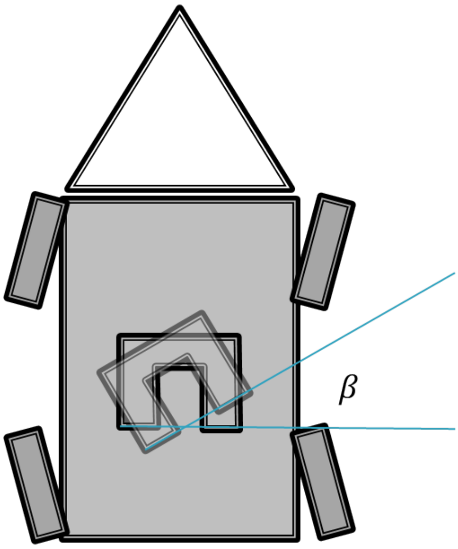

Figure 2.9: *Sketch of the concept 2*

The biggest advantage of this kind of model is, the Ackermann steering can be used. Which means, all the normal intersect at one point (shown in figure 2.10), so that the tire wear is minimal.

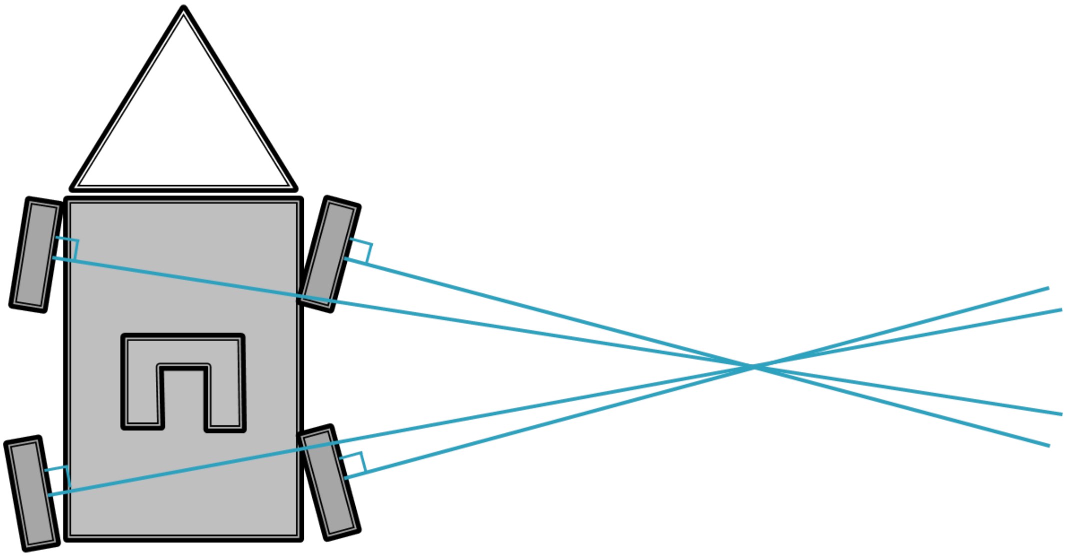

Figure 2.10: *Explanation of Ackermann steering*

Due to the steered axle it is not possible to use twin wheels, because the tire would be more abraded. Furthermore the steering angle is limited, so more turns for shunting are needed. In addition the practical implementation is more difficult, because the propulsion has to be in a steered axle.
So for the scaled dolly one engine and two servos would be used (one for the front and one for the rear side).

2.4 Comparison in common maneuvers

In this chapter two common maneuvers will be compared. On one side the double-lane-change, for example on a highway, and on the other side the smallest arc, which represents a shunting maneuver.

2.4.1 Double-lane-change

This maneuver indicates to move the full road train parallel to the side.

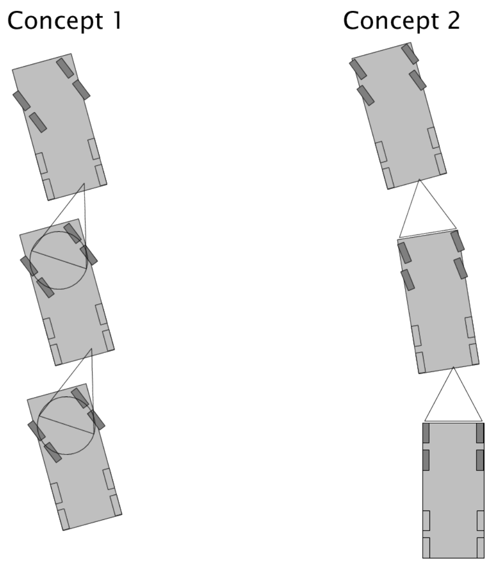

Figure 2.11: *Sketch of a double-lane-change*

This can be done in concept 1 by moving all units together to the side, like the picture above (see figure 2.11) shows. In the concept 2 the further degree of freedom is missing. So the trailers will follow more the previous trailer.

2.4.2 Smallest arc

Here should be shown how large is the improvement of maneuverability during a shunting maneuver.

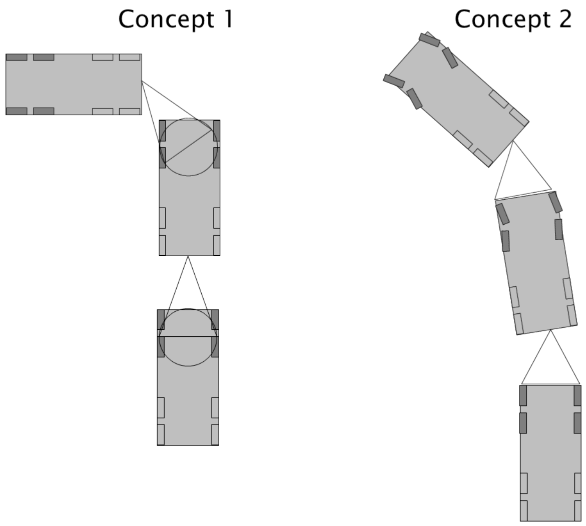

Figure 2.12: *Sketch of smallest arc*

In the concept 1 the dolly is able to go forward until the edge is almost reached and is turning as latest as possible. So really small arcs are possible to come about.
The concept 2 has a larger turning circle. Due to the missing degree of freedom the dolly has to follow the previous trailer earlier.

2.5 Decision

The previous chapters showed the advantages and disadvantages of the two concepts. Now a decision has to be made.

	Concept 1	Concept 2
Steering method	tracked	conventional
Steering angle	$\pm$ 90°(better)	$\pm$ 15°(worse)
Amount of engines	2 (worse)	1 (better)
Amount of servos	0 (better)	2 (worse)
Degrees of freedom	3	2
Normal load force	better	worse
Tire wear	worse	better
practical implementation	better	worse
maneuverability	better	worse

Table 2.1: Direct comparison of the two concepts

With the result of table 2.1, the concept 1 is selected to continue.

3 Electric

3.1 Circuit diagram

In the following figure 3.1, the circuit diagram is shown.

