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Development of a low-cost solution for the ball handling mechanism for a football robot
Part of creation of MSL Kickstart Platform

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# Development of a low-cost solution for the ball handling mechanism for a football robot

Part of creation of MSL Kickstart Platform

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# Abstract

RoboCup is an organisation that works to promote robotics and AI research. By creating multiple competitions, it stimulates teams to develop robotic solutions for different applications. The focus of this paper is in the Middle Size League of the RoboCupSoccer. Especially, the part researched is the ball handling mechanism that is currently used in the football robot of Tech United. The solutions for ball handling mechanisms are often expensive and require advanced technologies. This paper describes how to develop a low-cost solution for the ball handling mechanism that can be easily replicated and implemented by teams with limited resources.

In-depth evaluation of the presently used ball handling mechanism revealed the most expensive parts. For these parts new concepts were created, compared with each other and the best were picked. This led to a final design that was detailed to ensure similar performance to the current ball handling mechanism. Where possible, an increase of performance was researched without increasing costs. Finally, it was researched how this new design could be controlled within the current used control design.

It was found that the costs were mainly in the housing and drive mechanism. With the use of sheet metal for the housing and a stepper motor in the drive mechanism, the costs could be reduced significantly.

# Contents

| Symbol | Variable | Unit |
|---|---|---|
| $\vec{\alpha}$ | Angular acceleration | $rad/s^2$ |
| $\eta$ | Efficiency | $-$ |
| $\theta_m$ | Angle of motor placement | $rad$ |
| $\theta_w$ | Rotation of wheel | $degree$ |
| $\mu_k$ | Friction coefficient | $-$ |
| $\tau$ | Torque | $N \cdot m$ |
| $\phi_l$ | Arm angle | $degree$ |
| $\phi_step$ | Step angle | $degree$ |
| $\omega_{actual}$ | Actual angular velocity of wheel | $rad/s$ |
| $\omega_{signal}$ | Signalled angular velocity of wheel | $rad/s$ |
| $c_i$ | Rotational stiffness | $N \cdot m/rad$ |
| $d_{cm}$ | Distance to center of mass | $kg \cdot m^2$ |
| $F$ | Force | $N$ |
| $F_f$ | Friction Force | $N$ |
| $F_{impact}$ | Impact Force | $N$ |
| $F_n$ | Normal Force | $N$ |
| $h$ | Height difference between pivot axis and ball center | $m$ |
| $I$ | Moment of inertia | $kg \cdot m^2$ |
| $I_{cm}$ | Moment of inertia of center of mass | $kg \cdot m^2$ |
| $l_a$ | Length of arm | $m$ |
| $m$ | Mass | $kg$ |
| $m_{robot}$ | Mass of robot | $kg$ |
| $\vec{M}$ | Moment | $N \cdot m$ |
| $r$ | Radius | $m$ |
| $r_b$ | Radius of ball | $m$ |
| $r_pulley$ | Radius of pulley | $m$ |
| $r_w$ | Radius of wheel | $m$ |
| $s$ | Distance | $m$ |
| $t$ | Time | $s$ |
| $t_{impact}$ | Impact time | $s$ |
| $T_i$ | Gear teeth | $-$ |
| $v_{robot}$ | Speed of robot | $m/s$ |

# 1 Introduction

## 1.1 Context

In 1997, for the first time in history, artificial intelligence beat the world champion in chess. In the same year NASA's MARS Pathfinder mission made a successful landing on Mars and the first autonomous robotics system, Sojourner, was deployed on the surface of Mars. The organisation of RoboCup also started its journey for robotics and artificial intelligence in 1997, making this an extraordinary year for artificial intelligence and robotics.

For over two decades RoboCup has tried to promote and push robotics and artificial intelligence to new heights. By yearly organizing the Robot World Soccer Games and Conference they try to encourage this. Here different parts of the robotics and artificial intelligence are divided in five domains. These domains include RoboCupRescue, RoboCup@home, RoboCupIndustrial RoboCupJunior and RoboCupSoccer. From these domains, the focus will lay on RoboCupSoccer. This domain is also divided into five subdivisions; Humanoid, Standard Platform, Middle Size, Small Size and Simulation (RoboCup Federation, n.d.-a). The subdivision Middle Size League (MSL) will be the interest of this paper. The TU/e uses so called "TURTLE" (acronym for Tech United RoboCup. Team: Limited Edition) football robots, as seen in Figure 1.1.
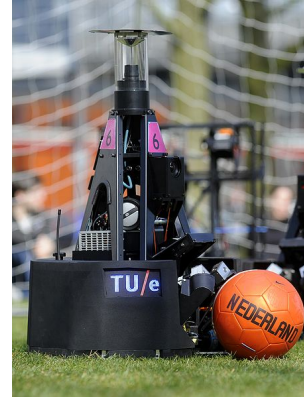


Figure 1.1: TU/e TURTLE Football Robot

The goal for RoboCupSoccer states as follows: 'By the middle of the 21st century, a team of fully autonomous humanoid robot soccer players shall win a soccer game, complying with the official rules of FIFA, against the winner of the most recent World Cup.' By setting this long term challenge in the soccer field, it motivates scientific progression while also creating more affinity by using a popular sport (RoboCup Federation, n.d.-b).

## 1.2 Problem definition

Since 2012 the Tech United team became world champions 6 times in the RoboCup MSL. All the times they were not in first place, they finished second. Through these accomplishments it can be seen that Tech United has a very strong team. Fortunately, Tech United has the budget to keep developing and improving their football robots. Not all teams are so fortunate and struggle with budget and staying on the level as the best teams. Therefore, the TU/e want to start the MSL Kickstart Platform. This will be an open source platform where other teams could find designs and working principles for a lower cost with their functionality as high as possible. By introducing this platform, smaller teams could make progress in their development more easily by using this information. Additionally, this also creates more competition for the bigger teams, eventually leading to faster innovation in the robotics and artificial intelligence field and realizing the goal for 2050 faster.

Another advantage of starting the MSL Kickstart Platform, is the fact that for companies or educational institutions that currently do not have a football robot team, the threshold for starting up a team can become lower. Resulting in more teams and thus eventually more competition in the MSL.

For this paper the focus will be on the ball handling system of football robot. Finding lower cost solutions for materials and working principles will hopefully eventually result in a more competitive and expanded RoboCup MSL. The goal is to eventually make a total robot for 2000 euros. The ball handling mechanism is currently approximately 10% of the costs of the approximately 20000 euros costing football robot. Therefore, a limit of 200 euros is set for new ball handling mechanism.

## 1.3    Research questions and objectives

The research question for this project is stated as follows:

*How can the current ball handling system be developed in a cheaper manner without loss of performance, which can be used for the MSL Kickstart Platform?*

The final goal of this project is to create a ball handling system for the MSL football robot that is more affordable for smaller teams or starting teams. To find how the ball handling system can be made cheaper, the total costs of the current design should be known first. Hereafter, alternatives for these parts can be researched. Additionally, it can be looked into if certain parts can be made better than the current ones with the same costs.

Resulting from this, the following objectives are formulated:

1. Evaluate which parts in the current ball handling system of the football robot can be reduced in cost the most.

2. Create concepts which are comparable in specifications but cheaper alternatives for the current design.

3. Analyze if these new parts could accomplish the same as the current ball handling system in terms of performance.

4. Show in detail how this new design can be developed.

5. Develop a way in which the newly chosen design can be integrated with the control design of the football robot.

6. Where possible, see if current parts can be improved in performance compared to the current ball handling system, without increasing costs.

This report will first give some insight about what the football robot is exactly and the rules that come with the MSL. Hereafter, in Section 3, the current setup, current costs and parts with the highest costs will be discussed. In Section 4, the concepts are made, discussed and eventually picked. Next, the final design will be detailed and shown in Section 5 Hereafter, the control for new concepts is researched in Section 6. Finally, a conclusion is formulated in Section 7 and additionally future work is discussed.

# 2    Background

In this section an introduction will be given to what the football robot is and how it works, the rules and specifications for the MSL will be explained and the requirement are set for the project.

## 2.1    Football robot

A football robot is an autonomous robot that is capable of playing the game of football. It typically has a mechanical body with wheels for mobility, and is equipped with a variety of sensors and actuators to enable it to move, perceive its environment, and interact with the ball. A football robot must be able to move quickly and accurately on the field, perceive the location of the ball and other players, plan and execute actions, and work together with other robots as a team. An exact breakdown of the current robot will be given in the next chapter to show how the ball handling mechanism is used in the robot.

## 2.2    Rules and specifications

When developing a new ball handling mechanism, the rules of the game should be followed. The rules that apply to the ball handling mechanism and its function are stated in the rulebook of Asada et al., 2021 as followed;

- In any case, it must be possible for another robot to take possession of the ball.

- The robots must comply with the following limits (measured along the orange axis in Figure 2.1):

    - The ball must not enter the robot body (any part of the robot, excluding the ball manipulators, and respective shielding) top projection convex hull by more than a third of its diameter. This limit becomes half of the ball diameter when the robot is stopping the ball - this case only applies to instantaneous contact between robot and ball lasting no longer than one second.

    - Any contact point with the ball must not exceed a third of the ball diameter.