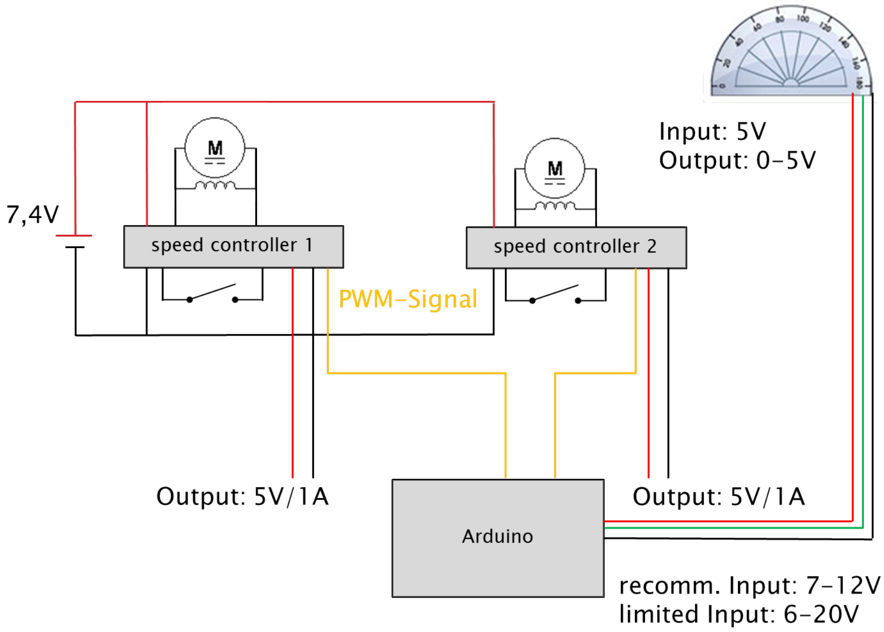

Figure 3.1: *Circuit diagram*

The source for both engines and the related controller is the battery (see chapter 3.6) with 7.4 V. The controllers have a special BEC (=Battery Eliminator Circuit), so an extra battery for the receiver is not needed in the normal case. This circuits have an output of 5 V and at maximum 1 A.

The "Arduino is an open-source electronics platform based on easy-to-use hardware and software. It's intended for anyone making interactive projects." [8] (see also chapter 3.4). It needs an input of at least 6 V, so it is not possible to use this source without modifying the arduino. The fact, that the arduino is running only with the USB cable and each USB device has an output voltag of 5.00 ± 0.25 V, leads to the result, that it should be possible to run the arduino with 5 V in a modified case.

It is also not possible to use the main battery, because the motors are able to send overload peaks in the voltage, which could destroy the arduino. At the moment the USB cable is needed to receive the data from the server, because the arduino uno has no WLan interface on board. So the USB cable supplies the power for the arduino.

Both controllers need a PWM (=pulse-width modulation) signal, which the arduino supplies only on the outputs: 3, 5, 6, 9, 10 and 11. The angle sensor is supplied by the output of the arduino with 5 V. The return signal is an analog one and between 0 and 5 V.

3.2 Electric motor

For the decision of the new engine, some parameters of the truck are needed:

Tire diameter: 0,075 m
Tire circumference: 0,2356 m

The truck has an engine and a gearbox with three gears:

	1.gear	2.gear	3.gear	new motor
speed in km/h	6,3	11,6	19,3	20
turns in 1/min	446	821	1365	1415
gear ratio	32,49	17,76	10,66	-
motor rounds 1/min	14.479	14.573	14.553	-

Table 3.1: Performance table for the old engine

In the last column are the values for the searched motor. The last two rows are only for interest. It is shown that the limit of the engine is around 14.500 rounds per minute. Due to the reason, that the dolly should be only a prototype and the components shouldn't be expensive, the limit of the supplier is Conrad and ELFA.

Supplier	Conrad	Conrad	Conrad	ELFA	should be
Name	Motraxx	MFA	Absima	-	-
Rpm with load	4040	1550	5300	-	1400
Power [W]	0.07	7.5	80	-	-
Size [mm]	12*10*20	39*80	35*75	-	-
Gearbox	01:01	06:01	01:01	-	-
Voltage span	2.5	5-15V	7.2-7.4	-	-

Table 3.2: Comparison of different engines

Figure 3.2: *Motraxx engine [9]*

Figure 3.3: *MFA engine [9]*

Figure 3.4: *Absima 540 with 80 turns [9]*

The main advantage of the first engine is the size. It is quite small, due to leave off the gear box and it can be used as a wheel hub engine. In the case of wheel hub engine, the torque would be multiplied by four and would be 0,00072 Nm.
In comparison the second engine is a little bit larger but is exactly in the rpm range of the searched motor. The torque of this engine (0,075 Nm) should be enough for two wheels respectively one side. That was the first idea. After building and testing the model, the third was ordered, because the power of the second motor was not strong enough. The power of the new motor is 10 times higher than the MFA motor.
The Swedish company ELFA offers a wide selection of engines, but almost all of them with the wrong direction of gear box. So there is no fitting engine at the moment[10].

3.3 Motor controller

The electronic direction controller is selected of the program of Conrad.

Type	Truck WP60 JR	Truck WP90 JR
Item no.	226994	226996
BEC voltage	5 V/DC	5 V/DC
BEC constant current	1 A	1 A
Functions	Forwards, brake, reverse	Forwards, brake, reverse
Dimensions (L x W x H)	approx. 41 x 35 x 16 mm	approx. 41 x 35 x 16 mm
Max. continuous connection output	432 W (max. 30 s at +25 °C)	648 W (max. 30 s at +25 °C)

Table 3.3: Comparison of different electronic direction controller [9]

Figure 3.5: *Electronic direction controller [9]*

BEC means the battery eliminator circuit. That is a special kind of circuit to use a constant voltage from the battery for example some smaller servos. Both controller are almost the same. The only different is the output power. Due to power of the engine of 160 W the smaller controller should be enough.

3.4 Arduino

For the first prototype the Arduino Uno will be used, because it is the same controller like in the truck of the road train.

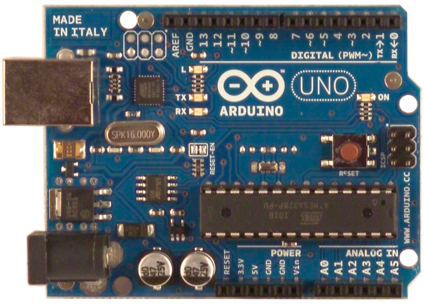

Figure 3.6: *Arduino Uno front side [8]*

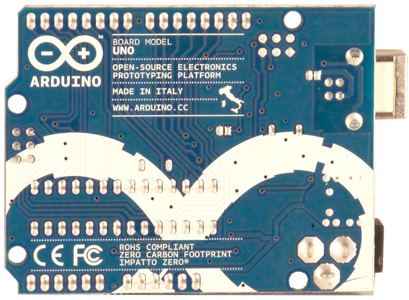

Figure 3.7: *Arduino Uno back side [8]*

Later the decision to design a custom arduino could be made, because for the dolly are only the following functions needed:

- One analog input for the angle / position sensor
- Two outputs to the controller of the motors
- The USB interface or WLAN interface

3.5 Angle / position sensor

Because it is difficult to get the exact position of the dolly with the visual positioning system (see chapter 5.1.1), an angle sensor has to be used.

Type	Kübler Compact Incremental Encoders	Cherry Angle / Position Sensor
Item no.	19813	276135
Resolution [per turn]	100	analog
Measuring range	360 degree	180 degree
Size (L x W x H)	37*37*28	50*49*38
Connector	RS422	analog (0-5V)

Table 3.4: Comparison of different angle sensors [9]

Figure 3.8: *Kuebler sensor [9]*

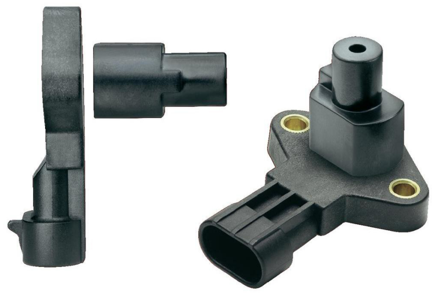

Figure 3.9: *Cherry sensor [9]*

The first sensor is a professional sensor for industrial use. It is robust and insensitive to disturbances.
The second one is originally for measurements of the throttle in internal combustion engines. Due to the analog output, the latter sensor is much easier to handle. The output will vary from 0 to 5 V and can be read directly from the arduino board. Inside the value will be transferred to digital values between 0 and 1023.

3.6 Battery

There is a huge market for the different kind of batteries. However, due to budget constraints the batteries which are already availible in the lab will be used.

Figure 3.10: *Battery 7.2 V 3500 mAh*

The figure 3.10 shows the first battery, which was used. Due to the change of the engine in the end (see chapter 3.2) and consequently with the new requirements the battery has to be changed.

Figure 3.11: *Battery 7.4 V 3300 mAh*

The new engine needs the higher voltage of 7.4 V, so the battery in figure 3.11 is used.

Figure 3.12: *Battery 14.8 V 3300 mAh*

For some smaller tests the battery in figure 3.12 was used to get a higher torque in the starting moment of the engine. Due to safety reasons the battery was replaced back to battery in figure 3.11.

4 Mechanic

In this chapter, all steps about the technical mechanic parts should be covered. In the beginning some drafts are shown and the chapter ends with concrete proposals for the project.

4.1 Optimization of the position of the components

This task is one of the most difficult ones in the real vehicle development. The final product should be minimal in size and each component should be accessible.

4.1.1 Optimization of the position first draft

The idea behind this draft is to bring all larger and fix components closer to the ground for a low center of gravity.

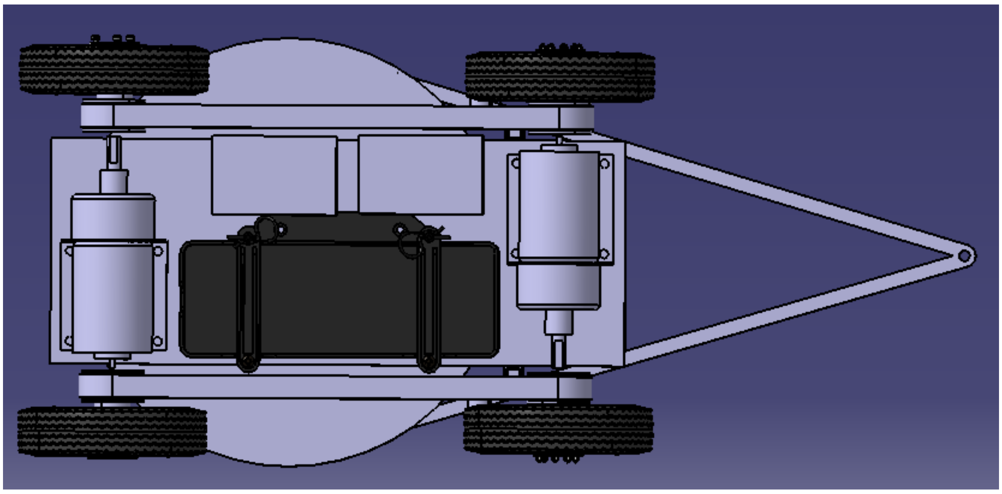

Figure 4.1: *Optimization of the position draft 1 / Bottom view dolly*

On the picture above (see figure 4.1) the sketch of the draft is shown. The two engines are at the outward position under the dolly. At the inner position the half of the space is reserved for the main battery (black plastic holder). The other half of space is prepared for one controller of each engine.

In the longitudinal direction at the outward position beside the wheels are the v-belts to transfer the torque from one to the other axle. The engines themselves are aligned with the direction of one wheel hub. One in the right front wheel and one in the left rear wheel.

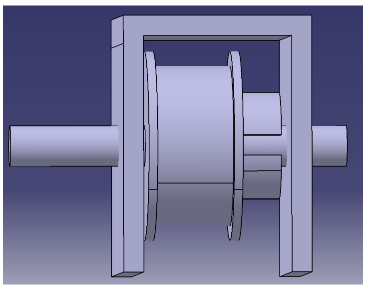

Figure 4.2: *Mounting point for the other wheel / Front view mounting point*

The other both wheels could be fixed similar to a construction like in the figure 4.4. Due to doubts in the stability the second draft was developed.

4.1.2 Optimization of the position second draft

The idea behind this draft is construct stable axles at first. The axle for the right and the left side is the same one. Therefore a new principle of fixing the wheels on that axle has to be used.

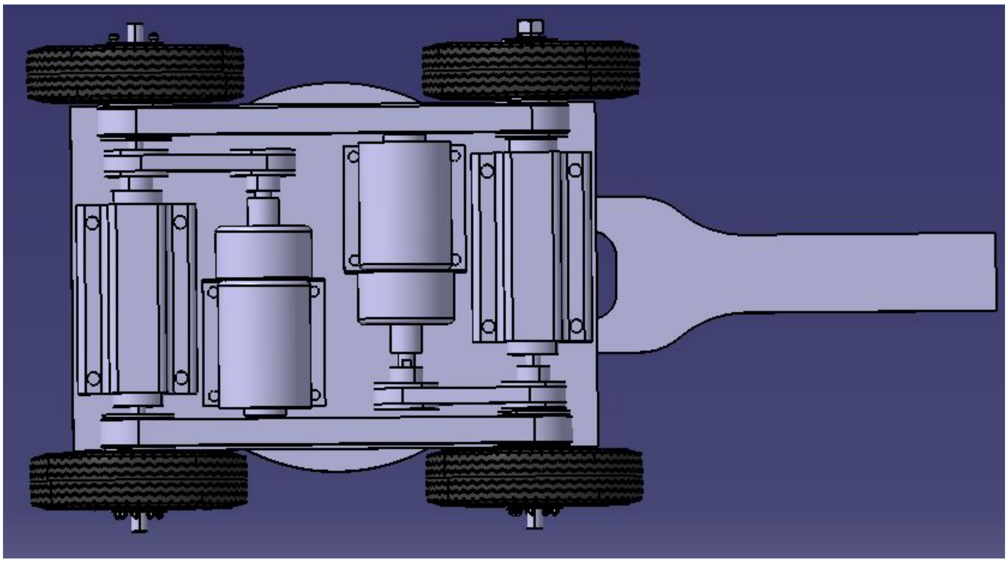

Figure 4.3: *Optimization of the position draft 2 / Bottom view dolly*

The normal case is to screw both cogwheels onto the axle. Due to the different speeds and / or direction of the two wheels, only one cogwheel is allowed to be screwed. The other one has to be free rotatable. The wheels are connected to the cogwheels with two special adapters. They are described in the chapter 4.2.3 and 4.2.4.

For stability reasons and little experiences with 3D plastic printing (described in chapter 4.2.1), the inner plastic part is overdimensioned. For less friction the outer bearings are out of brass. They are produced on a lathe.

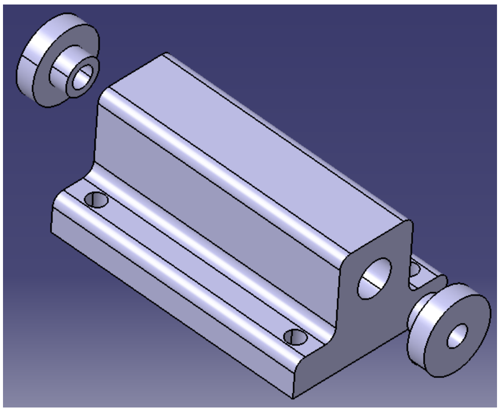

Figure 4.4: *Mounting point for the axle / Assembly drawing*

Due to the priority of stability and less priority of space-saving, the second draft is selected for the production. The battery as well as all other components have to be moved up and are positioned now on the trailer of the dolly.