    - An additional margin of 3cm (measured from the contact point limit) is allowed for ball manipulator mechanical shielding/protection, as long as this protection does not touch the ball.
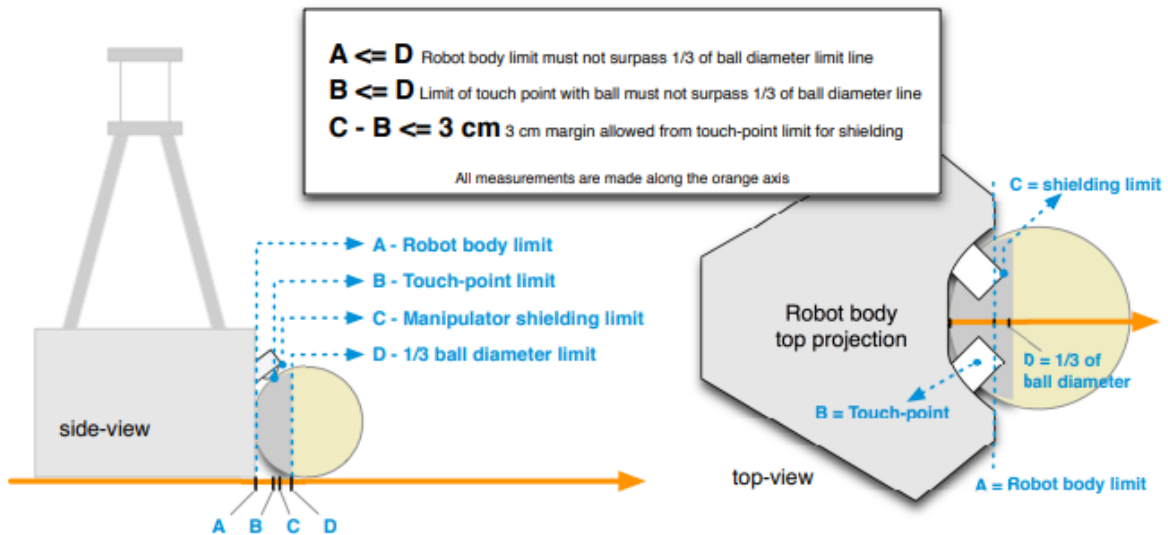


Figure 2.1: Specification of limits within ball handling mechanism

- The robot may exert a force onto the ball only by direct physical contact between robot and ball. Forces exerted onto the ball that hinder the ball from rotating in its natural direction of rotation are allowed for no more than one second and a maximum distance of movement of thirty centimetres. Exerting this kind of forces repeatedly is allowed only either after a waiting time of at least four seconds or if the robot has previously completely released the ball. Natural direction of rotation means that the ball is rotating in the direction of its movement. Forces exerted by the robot onto the ball in order to handle it, may not lift the ball out of the ground. If such situation occurs, a free kick is awarded to the opponent team.

## 2.3   Requirements

- The design must comply to all the Middle Size Robot League Rules and Regulations, see Section 2.2.

- The football robot must be able to receive the ball from a teammate, intercept the ball or overtake the ball from an opponent.

- The football robot must be able to dribble with the ball in a linear way and in a circular way while the ball moves naturally. This means no ball holding must occur. The exact rules for this can be seen in Appendix A.

- The football robot must be able to measure the position of the ball inside the receivers.

- The football robot must be able to retract the ball within 0.5 seconds.

- The drive mechanism must be able to exert a specified torque of 100 mNm or more to ensure similar performance when in a scrum.

- The newly designed ball handling mechanism must not obstruct other parts of the robot.

- The location of the ball holders, axis of the ball receivers and the wheels of the ball receivers must not change with respect to the current design.

- The ball handling mechanism must be able to withstand a collision at a maximum speed of 3.4 m/s with another football robot without having any damage or position change in one of its components.

- The price of the ball handling components of the football robot must not exceed 200 euros.

# 3    Current Setup & Costs

A schematic picture of the whole football robot can be seen in Figure 3.1 with its components noted. The total setup of the robot consists of a varied array of parts. Firstly, the omnivision unit on top of the robot is used to navigate in the playfield with the use of the field lines. It uses a rounded mirror at which a camera is pointed. The warped image can be translated to a the position of the robot in the field.
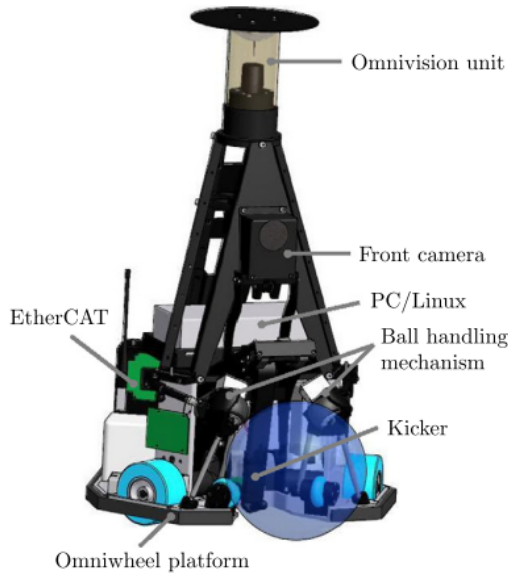
The front camera is used to visualize the position of the ball together with the omnivision unit. The PC/Linux is used for the control of the whole robot. The EtherCAT unit is designed to provide high-speed, deterministic communication between the components in the robots. This way they know how to act in certain situations. The kicker is used to kick the ball when passing or shooting. By a movable kicker arm the ball can be either shot over the ground or with a lob. A capacitor is used to store energy to create a powerful kick. The omni-wheel platform is used to drive the robot over the playfield. Because of the omniwheels, the robot can instantly go any direction without needing to turn.

For this paper the ball handling mechanism is of importance. The ball handling mechanism needs to be able to catch and dribble the ball. The exact functions will be elaborated in the coming chapter. The most important and expensive parts are taken into account when making the tables of costs of the ball handling mechanism. The housing is done separately at the end of the chapter.

Figure 3.1: Total robot with components and ball location is transparent blue

## 3.1    Ball receivers

As taken from CST Group TU/e, 2012; "The two ball receivers consist of actuated tyres which can 'drive' the ball. In this way, the ball can be pulled against the robot in order to 'dock' the ball before shooting (pulling it against the bottom ball holders), drive backwards, steer and even rotate around its axis without losing the ball."

The ball receiver, with a more detailed view in Figure 3.2, consists of a leg (1) from Aluminum-6061. This leg is connected using a shaft (2) and Permaglide PAF06080P bearings (3) to the base, which enables a single rotation around a line. On the top side it is connected to the damper (discussed in the next section) using a shaft (4) from hardened steel, assembled with two circlips (DIN 6799-5). The wheel that makes connection with the ball (5) consists of a tire on a rim, which on one side is connected with the leg (1) using a brass bushing (6), working as a bearing. On the other side a ABS bearing (8) is used to support the wheel axis (7) from CrNIMo. A plate (9), again from Aluminum-6061, supports the bearings and is bolted on to the leg (1). On top of this plate, the Gysin (GSR012-1-05-1) 5:1 gearbox (11) is connected, in which a Maxon Motor RE 25 (20W, 24V) with DC- Tacho DCT 22 0.52 V encoder is assembled. Finally the housing is closed using a cover plate (12) from St. 37-2." The costs of the most important parts can be seen in Table 3.1.
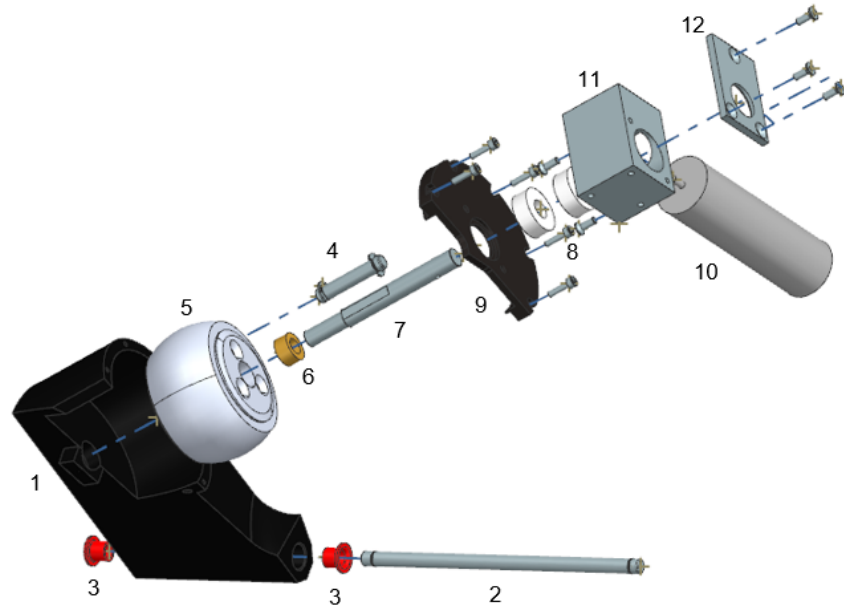
Figure 3.2: Ball receiver

Table 3.1: Parts and costs of ball receivers

| Number | Part(s) | Price |
|--------|---------|-------|
| 2-9 | Screws, shafts, bearings, wheel | €20,- |
| 8 | 2x ABS bearing | €7,- |
| 10 | Maxon Motor RE25 (20W, 24V) | €270,- |
| 10 | DC- Tacho DCT 22 0.52V | €64,- |
| 11 | Gysin (GSR012-1-05-1) 5:1 gearbox | €135,- |
| **Total 2x:** | | €980,- |

## 3.2   Ball holders

As taken from CST Group TU/e, 2012; "The ball holders are used to position/dock the ball together with the ball receivers and to make sure the ball rotates in a natural way when dribbled.