4.2 Parts manufacturing

This chapter is about the production of the parts. The table below (see table 4.1) gives a short overview about the main components, which have to be produced.

Count	Name	Metal	Plastic
2	Axis	x	
2	Supporter Block		x
4	Bearing	x	
1	Mounting Plate	x	
2	Free Adapter	x	x
2	Fix Adapter	x	x
1	Turntable Inner Circle		x
1	Turntable Outer Circle		x
1	Turntable Upper Circle		x
1	Turntable Magnet holder		x
1	Turntable Linkage Bar		x

Table 4.1: Parts manufacturing

For working with the metal parts, the following devices were mainly used: a lathe, a milling and a drilling machine, different kind of thread cutters, some files and a bucksaw. For the plastic parts, the 3D printer was used (see chapter 4.2.1).

4.2.1 3D plastic parts printing

The technology of 3D printing is a quite new technology. It is being developed as a rapid prototyping process since the beginning of the century. Since 2010 this process is moving more and more for private usage. So everybody could create virtual 3D models and is able to print them out directly.
"3D printers make things by building them up, a layer at a time, from a particular material, rather than removing it by cutting, drilling or machining—which is why the process is also called additive manufacturing." [11]

Figure 4.5: *MakerBot Replicator 2X [12]*

But it is more like a full time hobby, because there are so many factors, which are varying from project to project. That can be the specification of the raw material, the temperatures, the technology to harden or the tolerances or distortion during the cooling down period.
In this project the "MakerBot Replicator 2X" (like the figure 4.5 above) was used. The hardware limitation of maximum 150 mm width per part is the reason for the selected diameter of the turntable.

4.2.2 Engineering of the turntable

The turntable is the most important part of the dolly. It represents the degree of freedom between the linkage bar to the previous trailer and the dolly. Only with that part it is possible, that the dolly is able to turn on one position without moving any other vehicle.

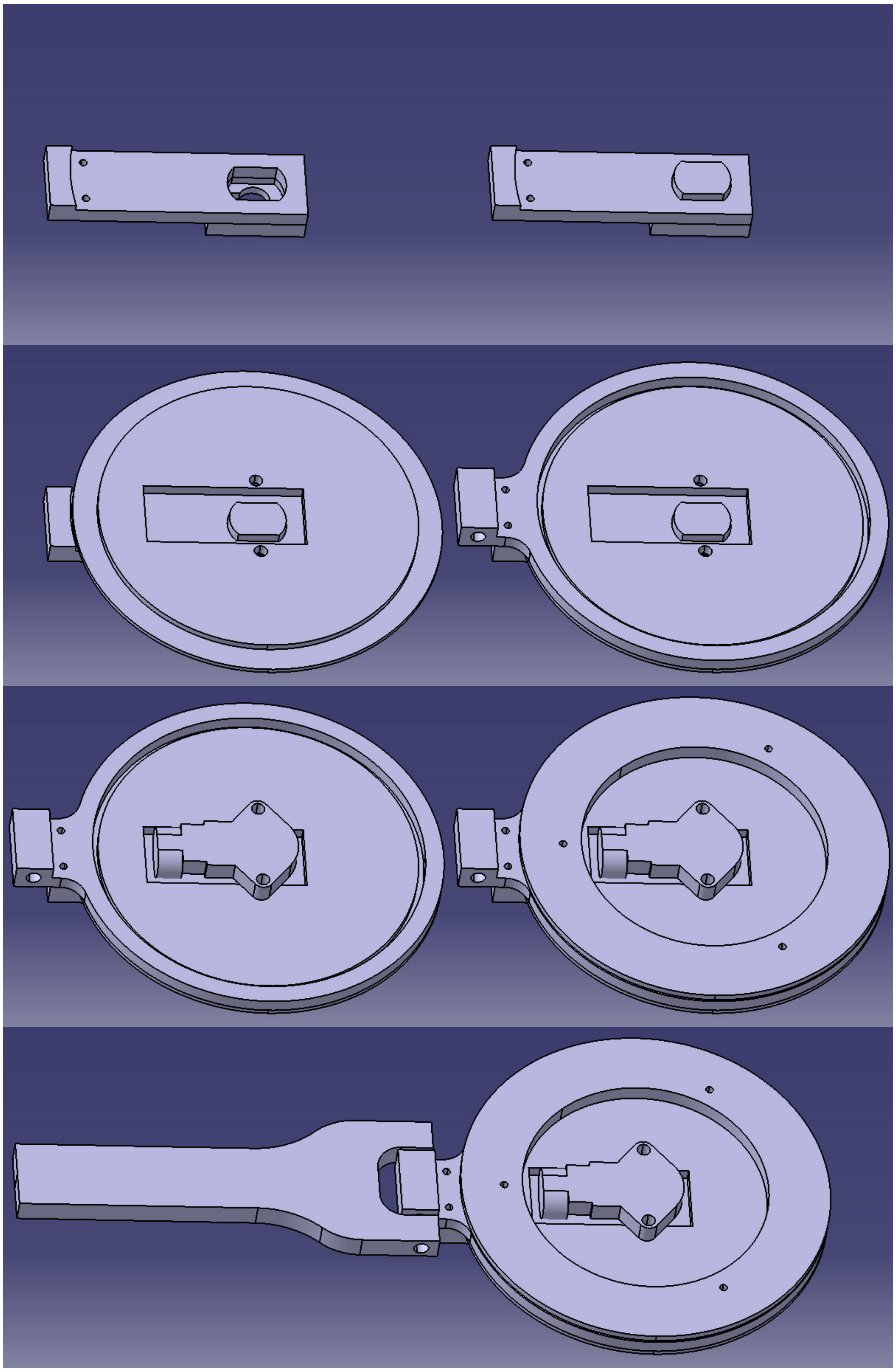

Figure 4.6: *Assembling of the turntable*

The turntable consists of 10 parts, which are almost all printed in plastic. In step 2 of the picture above (see figure 4.6), the magnet of the rotating sensor is plugged in and in step 5 the sensor itself is mounted. These both parts are buy parts all others are selfmade.

4.2.3 Engineering of the free adapter

The free adapter allows the wheel to rotate in another direction than the axle.

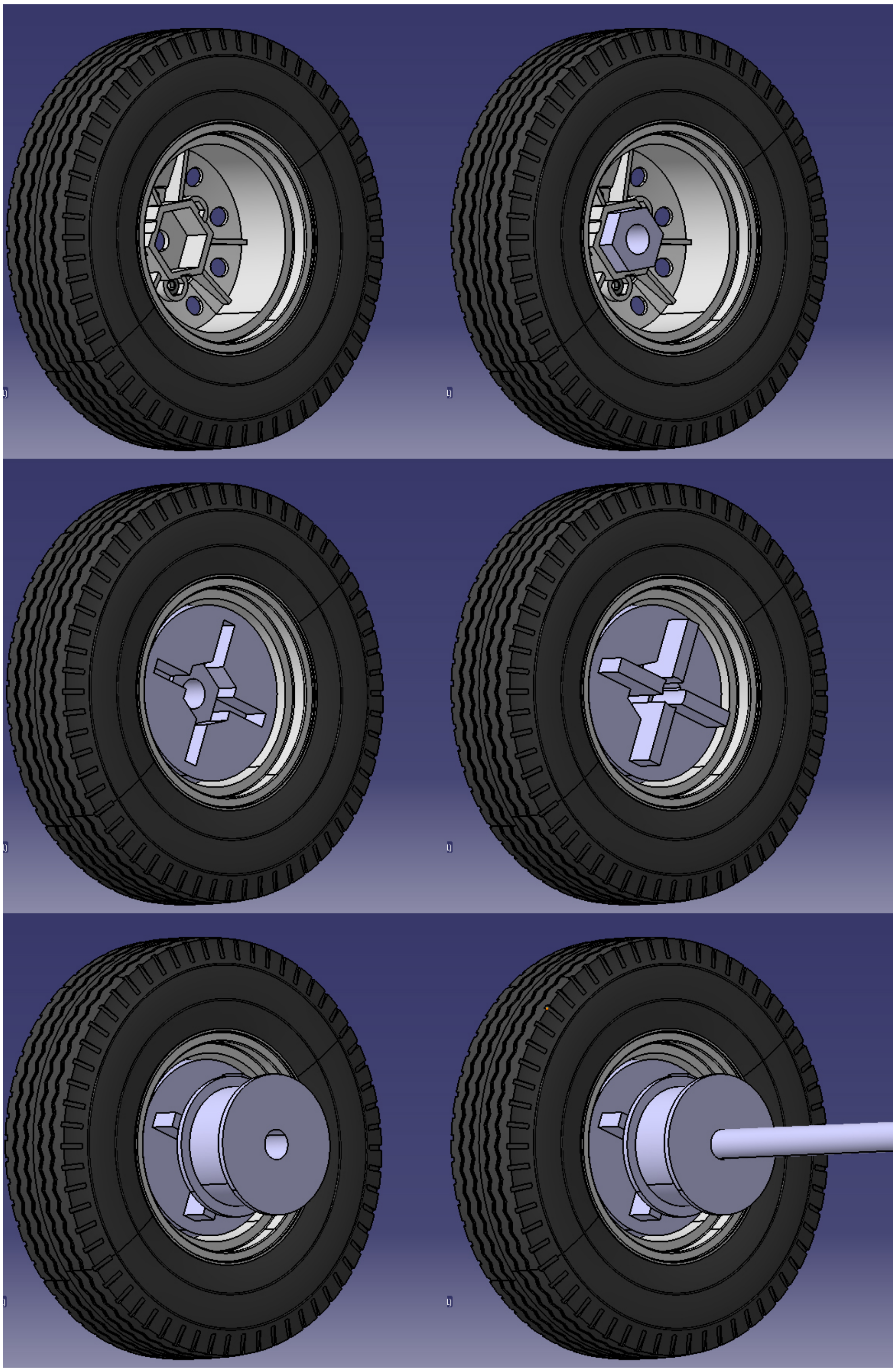

Figure 4.7: *Assembling of the free adapter*

The wheel and the cogwheel are buy parts. In step 2 of the picture above (see figure 4.7) a rigid connection to the wheel is constructed. In step 4 aluminum plates are inserted for the connection to the milled cogwheel. The screw of the cogwheel is removed for rotating free on the axle.

4.2.4 Engineering of the fix adapter

The fix adapter is similar to the free adapter, but with an fix connection to the axle.

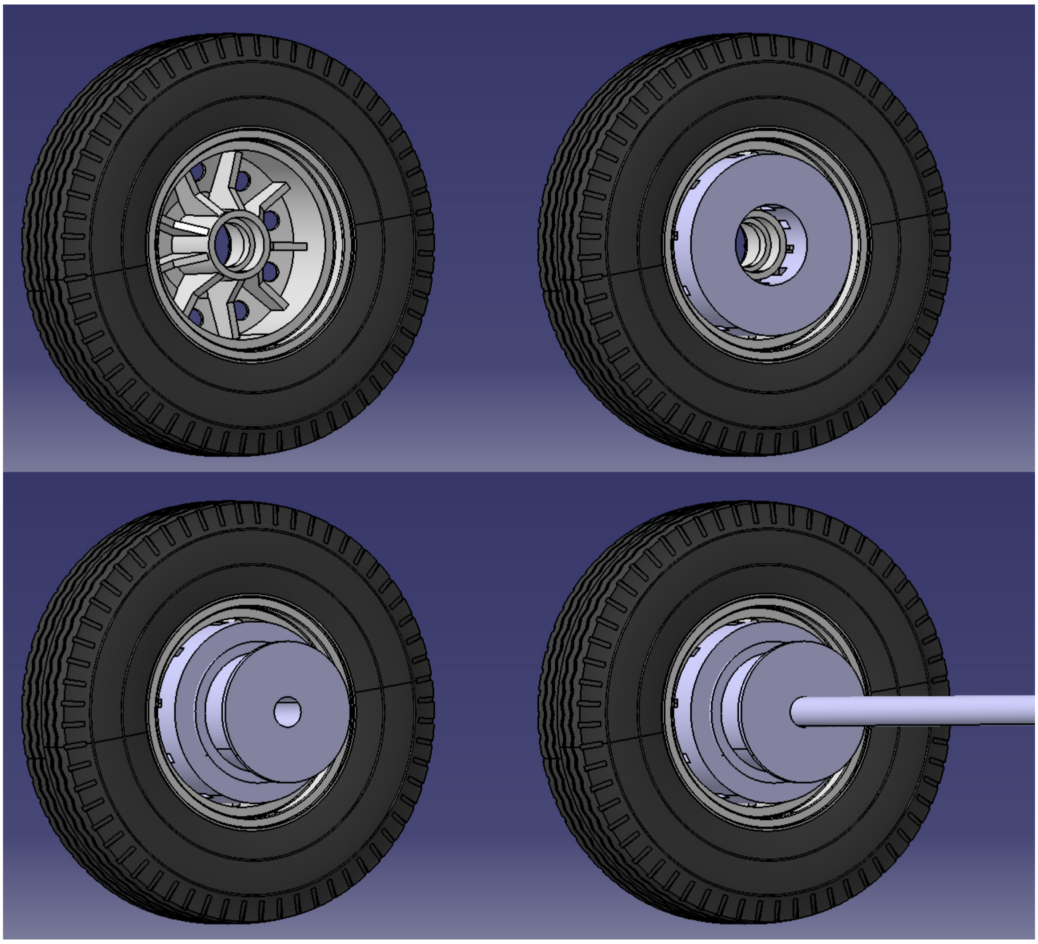

Figure 4.8: *Assembling of the fix adapter*

In step 2 of the picture above (see figure 4.8) a negative body of the wheel spokes is printed and inserted. The grub screw of the cogwheel is tightened in this case.

4.3 Economic aspects for the coupler and the wheels

Due to reason to keep the coupler and the wheels, the spare parts has to be ordered.
Because it is not possible to order really every spare part alone, complete packages has to be ordered, which are shown in the following table 4.2.

Package name	Package number	Price in €
E	T0005471	21,49
ME	T9415147	35,99
BA	T9465557	11,12
BB	T9465558	9,19
MA15	T50590	3,09
MD	T9415146	80,58
Q	T0115272	32,99

Table 4.2: Spare parts to order [13]

The sum of the costs of all spare parts, which would be ordered, is around 195 €. The costs for a complete new truck are around 240 €. So the decision to buy a complete new truck is made.

5 Controlling

At first a short overview about the complete controlling system is given. Afterwards there are the chapters of implementation of a simple controller and an outview for future controller projects.

5.1 Controlling System

At first the system (see figure 5.1) seems very complex, but every part of it is required.