In Figure 3.3 a more detailed view of the ball holders is visible, in which an Kornylak Transweel omniwheel (1) (which is a simplified representation of the wheel) is connected to a hollow shaft(2) using a gusset. This axis rotates inside SKF 61900 ball bearings, which are retained in position by circlips (2 x DIN 6799 8 and 2 x DIN 6799 10). Inside the hollow shaft (2), a splined shaft (3) can be found which is connected to the housing (7). Everything is bolted together using M3 x 8 Allen nuts (ISO 4762) (8)." The costs of the most important parts can be seen in Table 3.2.
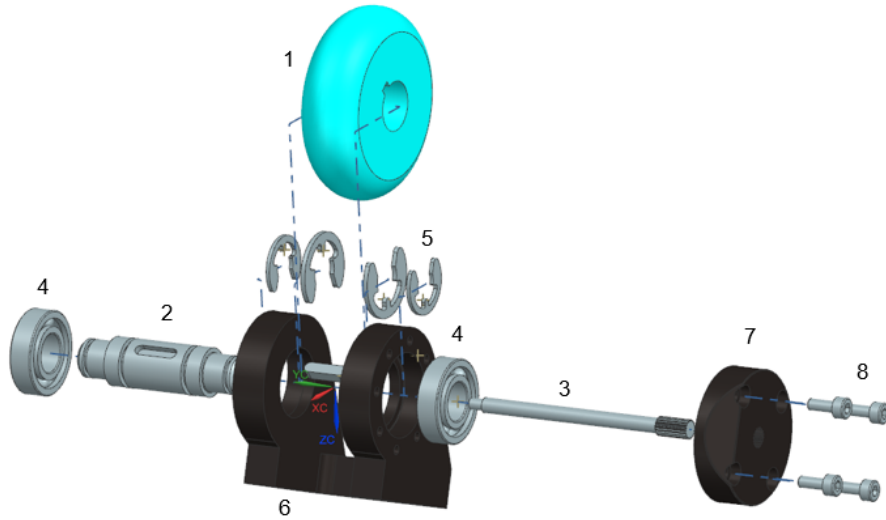
Figure 3.3: Ball holder

Table 3.2: Parts and costs of ball holders

| Number | Part(s) | Price |
|--------|---------|-------|
| 1 | Korniyak Transwheel Omniwheel 2" | €3,- |
| 5 | Circlips (2x DIN6799 8 and 2x DIN6799 10 | €2,- |
| 8 | M3 x 8 Allen Nuts (ISO 4762) | €7,- |
| 2,3,4 | Bearings and shafts | €5,- |
| **Total 2x:** | | €34,- |

## 3.3   Housing and other parts

The housing of the ball receivers and the ball holders, as seen in Figure 3.4 and Figure 3.5 respectively, is done by CNC milling. CNC milling is a manufacturing process in which computer numerical control (CNC) technology is used to control the movement of a machine tool. In CNC milling, a program is written that describes the movements of the machine tool, and the machine tool then follows those instructions to produce parts. CNC milling can be used to produce complex three-dimensional shapes, like the ones used for the housing. It is a highly precise process that can produce parts with tight tolerances and smooth finishes. The machines used for this are therefore very expensive which results in high prices for custom parts, like the ones used for the housing of the ball handling mechanism. In Table 3.3 the approximate price for each individual part can be seen.

Figure 3.4: Milling parts of ball receiver



Figure 3.5: Milling parts of ball holder

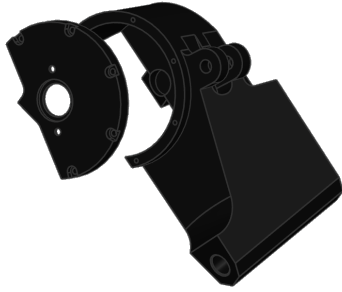Table 3.3: Costs of housing and other parts

| Part(s) | Price |
|---|---|
| Housing ball receiver | €250,- |
| Housing ball handler | €210,- |
| Potentiometer | €15,- |
| Spring loaded dampers | €30,- |
| **Total 2x** | €950,- |

## 3.4   Cost reducing applications

The total ball handling mechanism costs over €2000,- to make . There are several ways to reduce the costs of making the ball handling mechanism. When looking at Table 3.1 and Table 3.2, it is clear that most costs are made in the ball receivers. The motor, gearbox and tachometer in each arm are by far the most expensive mechanical parts in the ball handling mechanism. Also, when looking at Table 3.3 it can be seen that the housing is expensive to make as well. Therefore, these will be the parts that are looked into the most in the concepting fase.

When looking at other teams, the same principle gets used a lot. But there are some different approaches that can provide useful information. For example, the Falcons use a drive belt in their arm and place their motor in their arm. This can provide a solution when not using a gearbox. The University of Aveiro uses an inline solution which implies that the rotating plane of the grabbing wheels present themselves normal to surface of the ball. This also eliminates the use of a gearbox when using a motor with high enough torque. These solution are kept in mind when creating concepts.

# 4 Concepts

## 4.1 Functions

To find working alternative mechanisms for the ball handling system, the ball handling system is divided in the different functions it should have to work properly. By dividing these functions, the concepts can be thought of with each of these functions in mind.

### Ball receiving

The ball handling mechanism of the football robot should be able to receive and hold the ball when it intercepts a ball or gets a pass from another teammate from as many angles as possible.

### Dribbling (linear & circular)

The football robot should be able to hold the ball while moving forwards or backwards (linear). Therefore, it needs a motorized wheel or another actuator that holds the ball into place while driving. Moreover, it should have a similar system for turning in a circular way. The ball should be able to roll in a natural way when turning and moving. Therefore, the ball holders should have an as low as possible friction coefficient to ensure this. The ball receiver arms should support this movement to make sure the ball does not fall out of the grip of the robot.

### Positioning of ball

When the football robot is receiving, dribbling or wants to shoot the ball, it should know at which position the ball is in the ball handling mechanism. This is necessary to be able to retract the ball correctly within the given limits, to know what motors to actuate when dribbling and how to position the ball when shooting.

## 4.2 Ball receivers

The biggest costs are found at the ball receivers, as previously seen in section 3. Therefore, these will be divided into different parts to find a cheap but effective alternative for the current ball handling system.

### 4.2.1 Drive mechanism

The current setup of the drive transmission in each of the ball receivers consists of an electric motor, a gearbox and a tachometer to measure the position of the wheels.

For the new drive mechanism the effective torque should remain roughly the same to ensure the same quality as the current drive mechanism. This torque is important for when the robots are in a scrum. This means that when a robot tries to take the ball from another robot, the one that can create the most force on the ball wins the scrum most of the time. This leads back to the torque the robots can deliver in their wheels.

The current motor delivers a nominal torque (max. continuous torque) of 26.3 mNm, as seen in the datasheet in Figure B.1. The gearbox currently used, has an efficiency of 75% and a gear ratio of 5:1, finally resulting in a theoretical torque of 98.63 mNm on the ball by using Equation 4.1. The exact data for the current gearbox can be seen in Figure B.2.

$$\tau_{theoretical} = \tau_{motor} \cdot \eta \cdot \frac{T_2}{T_1} \tag{4.1}$$

where $\tau_{motor}$ is the torque exerted by the motor, $\eta$ is the efficiency of the gearbox and $T_2$ and $T_1$ are the amount of teeth on the gears. This theoretical torque will probably not be the effective torque eventually created by the robot's drive mechanism due to external forces like friction and the efficiency of the motor. Therefore, a test is done to see how much force the drive mechanism actually performs on the ball. By testing it at multiple angles, as seen in Figure 4.1, the maximum torque and corresponding angle can be found. The most interesting angles on which to do a pull test are straight forward (in the middle of both ball receivers) and directly in line with each ball receiver. Hereby it can be seen what the maximum torque is per ball receiver, and how much torque is needed at average when pulling at both ball receivers equally.
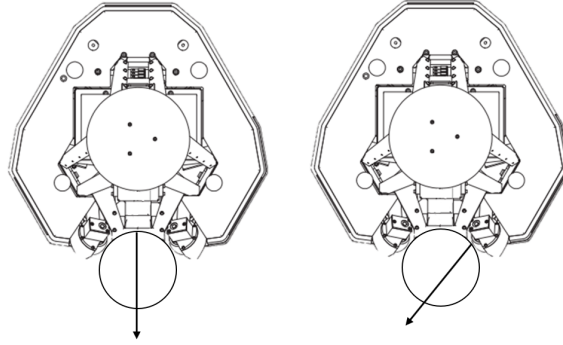
Figure 4.1: Test angles for torque of motors

The tests are done by taping a force meter to a ball and pulling until the ball has enough force to get out of the grip of the ball handling mechanism. This force can then be translated to a torque per motor by the use of Equation 4.2.

$$\tau_{eff} = \frac{F_{measured}}{2 \cdot cos(\theta_m)} \cdot \frac{T_2}{T_1} \cdot r_w \tag{4.2}$$

where $F_{measured}$ is the measured force, $\theta_m$ is the angle at which the motors are positioned and $r_w$ is the wheel radius. The tests showed a mean force of approximately 20N for the left configuration of Figure 4.1 and a mean force of 16N in the right configuration . By the use of Equation 4.2, a known wheel radius of 21.6 mm, a known angle of 43°, and a 5:1 gear ratio, an effective torque of 59 mNm was measured per drive mechanism. This value is the minimum the new drive mechanism should be able to provide. A higher torque is aimed for to ensure similar or better performance.The right configuration of Figure 4.1 gives a higher effective torque. However, this test configuration was not optimal due to grip of the other wheel and the difficulty to pull in the exact same line as the motor is working.

With this effective torque known, a drive mechanism can be designed with roughly the same torque as the current drive mechanism. Different options can be used to obtain this result;

- **Same components but cheaper:** By using lower quality components, different gear ratios and a cheaper way of measuring the wheel speed, the same result may be obtained.

- **Higher torque DC motor** By the use of the current 5:1 gearbox, the torque gets multiplied by a factor of five, resulting in a motor used that has lower torque than needed function. An alternative way of getting the desired torque, is by using a motor that directly delivers the desired amount of torque. This way, the gearbox and accompanying housing and mounting gets eliminated from the ball receiver. Yet, this leads to the problem that the current motor will then be mounted directly on the wheel, creating a spacing problem within the whole ball handling mechanism. To solve this problem, a belt drive could be used to give the motor a different position on the arm, this is further elaborated in subsubsection 4.2.2. A tachometer or alternative wheel speed measurement will still need to be mounted on the motor or wheel.

- **High torque stepper Motor** A different approach is to use a stepper motor with more torque than needed initially. Stepper motors are generally a lot cheaper than DC motors and would therefore be a good cost reducing alternative. Stepper motors can create a high torque with small dimensions at low speeds. Additionally, these can be controlled without knowing exact angles due to the fact that they have steps they work in.

- **Low torque DC motor** This is the approach that is used at the moment; a low torque DC motor with a gearbox to increase the torque output. By the use of a tachometer or Hall-sensor the angle can be measured of the wheels.

- **Low torque stepper motor** To make the current approach cheaper by only changing the motor, a low torque stepper motor can be used of which the output torque can be increased by the use of a gearbox.

### 4.2.2   Housing

For the housing, multiple aspects should be taken into account. The way it is manufactured and in what shapes in can be manufacturedare researched and how this affects the placement of the drive mechanism.

**Manufacturing & shape**

There are different options to manufacture the housing of the ball receiver arms. Currently, CNC milling is used. This is very useful for the milling of 3D shapes, but uses very expensive machines and takes longer than most other ways of manufacturing. This results in high costs, as can be seen in Table 3.3.