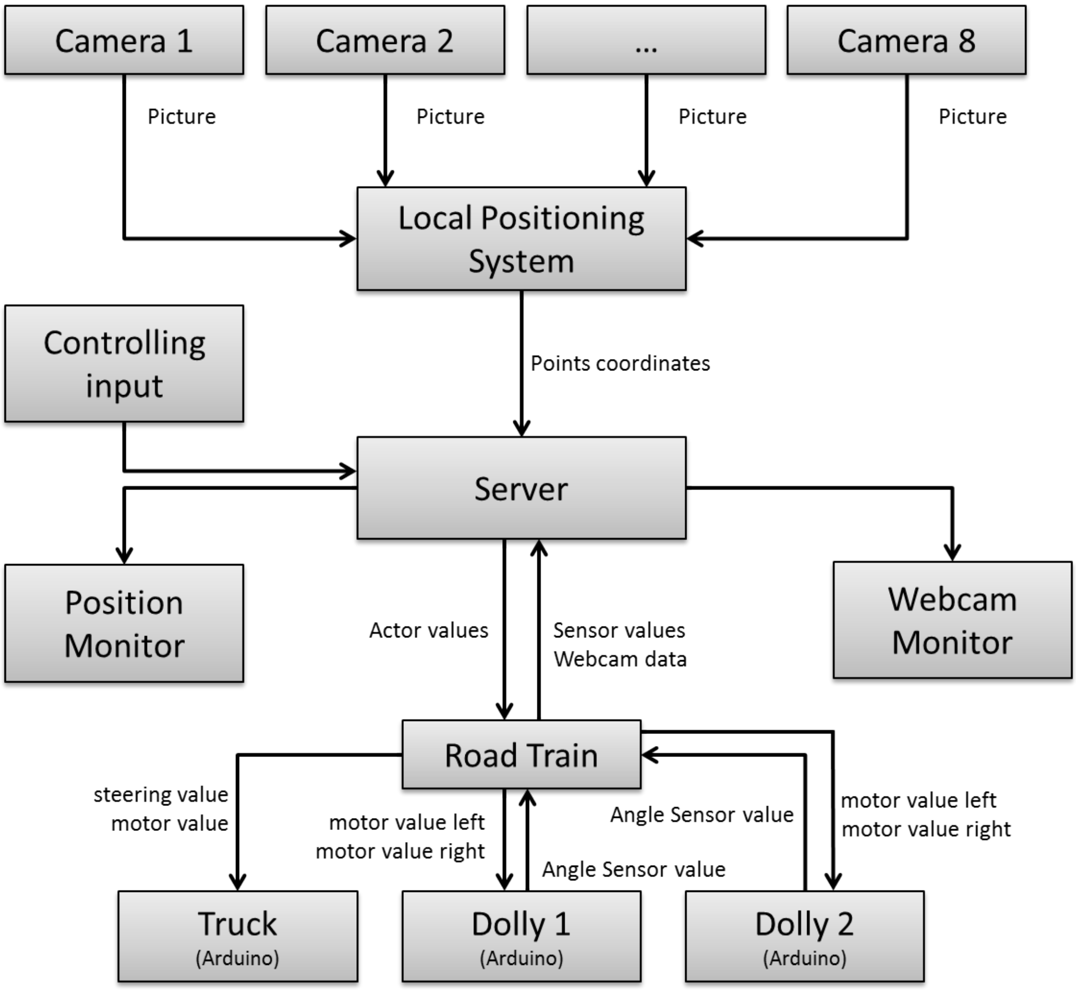

Figure 5.1: *Controlling System*

5.1.1 Local Positioning System (LPS)

In the beginning there are eight infrared cameras of the type "ProReflex" (see figure 5.2), which are almost equal distributed to detect the whole test area. This "ProReflex camera uses short but quite strong infrared flashes to illuminate the markers" [14]

Figure 5.2: *ProReflex Camera*

These markers are on the truck and shown in the pictures below (see figure 5.10). The markers are like small reflectors for the infrared light. This can be well seen in the image below (see figure 5.4).

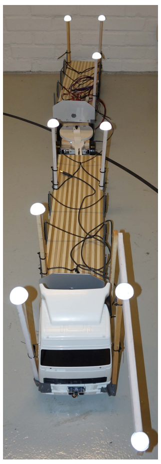

Figure 5.3: *LPS: roadtrain*

Figure 5.4: *LPS: reflector*

For each vehicle three markers have to be used for the exact detecting in a 3D room. So the position and heading of each vehicle could be calculated.

In the next picture (see figure 5.5) the received images of the cameras in the LPS computer are shown.

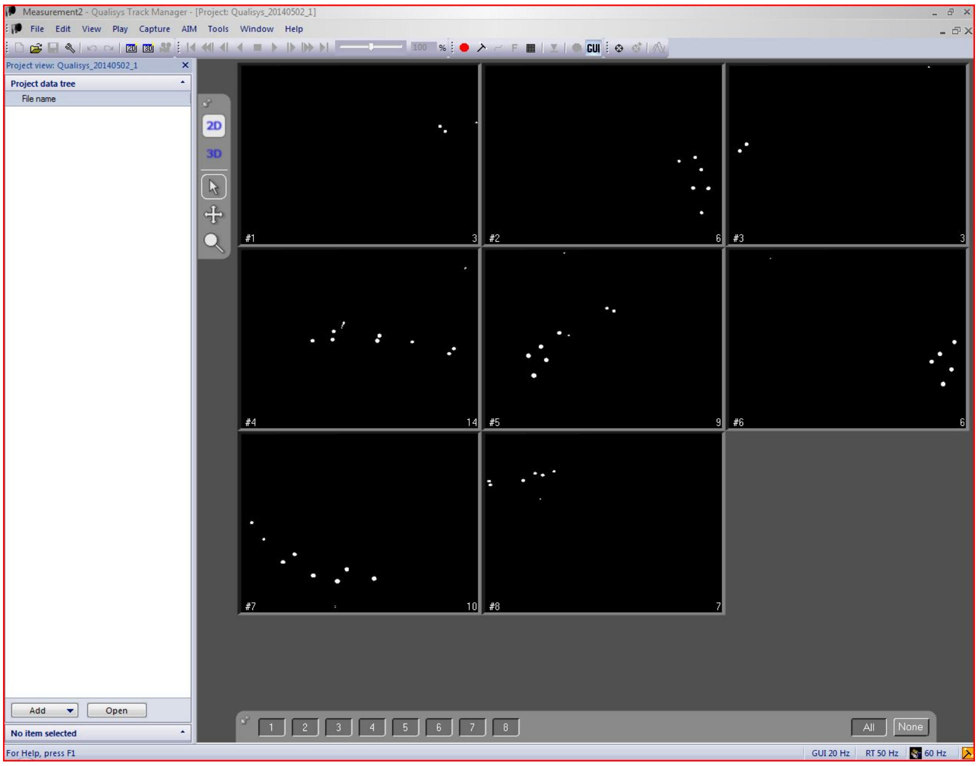

Figure 5.5: *QualisysTrackManager 2D View*

These images are processed in the LPS to single coordinates of the different markers. This coordinates are drawn in a 3D simulation, which is shown in the picture below (see figure 5.6).