An alternative for this would be CNC laser or waterjet cutting, this will be cheaper in terms of manufacturing speed. However, this way of manufacturing will come with two disadvantages over other ways of manufacturing. Firstly, laser cutting only works on sheet metal. For example, aluminium can only be cut 10mm deep, stainless steel 15 mm and steel 20 mm. These are general margins given by companies, but deeper would be possible at higher costs. Waterjet cutting can basically cut through every material and thickness, but the time greatly increases on harder and thicker materials. Another disadvantage is that it can only cut in one direction of the metal, so no 3D shapes can be made from the material. A different way to cut the ball receiver arms would be to hand cut sheet metal. This even decreases the costs further but will not be as precise as using CNC applications.

Bending sheet metal increases its strength by altering the distribution of stresses within the material. By bending it into a stiffer and stronger form, it can resist higher forces that are applied to it. Next to its adaptability, folding sheet metal is also very cheap compared to other ways of manufacturing. However, the sheet metal needs to be cut, and the way of doing this also influences the final cost for it. The disadvantage of folded sheet metal, is that it can not be folded in curved edges. This leads to only straight edges to work with. However, for the ball receiver arms this should not be a big problem because the arms can be made with straight bends.

3D-printing can also be used to make the arms. This way, there are no restrictions on the shape of the arm and the costs of this manufacturing style are relatively low when having your own 3D printer. The downside of 3D-printing is that the filament used has very low yield stress compared to steels.

**Motor placement**

At the moment, the motor is connected to the wheel through a gearbox at an angle of 90 °, creating the option to put the motor at this angle. This is beneficial for the spacing within the ball handling mechanism because the motor would not stick out and obstruct any movement of the ball receiver arms. However, when finding a motor with enough torque as discussed before, the gearbox would be eliminated and thus also the option to put the motor at a 90°angle.

An option to fix this problem would be to put the motor further down the arm and connect it through a belt drive to the wheel. This would not only fix the spacing issue, but also decrease the moment of inertia. This would result in better overall dynamic behaviour for the ball receivers as the moment of inertia influences the quality of the contact behaviour with the ball. This will be further discussed later on.

A lower moment of inertia means a quicker recovery back to contact with the ball after the arm gets bounced of the ball due to disturbances or bumps. This happen because the moment of inertia determines the moment

that work on the arm, as seen in Equation 4.3.

$$\vec{M} = I_{tot} \cdot \vec{\alpha} \tag{4.3}$$

The moment $\vec{M}$ is determined by the total moment of inertia $I_{tot}$ and angular acceleration $\vec{\alpha}$. The moment of inertia for an object around its center of mass is determined by its mass and the distance to its own center of mass, as stated in Equation 4.4. However, for the ball receivers the moment of inertia is taken around the axis of the ball receivers their pivot point.

$$I = m \cdot r^2 \tag{4.4}$$

where $m$ is the mass and $r$ the distance to the center of mass. To determine the moment of inertia around an axis that is not the objects own center of mass, the parallel axis theorem needs to be used, which is stated in Equation 4.5

$$I = I_{cm} + m \cdot d_{cm}^2 \tag{4.5}$$

Here, the moment of inertia is determined by the moment of inertia around the object's center of mass $I_{cm}$, plus the mass of the object $m$ times the distance from the center of mass to the new axis $d_{cm}$ squared. The effect on the moment of inertia by the change in motor location can be seen in Figure 4.2.
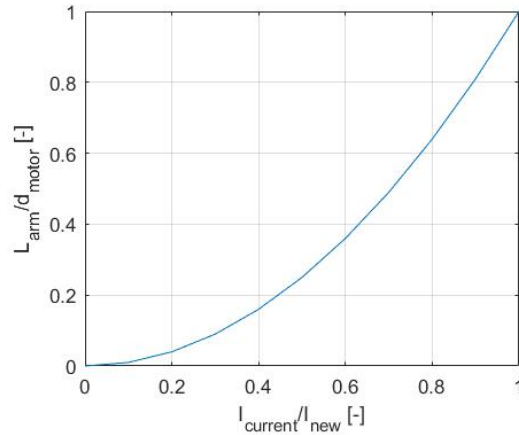


Figure 4.2: Effect of motor placement on inertia acting on pivot axis

It can be seen that the closer the motor is placed to the pivot axis, the lower the moment of intertia will be acting on the pivot axis. The total moment of inertia around the pivot axis is determined by adding all moments of inertia together of the different parts using the parallel axis theorem. Currently, it is determined according to Equation 4.6.

$$I_{tot} = I_{arm} + I_{motor} + I_{gearbox} + I_{wheel} \tag{4.6}$$

As the position and kind of wheel will not be changed, the moment of inertia of the wheel will not change. However, by eliminating the gearbox and moving the motor we see that changing the distance of the motor in the arm decreases the moment of inertia around the pivot point. Therefore, this will not only benefit the spacing issue occurring by removing the gearbox, but also improve the dynamical behaviour. The moment of inertia of the arm will also change due to its new configuration.

### 4.2.3   Angle determination

The current way of determining the angle of the ball receivers is done by a potentiometer attached to the arms by a string under tension. This already provides a low in cost, robust solution. The string makes sure that during a collision, nothing can break. The string will just lose its tension and get back in its original position due to the spring force of the springs attached. Therefore no change needs to be made in this part.

## 4.3   Ball holders

The ball holders should keep the ball in the robot in a steady manner. Additionally, the ball should keep rolling in a natural way when it is being dribbled by the robot in a linear or circular motion. Therefore it is important that the ball holders have as little friction as possible. This ensures the ball will roll in a natural way. To calculate this friction force, Equation 4.7 is used.

As seen in section 3, the current ball holders are already relatively cheap. So, the costs cannot be reduced a lot more. However, it is possible to look into upgrading the performance while staying at approximately the same cost.

The cheapest option is to use a material with a low friction coefficient. Placing this material on a spherical surface to reduce the contact area and thus also reduce the normal force on this area, minimizing the friction force acting on the ball that is determined by the means of Equation 4.7.

$$F_f = \mu_k \cdot F_n \tag{4.7}$$

where $\mu_k$ is the kinetic friction coefficient and $F_n$ is the normal force. Another option will be to use ball casters. These can be found for approximately the same price as the omni wheels, and less housing, bearings, screws and bolts will be needed eventually leading to a similar or better performance at a lower price. This might be a great way to lower the costs even a little more.

Additionally, the ball casters often just have two screwholes through which they can be attached. This gives the option for a simpler housing to attach the ball casters to.

## 4.4   Concept picking

When looking at the different concepts, the main aspect of the chosen design is that it should lower the costs of the total ball handling mechanism. Therefore, costs are the main criteria when choosing. However, it should not be forgotten that the functionality of the concepts should be considered to ensure that a working principle can be obtained.

### 4.4.1   Drive mechanism

When picking the best drive mechanism for the ball handling mechanism, certain aspects are important. Firstly, costs will be the most important aspect, as the goal is to design a cheaper alternative. Next is the functionality, as the performance should be roughly the same as the current ball handling mechanism or better. Also, the complexity is of importance, as the mechanism should be able to be made by all kind of MSL teams around the world. Finally, weight is also taken into account, as it influences the performance of the arm which is explained in subsubsection 4.2.2. The main choices are choosing between a DC motor or stepper motor, high or low torque and which way is used to determine the position of the wheel.

A high torque DC motor will be around €250,- and upwards, where a high torque stepper motor can be found for as cheap as €3,-. This difference is a little less when using a gearbox and having lower torque motors. However, the gearbox itself also has a price starting at €100,-, resulting in still a fairly expensive drive mechanism.

Another difference between a DC motor and a stepper motor is that a stepper motor has incremental motion (except when using microstepping), where a DC motor can provide a continuous motion. The incremental motion will only be a problem when the steps are not accurate enough for the ball handling mechanism. This

step angle determines how much the wheel moves and what part of the ball can be taken in per step. This circumferential distance can be calculated through Equation 4.8.

$$s = \phi_{step} \cdot \frac{\pi}{180°} \cdot r_w \tag{4.8}$$

where $\phi_{step}$ is the step angle and $r_w$ is the wheel radius. The step angle of most stepper motors that are available, is 1.8°. With the wheel radius being 26.3 mm, this results in a circumferential distance of 0.83 mm of the wheel per step or 165 mm per full rotation. With the football having a circumference of 70 cm and only a third of the ball can be in the robot, a circumferential distance of 23.3 cm needs to be covered to get a third of the ball in the ball handling mechanism. To do this in 0.5 seconds, the wheel only needs to make 2.82 rotations per second or 169.5 RPM. Both DC motors and stepper motors have enough choice in specifications to be able to reach this.

Next to that, a stepper motor needs a driver to operate while a DC motor does not. However, a DC motor needs an amplifier, but a drive is more complex due to its different applicable function. This also increases the complexity of the signals needed to be sent to the motor as the driver needs multiple inputs.

For the spacing, no gearbox will mean that the motor has to be in the arm and connected to the wheel through a drive belt. When using a gearbox, the placement of the motor can be roughly the same as how it is done currently, because the gearbox provides a 90 °angle on which the motor can be placed. Because DC motors are slimmer and longer than stepper motors, this would fit better. However, when using a drive belt, the stepper motor is a better choice as they are more compact and fit in the arm better.

Regarding the weight, the use of no gearbox will logically be less heavy than using a gearbox. The weights of stepper motors and DC motors with the same specifications are close, but the DC motors are a little heavier generally. The weight of the motor influences the inertia of the arm as seen in Equation 4.4. When lowering the weight, the pressure of the springs should increase to keep the same pressure on the ball when controlling it. Additionally, stepper motor are often more compact than DC motors, making it easier to place them within the drive mechanism without obstructing other parts.

In Table 4.1 all the different options for the drive mechanism are presented in a decision matrix. Here the spacing is used to express how big the overall mechanism is and if it can be place in a non-obstructing way. The weight is compared to see which option gives a lower moment of inertia and thus better dynamical performance.

Table 4.1: Decision matrix for drive mechanism

| Criteria | Cost | Spacing | Weight | Score |
|---|---|---|---|---|
| **Weight** | 0.6 | 0.3 | 0.1 | 1.0 |
| High torque DC with drive belt | 3 | 6 | 7 | 4.3 |
| High torque stepper with drive belt | 7 | 8 | 8 | 7.4 |
| Low torque DC with gearbox | 2 | 8 | 4 | 4.0 |
| Low torque stepper with gearbox | 6 | 7 | 5 | 6.2 |

All CNC machined applications are more expensive than cutting by hand logically, as CNC applications use expensive machines. The manhours may be higher when cutting by hand, but this will mostly be done by members of the team. CNC milling is the most expensive of the methods, because it can make the most complex parts in all three dimensions. CNC lasercutting and waterjet cutting can only work in two dimensions as they work with a laser or jet that can only cut in one direction.

In general, laser cutting is typically more cost-effective than waterjet cutting for most materials. This is because laser cutting is faster and more precise than waterjet cutting, which allows for higher production

rates and less waste. One advantage of laser cutting is that it uses a highly focused beam of light to cut through materials, which allows for very precise cuts with minimal kerf. This can help to reduce the amount of material waste and increase the overall efficiency of the cutting process. In addition, laser cutting is generally faster than waterjet cutting, which can further reduce costs for production runs.

On the other hand, waterjet cutting uses a high-pressure stream of water mixed with abrasive particles to cut through materials. While this method can be used to cut a wide range of materials, it is generally slower and less precise than laser cutting, which can increase costs. Waterjet cutting is also more expensive to operate because it requires the use of large pumps and high-pressure hoses, which can add to the overall cost of the cutting process. When using waterjet or laser cutting, the product will need to be flat and relatively thin. This results in the use of sheet metal and because a piece of flat sheet metal is not very rigid it also needs to be bent to get a strong construction.

Sheet metal can also be cut without CNC methods. By using a (electronic) metal saw, it can greatly reduce the costs of manufacturing. This will not be as precise as CNC methods, but eventually will get the job done. Depending on the preciseness wanted and budget available, it can still be chosen to use CNC methods for cutting the sheet metal. The manhours needed for this may be higher, but the team itself can perform these actions. This way, the actual price to pay will not be as high as asking a company to use CNC applications for cutting. However, CNC applications are not as widely available in the worlds as they are in the Netherlands, making hand cutting maybe even the only option.

Bending the metal can introduce compressive stresses along the bend, which can help to counter the tensile stresses that the metal may experience when it is subjected to external loads. This can make the metal more resistant to failure due to these loads. Bending the metal can also increase its stiffness and rigidity of the shape, which can make it more resistant to deflection and deformation under load. The bending of the metal needs to be done with specific tools which can be found in most workshops, thus making it not too complex to do.

3D-printing is an easy way to make an arm that has a custom shape in all directions. Next to that, it is very low in material costs compared to the others, but this comes with a great reduction in strength as well. This is not wanted when crashing.

In Table 4.3 all different options for the housing are presented in a decision matrix. The simplicity is based on the difficulty to perform the action.

Table 4.2: Decision matrix for housing

| Criteria | Cost | Strength | Simplicity | Functionality | Score |
|---|---|---|---|---|---|
| **Weight** | 0.4 | 0.3 | 0.15 | 0.15 | 1.0 |
| CNC Milling | 3 | 8 | 4 | 8 | 5.2 |
| CNC Lasercutting sheet metal | 5 | 6 | 6 | 7 | 5.8 |
| CNC Waterjet cutting sheet metal | 4 | 6 | 6 | 7 | 5.4 |
| Hand cut sheet metal | 8 | 6 | 8 | 7 | 7.4 |
| 3D-printing | 9 | 3 | 7 | 8 | 6.3 |

### 4.4.2   Motor Placement

When using a gearbox, the motor can be placed at an angle. When not using a gearbox, there are two options for the placement of the motor. The first is halfway of the arm, incorporating the motor inside of the arm. This will need a belt drive that can be directly attached to the wheel. As seen in Figure 4.2, the placement influences the dynamical behaviour of the arm. Therefore, the second option would be to place the motor directly above the pivot point of the arm. For this setup to work, a special construction should be made to hold the motor in place at the pivot point where you want the arm to move as freely as possible to prevent obstructions. Also, the belt drive should go through the arm and create a hole, losing strength in

the middle of the arm. This together would make it more complex than putting the motor halfway the arm. A comparison can be seen in Figure 4.3 and Figure 4.4. This would only increase the dynamical behaviour while making it more complex and less rigid.

A third option would be a motor that is not attached to the arm at all. This will eliminate the weight of the motor acting on the arm itself and thus decrease the moment of inertia. However, this also introduces a problem with the belt drive, which is needed. When the motor is not attached to the arm, it will not move when the arm moves. Resulting in losing tension or experiencing too much tension. For the belt drive to remain under tension, the motor should stay on the arm and therefore this option is not possible.
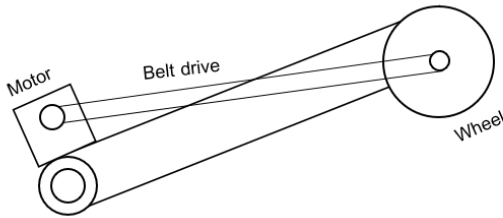


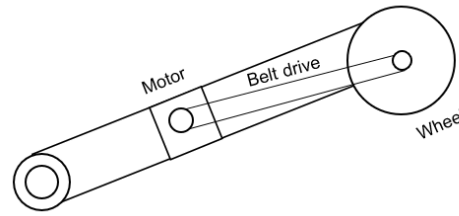Figure 4.3: Schematic drawing of motor on pivot point    Figure 4.4: Schematic drawing of motor in arm

Table 4.3: Decision matrix for motor placement

| Criteria | Cost | Functionality | Simplicity | Strength | Score |
|---|---|---|---|---|---|
| **Weight** | 0.4 | 0.2 | 0.2 | 0.2 | 1.0 |
| Motor halfway with belt drive | 8 | 6 | 6 | 7 | 7.0 |
| Motor on pivot point with belt drive | 7 | 6 | 4 | 8 | 6.4 |

### 4.4.3   Ball holder

The omni wheels used for the ball holders are not very expensive, but can be improved in terms of complexity and performance while even decreasing the costs .

By using a low friction material on a spherical surface, costs can be reduced even further. Only a spherical surface should be created, or made from excess material and the low friction material should be attached on top. However, this option is static and therefore would not have the lowest friction coefficient working on the ball compared to dynamic options. When looking into low friction materials, it does not go below 0.02.

Ball casters can be easily attached to the robot because most of them already have hole for screws. A small part where the screws can be attached needs to be added to the football robot. Next to this, ball casters have the lowest friction coefficient of all options. With an approximate friction coefficient of 0.001 to 0.005 it is a great option to improve the current ball holders while staying in the same price range.

For omni wheels the exact friction coefficient cannot be found, but will be approximately around the same value as for the ball casters as there are also bearings used in the omni wheel. However, due to the fact that the omni wheels are made of plastic, some irregularities will be present on the wheels themself. By molding the plastic pieces, seams will be present on which the ball will not roll as good as on smooth surfaces. On top of that, the omni wheels are the most complex to attach to the football robot, as they will need a housing and a shaft to be attached to the robot.

In Table 4.4 the different options for the ball holder are presented in a decision matrix.

Table 4.4: Decision matrix for ball holders

| Criteria | Cost | Functionality | Simplicity | Score |
|---|---|---|---|---|
| **Weight** | 0.5 | 0.3 | 0.2 | 1 |
| Low-friction material | 9 | 6 | 6 | 7.5 |
| Ball casters | 8 | 8 | 7 | 7.8 |
| Omni wheel | 7 | 7 | 6 | 7.3 |

# 5   Final design

As seen in the previous section, the final design will consist of a ball receiver arm made from folded sheet metal with a high torque stepper motor in the middle of the arm with a drive belt. For the ball holders, ball casters will be used. In this section, the choices are elaborated and detailed.

## 5.1   Stepper motor

When picking a stepper motor, it is important to keep the requirements in mind and to define several undefined details to get a functioning ball handling mechanism. The torque the motor can produce is the most important part. This will determine if the motor can function as well as the current drive mechanism used in a scrum and when retracting the ball. The measured torque per drive mechanism is 59 mNm, see subsubsection 4.2.1. It was seen that the torque on the specifications of the old motor did not meet the measured torque, this is why the requirement of 100 mNm was set to ensure steady performance. A higher torque is always preferred to increase the performance in scrums. The motor should be placed within the arm to avoid obstructing any other parts as the requirement states. Therefore, it should fit within the 75 mm wide axis. The speed of the stepper motor in combination with the step angle should be able to retract the ball within 0.5 seconds. This was therefore also a requirement when searching for a suitable stepper motor.

After extensive research in motors with different specifications, a motor that met the requirements was found. The stepper motor chosen has a maximum torque of 420 mNm, a step angle of 1.8 °and a maximum operating frequency of 1400 phases per second (PPS) with two phases. The depth of the motor is only 24 mm with a shaft length of 23 mm, making it easy to fit in the arm that is 75 mm wide at max. The motor itself with its parameters can be seen in Figure 5.1. This motor was chosen because it has a torque that is more than four times the given torque for the current motors. Because the parameters state two different torques, the specifications may differ from reality. Therefore, when the torque is even half of the said torque, it would still function in the ball handling mechanism.