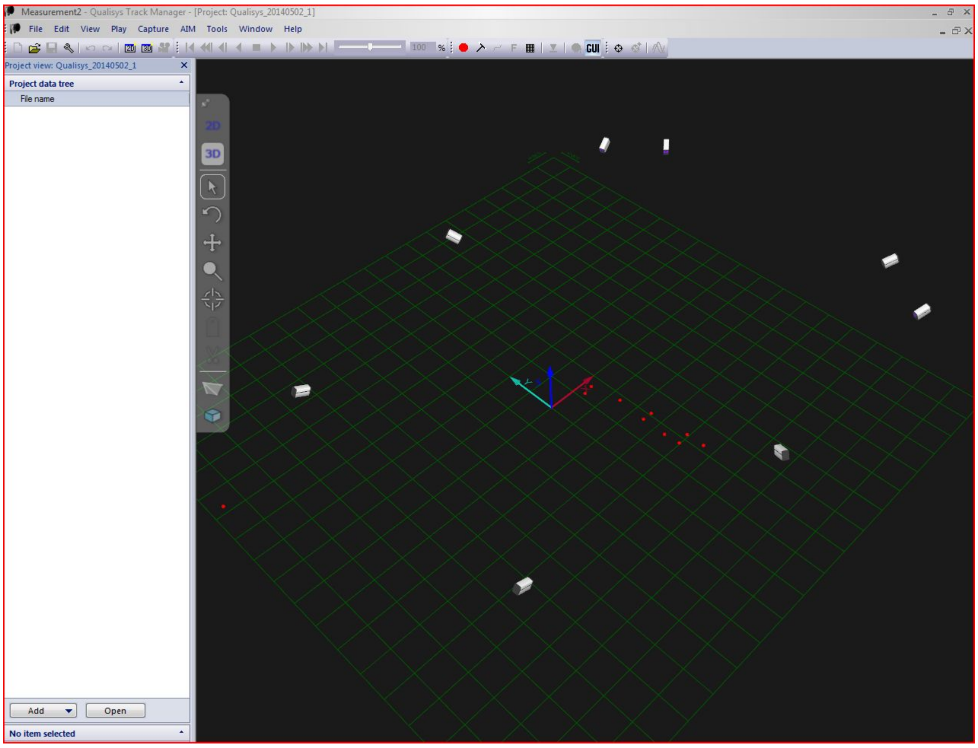

Figure 5.6: *QualisysTrackManager 3D View*

These marker coordinates are sent to a separate computer, the server.

5.1.2 Server

The server is the communication interface for almost every action. The points coordinates are sent to it and also the controlling values (see chapter 5.1.4) and the data from the road train. The server collects, processes and sends all the data again to each communication partner.

Object detection

Each object is marked with 3 points in a perpendicular triangle. The ratio of adjacent side and opposite side of the objects has to be different. So the transferred points of the Local Positioning System could be something like the picture below (see figure 5.7).

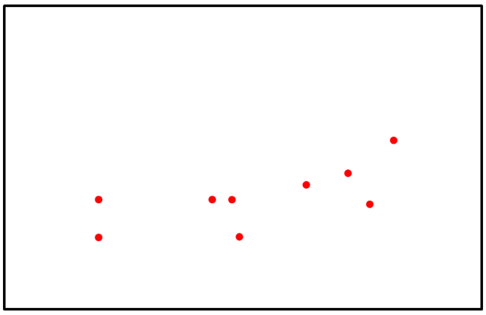

Figure 5.7: *Object detection: transferred Points*

In a matrix all distances between all points will be calculated. In a second matrix all angles between all possible lines will be calculated. If one angle is around 90 degree, the ratio between the adjacent side and opposite side will be computed. Is the ratio in the database of objects, one object is identified. This is shown in the figure below (see figure 5.8).

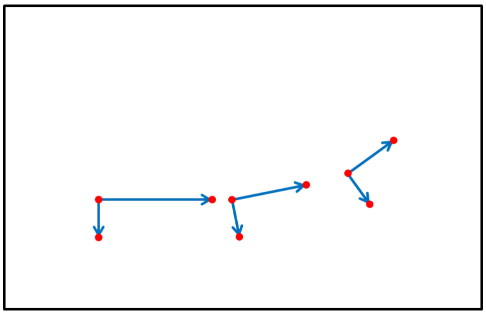

Figure 5.8: *Object detection: transferred Points*

After finding all objects, the offset has to be inserted. This offset exists, because the triangle points are not always in the edges of the objects.

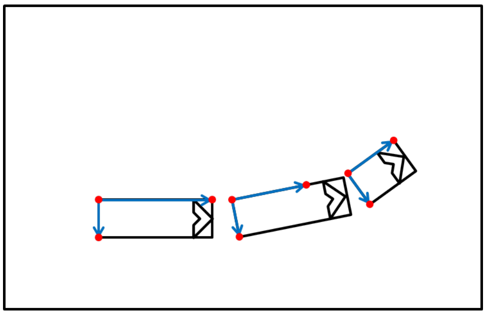

Figure 5.9: *Object detection: transferred Points*

This algorithm seems easy in the 2D room. In the 3D room, the principle is the same but with some more calculations.

5.1.3 Position Monitor

The calculated positions of the objects are sent to the next program. The monitor routine:

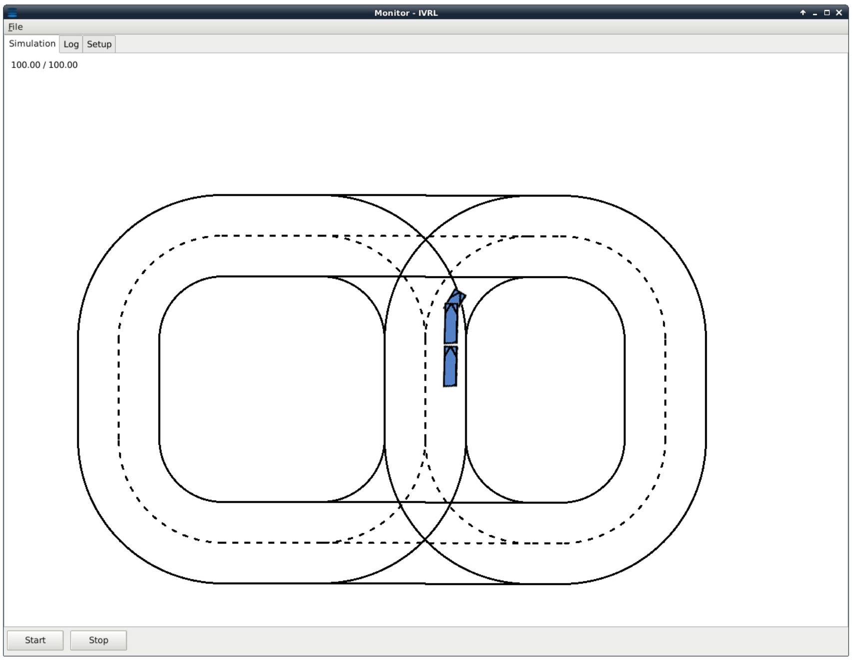

Figure 5.10: *ivrl-monitor*

In the picture above (see figure 5.10) the marked lines in the laboratory are fix drawn. Relative to the lines the actual position of the objects are drawn. The front side of each vehicle is in the direction of the small triangle in the objects.

5.1.4 Controlling input

At the moment the system is an open loop system. Which means, that there is an input, but the output is not checked or is checked manually. In the picture below the manual control input is shown (see figure 5.11).

Figure 5.11: *Hama Racing Wheel Thunder V5 [9]*

There are two pedals and one steering wheel of the company Hama. The values are collected and directly sent to the server.

5.1.5 Road Train

The program of the road train computer splits the incoming data and transfers it to the different arduinos. So only one computer with a WLan interface is needed and for each new dolly one cheaper arduino has to be purchased.

5.2 Synchronization of engines

Before the road train can start. The speed of the engines of the truck and the dolly should be almost equal. Because the system is an open loop system, the "controlling part" is only an estimate in this part. So some preparation has to be done:

At first the truck is running with the values from the neutral value to the fastest forward value and the speed has to be measured and saved.