### The parameters

параметр

| Type | Torque | current | Voltage | line order | Axle diameter | Shaft length | high |
|------|--------|---------|---------|------------|---------------|--------------|------|
| 17HS0423 | 0.42N.m | 1.5A | 12V | ABCD | 5mm | 23mm | 23mm |

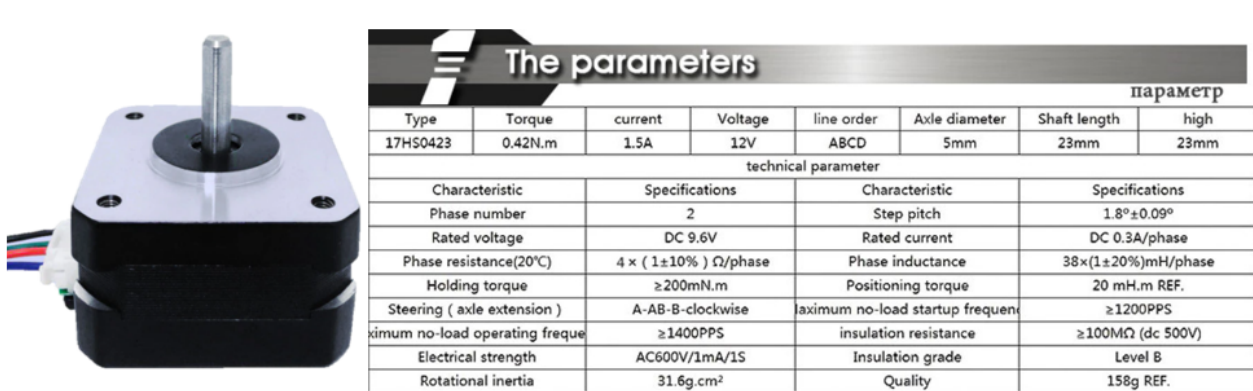| technical parameter | | | |
|---|---|---|---|
| Characteristic | Specifications | Characteristic | Specifications |
| Phase number | 2 | Step pitch | 1.8°±0.09° |
| Rated voltage | DC 9.6V | Rated current | DC 0.3A/phase |
| Phase resistance(20℃) | 4 × ( 1±10% ) Ω/phase | Phase inductance | 38×(1±20%)mH/phase |
| Holding torque | ≥200mN.m | Positioning torque | 20 mH.m REF. |
| Steering ( axle extension ) | A-AB-B-clockwise | Maximum no-load startup frequency | ≥1200PPS |
| Maximum no-load operating frequency | ≥1400PPS | insulation resistance | ≥100MΩ (dc 500V) |
| Electrical strength | AC600V/1mA/1S | Insulation grade | Level B |
| Rotational inertia | 31.6g.cm² | Quality | 158g REF. |

Figure 5.1: Stepper motor with parameters

For a stepper motor, the torque that can be produced without skipping (pull-in torque) gets lower when the speed gets higher, as seen in Figure 5.2. So, more pulses decrease the torque that can be produced. For every stepper motor this pull-out torque curve should be measured to know the exact shape of this curve, but the shape of the curve is similar to the one seen in the figure. The curve is not a linear relation due to the fact that at higher speeds, sufficient current cannot get into the winding fast enough before the current is switched to the next phase, thereby reducing motor torque and making it a curve instead of a line.
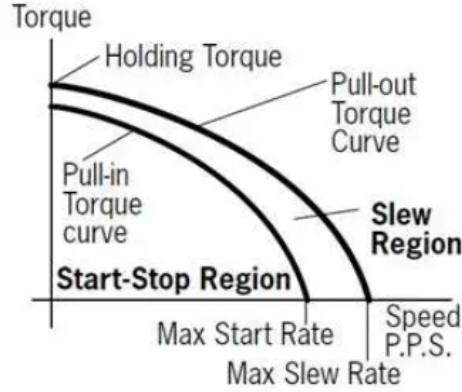
Figure 5.2: Torque-speed curve for stepper motor

When in a scrum where the ball is in the robot, the holding torque is of importance together with the torques at low speed. It is important that during a scrum where the ball is in the opponents robot, the speed of the motor stays below approximately half of the maximum speed to produce enough torque to be able to win the ball. The maximum rated torque is 420 mNm, which is also the holding torque when motor does not move and is energised. The holding torque of 200 mNm in the table is reckoned to be the detent torque when the motor is not energised.

At the maximum frequency the motor can operate, the torque will be very low. The highest speed the motor needs to acquire is when retracting the ball. A requirement is set to do this within 0.5 seconds. With the use of Equation 4.8 it was calculated that the speed should be 169.5 RPM to accomplish this. With the use of Equation 5.1, it is seen that the maximum operating frequency of 1400 PPS compares to a speed of 420 RPM. This is almost 2.5 times the desired RPM to retract the ball in 0.5 seconds. This means that at approximately 40% of the speed, and thus approximately at approximately 60% of the maximum torque of 420 mNm, the drive mechanism should be able to retract the ball in 0.5 seconds. It is evaluated that this torque is high enough to retract the ball because the motors exerted a torque of 59 mNm to keep the ball in the ball handling mechanism when a force was applied to the ball.

$$RPM = 60 \cdot \frac{PPS \cdot \phi_{step}}{360°} \tag{5.1}$$

The driver that is used, is a constant current driver or also named a chopper driver. A working current can be chosen by flipping switches as seen in Figure 5.3. A current of 1.5 A is the working current of the motor, so this should be chosen. It is also possible to use microstepping by flipping switches. Microstepping increases the resolution and creates a smoother operation. However, it also decreases speed as more pulses are needed for a full revolution. The accuracy is already sufficient and the speed necessary to stay within the 0.5 seconds with enough torque is also reached. This means that microstepping is not necessary for the current stepper motor.
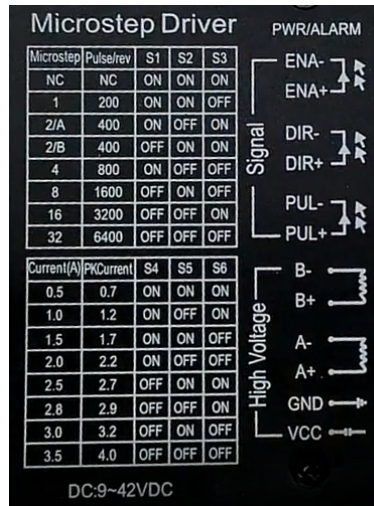
Figure 5.3: Options on the driver used

A constant current driver or chopper driver for a stepper motor works by regulating the amount of current flowing through the motor coils. The driver uses a control circuit to monitor the current flowing through the coils and adjust it as necessary to maintain a constant level. This is done by adjusting the voltage applied to the coils.

The control circuit typically includes a current sensing element, such as a shunt resistor, that measures the current flowing through the coils. This measurement is then compared to a reference voltage, which represents the desired level of current. If the measured current is higher or lower than the reference voltage, the control circuit will adjust the voltage applied to the coils to bring the current back to the desired level.

The input signals for the driver consist of a pulse (PUL), direction (DIR) and enable (ENA) input. The pulse input needs a pulse wave as seen at the top in Figure 5.4 that creates waveforms per phase. The direction input only needs an input to know if the motor should move in a clockwise or counterclockwise manner. The enable input can be used to turn the motor on or off, thus switching between detent and holding torque when not moving. The exact control will be discussed in the next chapter.
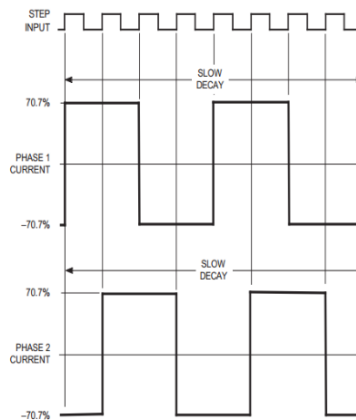


Figure 5.4: Pulse wave used to control stepper motor

## 5.2   Housing

The detailing of the housing of the ball receiver arms in sheet metal needs to be specified. Additionally the way to make the arms is explained.

**Shape**

Firstly, the exact shape of is determined by the placement of the wheel and the spaces available. The axis of the wheel should be twisted 27.8 °to have the same angle as the current ball handling mechanism. This angle is proven to work the best so this is what is used to ensure the same performance. The sheet metal should therefore be folded in a way as seen in Figure 5.5
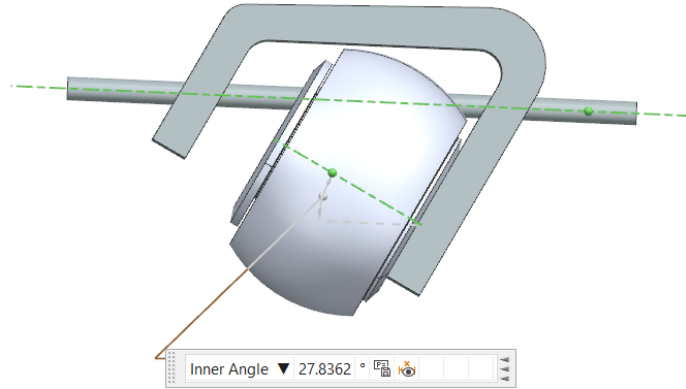


Figure 5.5: Angle of sheet metal for wheel placement with turning axis

When designing the arm, it was seen that the current place of the pivot axis interfered with the housing of the connected to the base plate. This resulted in the sheet metal arm going through the housing. Therefore, the housing was adapted by removing a piece so the arm could move freely. The adapted piece can be seen in Figure E.1.

**Material and stresses**

An important factor of the housing is that it should handle the impact of another robot. It is most likely that the other robot would hit from the front as the sides are protected by the base. The most critical force is experienced at the holes where the shafts are put through. If these deform, the shafts can lose their position and play can arise. The shafts themselves are not taken into account as they show no problems on the current robot.

For the maximum force that is experienced, it is taken that the force hits on the wheel and transfers directly to the arm through the front holes. The impact force is calculated by the use of Equation 5.2.

$$F_{impact} = m_{robot} \cdot \frac{v_{robot}}{t_{impact}} \tag{5.2}$$

where $m_{robot}$ is the mass of the robot, $v_{robot}$ is the speed of the robot and $t_{impact}$ is the impact time. For the impact time, a value of 0.01 seconds is taken. The mass of the robot is approximately 35 kg and the maximum speed of the robot without ball is 3.4 m/s. From this, an impact force of 11.9 kN follows.

By the use of a FEM (Finite Element Method) simulation, the stresses and loads on the arm can be simulated and so it can be seen if the stresses exceed the yield stress of steel. Steel is chosen because it has the highest yield stress of the common metals. The yield stress of most common steels lays around 250 MPa. For this load case, the front holes are loaded with an impact force of 11.9 kN at an angle of 35°(maximum operating angle of the arm). The arm was fixed at the back holes to simulate the axis it is attached to.
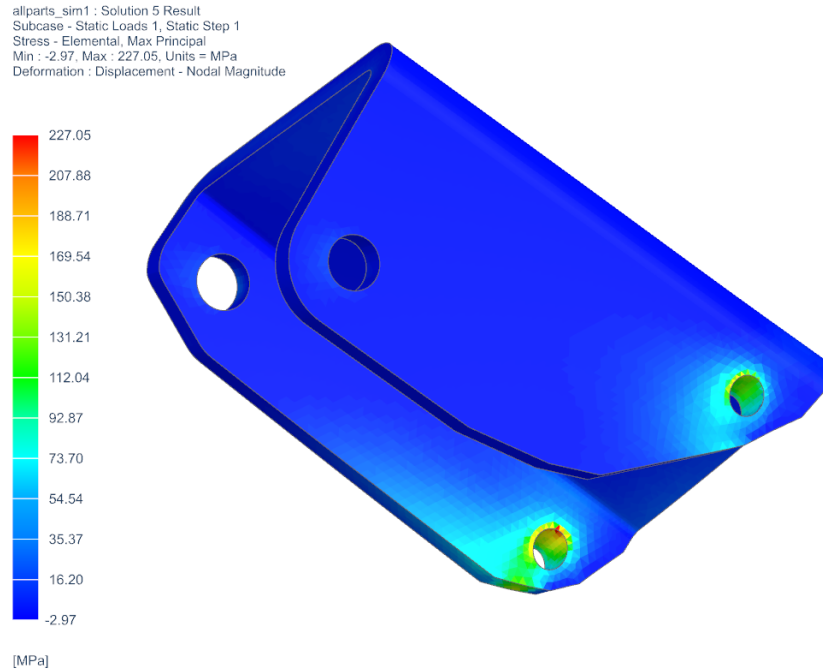


Figure 5.6: Stress on arm by impact force

It can be seen that the stresses acting on the arm with this impact force do not exceed the yield stress of steel. When using a thickness of 8 mm, these values were found. Therefore, a sheet metal thickness of 8 mm will be used. The stress seen, will be the maximum stress that the robot will endure during a top speed collision. The odds of this happening are not high, but the arms will be able to resist the impact without deforming permanently.

With the shape, material and thickness of the arms known, the exact motor placement and drive belt placement can be found. The final shape can be seen in Figure 5.6. The flat pattern with bend angles and bend radii can be seen in Figure C.1. An 8 mm thick piece of sheet metal that is 151.3mm x 120mm is used per arm. The front holes are 12mm in diameter and the back holes are 10mm in diameter and cut at an angle of 27.8 °.

### Motor placement

With the motor being placed halfway in the arm it needs an attachment piece. Fortunately, the stepper motor comes with holes for screws in the front. Because the arm itself does not have the space to attach the motor to, a piece needs to be welded on the inside to attach the motor to with an attachment piece. These will both be made of 3mm thick sheet metal. The attachment piece can be seen in Figure 5.7 and the extra piece can be seen in Figure 5.8. This extra piece can also act as a stopper so the arm does not move further down than desired. It also has holes for the attachment piece to be screwed onto. When attached to the arm, it greatly increases the strength of the arm by holding the flanges in place. The attachment piece has long holes that make it possible for the motor to be navigated upwards and downwards in the arm. This also

makes it possible for the tension of the drive belt to be increased by sliding it up or down and increasing the distance between the two axes. The flat patter of the attachment piece can be seen in Figure C.2, the piece is 75.3mm x 40mm. The extra piece is 56.8mm x 55mm with 3mm blend corners on the top to fit in the arm.
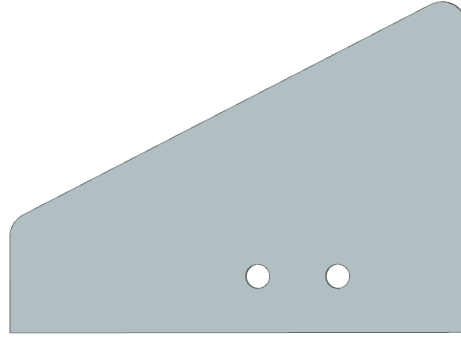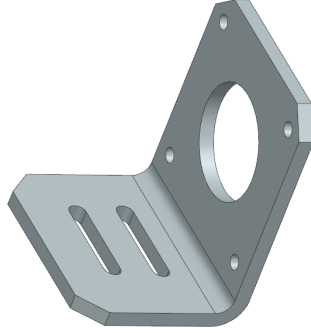


Figure 5.7: Attachment piece for motor   Figure 5.8: Extra piece for attachment of motor

For the springs to be attached to the arm, the piece seen in Figure 5.9 is used. This piece is welded to the arm to connect the springs to. This has the same dimensions as the part where the spring is currently attached to. The flat pattern can be seen in Figure C.3. This part is 5.8mm x 1.6mm of 3mm thick sheet metal with an 8 mm radius rounding on each side.
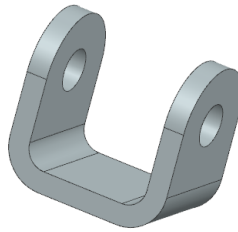


Figure 5.9: Spring attachment piece

This results in approximately 0.04 $m^2$ of 8mm thick sheet metal and 0.015 $m^2$ of 3mm thick sheet metal per robot. For this the price are taken per square meter to calculate the costs of this, which can be found at the end of this chapter. 8mm sheet metal costs approximately 500 euros per square meter and 3mm sheet metal costs approximately 100 euros per square meter. This leads to approximately €25 euros in sheet metal per robot.

**Drive belt**

A wide variety of belt drives can be found in all different sizes. It is important that there is no slip to ensure the speed of the motor transfers correctly to the wheel. That's why it is chosen to use a belt with increments. The pulleys the belt will be rolling over can be 3D-printed to match the diameter of the shafts and the height of the increments.

The diameter of the pulley should be as big as possible to increase the rotational stiffness. This relation can be seen in Equation 5.3. It was chosen to pick a diameter of 13mm for the pulley as this was the biggest that fits normally in the arm.

$$c_2 = (\frac{r_{pulley2}}{r_{pulley1}})^2 \cdot c_1 \tag{5.3}$$

where $c_i$ is the rotational stiffness and $r_{pulleyi}$ is the radius of the pulley. The pulleys can be found in all different sizes and diameters. They are often made from aluminium and have screw holes to attach them to the shafts. Screws are also included. A combination as seen in Figure 5.10 should be used and will cost approximately €10,- together with the belt.



Figure 5.10: Possible pulleys used for the drive belt

While it is not necessary, the output torque can be increased even more by the use of a gear ratio in the drive belt. The use of a higher gear ratio also gives the option to increase the accuracy of the steps. Nevertheless, this will eventually lead to a slower speed. The influence of the gear ratio can be seen in Figure E.2.

## 5.3   Ball caster

The size of the roller ball bearings does not matter as long as they can endure the force of the ball and do not obstruct anything. Therefore, smaller cheaper ones are preferred. The attachment should be directly to the robot or with an attachment piece.

The chosen ball casters can be seen in Figure 5.11. These ball casters have a load capacity of 180kg while the ball is only 0.43kg. This is more than enough to support the speeds at which the ball will hit the ball caster. These ball casters are also cheap compared to the now used omni wheel; 16 pieces are available for only €30,-.

The attachment of the ball casters can be done easily by making a block of wood or plastic that can be screwed onto the base plate of the robot. This block can have all shapes that fit the robot it needs to be applied to, as long as the holes are aligned to the block. Due to the holes in the ball caster, it can be attached to the block by screws as well. This can be seen in Figure 5.12.
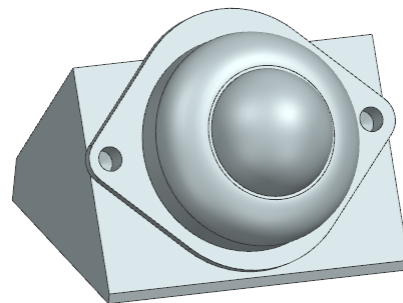


Figure 5.11: Caster ball used



Figure 5.12: Caster ball on attachment piece

## 5.4   Additional components

Some additional components as bearing, screws and clips are needed to secure everything in place. For every arm, two plain bearings will be necessary for the pivot axis, two plain bearings will be necessary for the wheel axis. Four M3 screws will be needed for attachment of the motor to the attachment piece and another two for the attachment to the arm. A pivot axis and a wheel shaft are needed and four clippings to secure the wheel axis and pivot axis. These additional components will result in a cost of approximately €15,- per robot as these parts are all sold in bulk for a low price.

## 5.5   Complete design

The complete design of the new ball handling mechanism in the robot compared to the old one can be seen in Figure 5.13. Additional figures can be seen at Figure D.1 andFigure D.2. The total costs of the total design can be seen in Table 5.1.
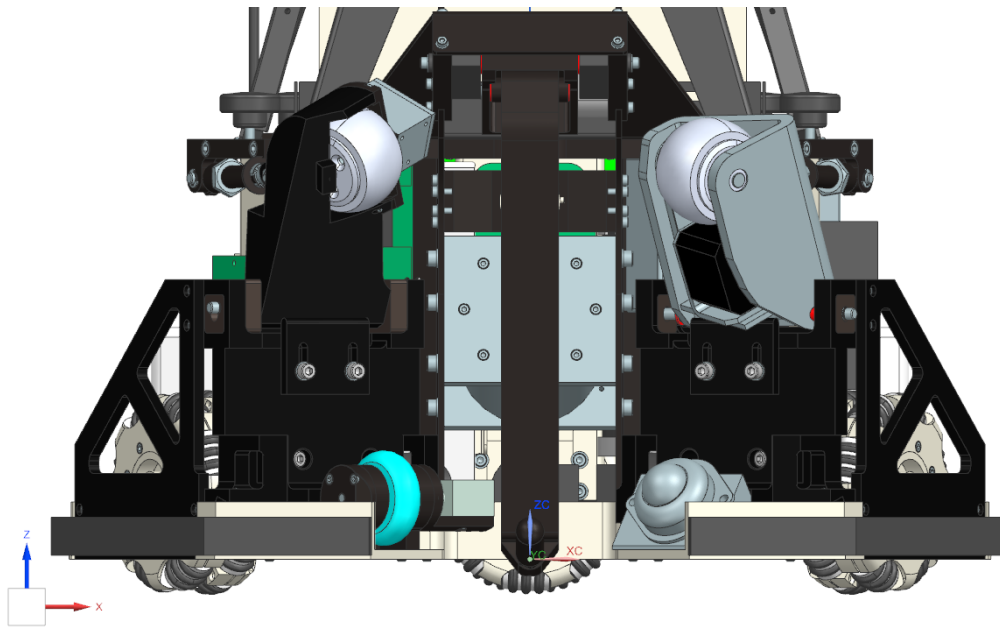


Figure 5.13: Assembly of the new arm compared to the current ball handling mechanism

Table 5.1: Prices for final parts of ball handling mechanism

| Part | Price |
|---|---|
| 2x Stepper motor | €6,- |
| 2x Driver | €20,- |
| 2x Drive belt | €20.- |
| Sheet metal arms | €25,- |
| 2x Caster ball | €3,50 |
| 2x Attachment ball caster | €2,- |
| 2x Potentiometer | €30,- |
| 2x Spring loaded dampers | €60,- |
| Shafts and screws | €15,- |
| **Total:** | €181,50 |

29

# 6   Control

A stepper motor by itself is an open-loop system; the amount of pulses that are signalled translate to a rotation of the shaft. This results in no feedback of the position of the wheel when it stalls or slips. To ensure that the stepper motor executes the amount of steps that it is meant to, a closed loop control should be added.