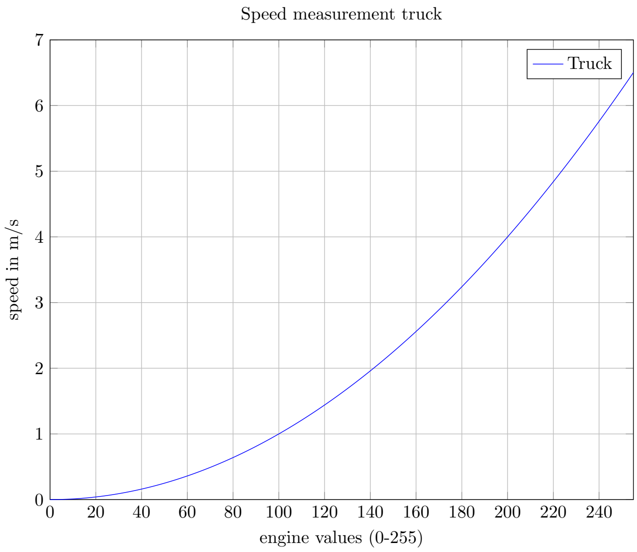

Figure 5.12: *Fictitious values versus speed Truck*

The same procedure has to be done for the next vehicle, the dolly. Afterwards both plots has to be fitted together and rotated around 90°.

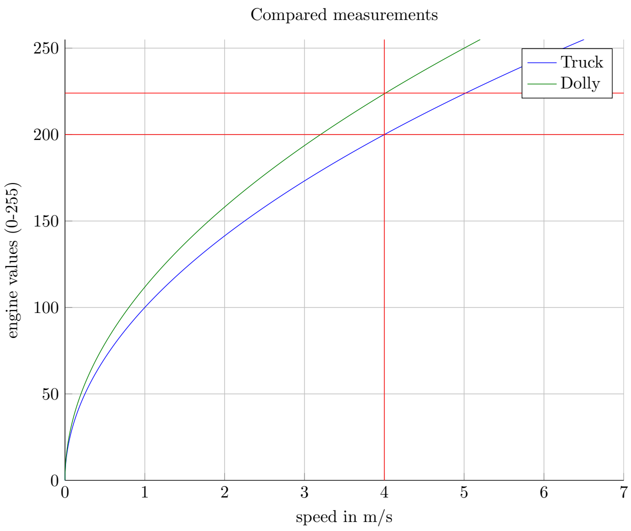

Figure 5.13: *Fictitious required engine value calculation*

The truck engine value is given from the controlling input (see chapter 5.1.4) and can be processed to speed with the picture above (see figure 5.13). The required engine value for the dolly is given now in the same plot.

5.3 Implementing of a simple controller

Due to the building up process of the server, it is not possible to implement a closed loop system and an improvised controller has to be designed. Therefore the input controller (see chapter 5.1.4) gives manual the steering and the speed of the truck. The speed value for the dolly is calculated, like in the chapter before (see chapter 5.2).

$$\begin{aligned} \text{EngineLeft} &= \text{SpeedDolly} + \text{DeltaAngle} * k \\ \text{EngineRight} &= \text{SpeedDolly} - \text{DeltaAngle} * k \\ k &= \text{const} \end{aligned}$$

The DeltaAngle is the input of the angle sensor of the dolly with values between -90°and 90°. So the dolly tries always to go back in the neutral position.

5.4 Outview in future controller projects

If the server is completely built and the closed loop system is working, a full autonomous vehicle model can be implemented. With such an model it would be possible to drive the whole road train backwards via a remote device in slow speeds. This would be perfect for shunting maneuvers. An example maneuver is shown on the picture below (see figure 5.14).

Figure 5.14: *Outview in future controller projects*

6 Conclusion

The following picture (see figure 6.1) shows the complete road train after finishing this project thesis.

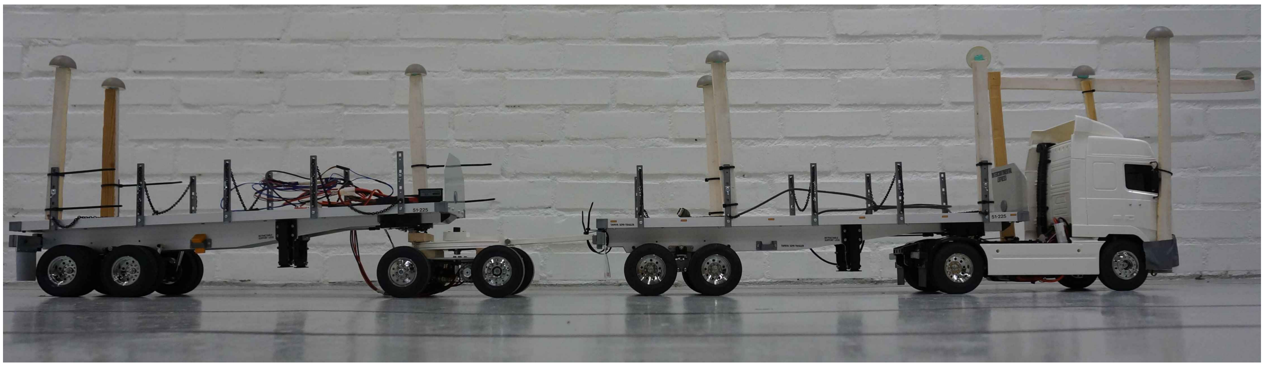

Figure 6.1: *Finished road train side view*

The required tasks of the beginning are fulfilled. The dolly is steerable with a track steering construction (see figure 6.3).

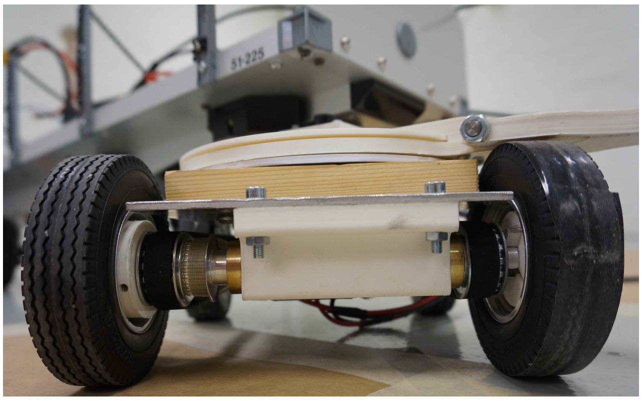

Figure 6.2: *Detailed view of the front axle of the dolly*

It is driven by two electric engines and controllable over the communication interface of the server. The complete road train is in a scale of 1:14 and all parts could be produced in series. The plastic parts could be produced in an injection molding process instead of the plastic 3D printer. Furthermore it is possible to change the trailers, which means the dolly is self-contained system (see figure 6.3). The requirement to combine the two joining points between the drawbar, unsprung mass and coupler is not fulfilled, due to limitations in the height.

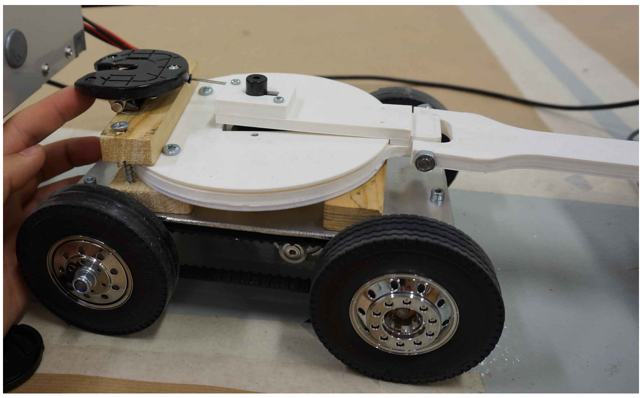

Figure 6.3: *View from above of the finished dolly*

As one further development, it is recommend to replace the current engine with a gearboxed-engine. So the starting torque is much higher than the current one and smaller steps are possible. In addition the lower part of the dolly should be redesigned to decrease the wheelbase. So the rotation on one position would be much easier. However, in conclusion the project was considered successful, since the initial objectives were met. Moreover, a way for many future projects regarding LHVs is prepared.

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