When the robot signals for a movement of the wheel, the wheel moves at angular velocity that can be calculated by the use of Equation 6.1.

$$\omega_{signal} = PPS \cdot \phi_{step} \cdot \frac{\pi}{180°} \tag{6.1}$$

However, if the stepper motor skips or the belt slips, this distance will not be accurate anymore. To adjust for this error, a feedback loop can be made. The angle of the arms can be used as indicator of the location of the wheel on the ball without the use of extra sensors. The rotation of the wheel when traveling over the ball corresponds to a certain angle of the arm. This relation can be calculated by the use of Equation 6.2, which appears as (5) in (De Best et al., 2011).

$$\theta_w = \frac{l_a \cdot cos(\phi_l) + \sqrt{(r_w + r_b)^2 - (l_a \cdot sin(\phi_l) + h)^2} - \dfrac{l_a \cdot sin(\phi_l) + h}{r_w + r_b}}{r_w} \tag{6.2}$$

where $l_a$ is the arm length, $\phi_l$ angle of the arm, $r_b$ the radius of the ball and $h$ the height between the pivot axis and center of the ball. With the rotation known, the angular velocity at which the wheel travels can be calculated by the use of Equation 6.3.

$$\omega_{actual} = \frac{\theta_w \cdot \dfrac{\pi}{180°}}{t} \tag{6.3}$$

To check if the sent pulse signal and accompanying rotation correspond to the actual rotation, $s_{signal}$ and $s_{actual}$ should have the same value. If they deviate, more pulses should be sent to the motor to correct for the error. This would work when the robot receives the ball, or is a scrum, because in both situation the ball should be fully retrieved in the ball handling mechanism. However, when dribbling the ball, the ball should fully stay in the ball handling mechanism. This means that the distance the ball travels, corresponds to the distance the wheels need to turn without a change in angle of the arms.

This might not be the most accurate solution for checking for misalignment, but it is a low cost solution without the need to add more sensors. When more accuracy is wanted, a sensor that measures the actual position and speed of the wheel should be placed and correct its position. This is done by checking if the desired position and speed correspond with the amount of pulses sent.

To implement this in the current control scheme as seen in Figure 6.1, the torque input and angular velocity output need to be changed. Almost all scenarios where the wheels need to be used involve the ball. The way of controlling the ball speed as explained before can then be used. Stalls normally happen when the pull-out torque is exceeded, which mostly happens due to a higher force acting on the wheel than it can handle. Meaning, when there is no ball to be grabbed, the angular velocity can be fairly safe taken from the signals sent by the use of Equation 6.1.
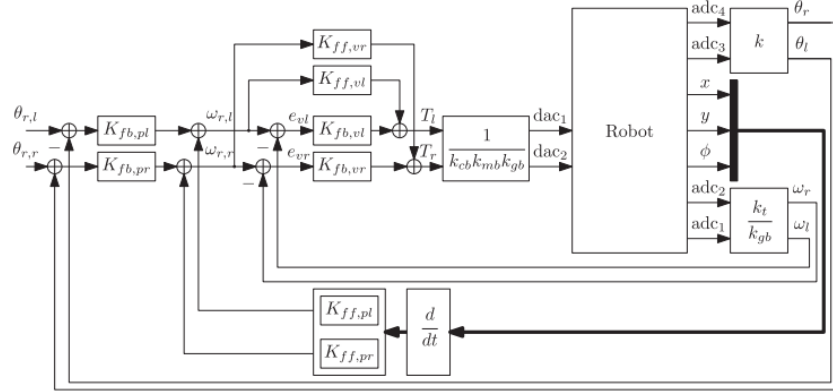
Figure 6.1: Hierarchical control scheme. From "Mechatronics 21" by J. De Best et al., *A novel ball handling mechanism for the RoboCup middle size league* (p. 474), 2011

This eliminates the use of adc1 and adc2 in the control scheme. The angular velocity without ball will become open loop and the angular velocity with ball is controlled by adc3 and adc4, as these translate the signal of the potentiometer in an angle. The angular ve

To have an input for the torque, the speed-torque curve as seen in Figure 5.2 needs to be known. For the motor picked, this is not included in the characteristics, so it should be measured to the achieve data that can be used as input. This would result in a torque known for every speed the motor would work on.

How the new scheme would look depends on the torque input. The rest of the scheme remains the same as the potentiometers for the angle of the arms remain in the ball handling mechanism. An updated version of the control scheme can be seen in Figure 6.2. Here, adc1 and adc2 are replaced with adc3 and adc4 which lead to the angular velocity. The torque input behaviour should be measured so a question mark is placed here as this is not known.
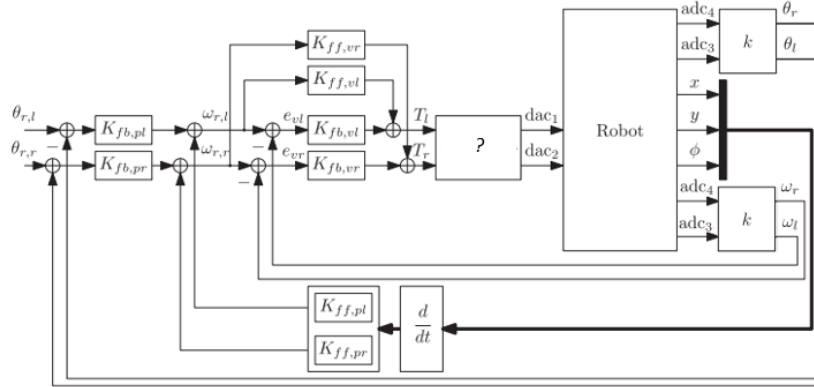


Figure 6.2: Updated hierarchical control scheme

New frequency response functions and nyquist plots should be measured to design the full control of the new ball handling mechanism but this can only be done when the ball handling mechanism is made.

# 7   Conclusion

## Conclusion

In this report, the current ball handling mechanism of the football robot of Tech United was shown and its costs were evaluated. It was seen that mostly the housing and drive mechanism were the most expensive parts of the ball handling mechanism. The total costs of the current ball handling mechanism are a little over €2000,-.

To reduce the costs, multiple concepts were thought of that would not lead to a significant loss of performance. By comparing the concepts on criteria as cost, simplicity, functionality, strength and weight, the best options were chosen.

It was chosen that a stepper motor with a driver and drive belt would be the best low-cost solution for the drive mechanism. By eliminating the expensive gearbox from the design, the motor could not be attached to the arm at a 90°angle. This was therefore resolved by placing the motor in the arm and connect it to the wheel via a drive belt.

For the housing of the ball receiver arms, it was chosen to use 8 mm thick sheet metal. Sheet metal provides a low material cost, while the ability to bend it still gives the desired strength to endure crashes and create a usable shape. The total ball holders were replaced by ball casters and an attachment block. This would slightly reduce the costs of the ball holders while slightly increasing the performance.

The total cost of the new ball handling mechanism could be reduced to approximately €181,50 without major performance loss. This meets the requirement of making a ball handling mechanism under €200,-

The control of the newly chosen stepper motor could be adapted in the current control scheme by using the potentiometer to convert the angle change of the arms into an angular velocity. This eliminates the use of extra sensors but the accuracy would depend on the accuracy of the potentiometers used. The accuracy would not be as high as when the angular velocity would be measured by the now used tachometers, but the cost reduction outweighs the accuracy loss for this project. For the torque input the speed-torque needs to be known of the stepper motor. This is not given and should therefore be measured to know exact torque outputs at certain speeds. To completeely design the control of this new ball handling mechanism, more time is needed and the ball handling mechanism should be made to test all characteristics.

# References

Asada, M., Balch, T., Bonarini, A., Bredenfeld, A., Gutmann, S., Kraetzschmar, G., Lima, P., Menegatti, E., Jonker, P., Fadaei, A., Nakamura, T. T., Steinbauer, G., Lauer, M., Takemura, Y., Lu, H., Pagello, E., Ribeiro, F., Schmitt, T., Shen, W.-M., . . . Gies, V. (2021). Middle Size Robot League Rules and Regulations for 2022.

CST Group TU/e. (2012). Robotic Open Platform. http://roboticopenplatform.org/wiki/TURTLE_Ball_Handling_and_Kicking_Mechanism

De Best, J., Van De Molengraft, R., & Steinbuch, M. (2011). A novel ball handling mechanism for the RoboCup middle size league. *Mechatronics*, *21*(2), 469–478. https://doi.org/10.1016/j.mechatronics.2010.04.001

RoboCup Federation. (n.d.-a). Leagues. www.robocup.org/leagues

RoboCup Federation. (n.d.-b). Objective. https://www.robocup.org

# Appendices

## A   Additional rules

- Ball rotation also implies that the ball is rotating continuously, even if slightly slower than its natural rotation speed. Movements of the ball such as "roll-stop-roll-stop" are not considered a valid ball rotation and will be considered ball holding.

- For any kind of ball dribbling, direct contact between the robot and the ball can only be maintained within a circle with a radius of three meters, centered on the point where the robot last caught the ball. To move past that circle, the robot has to completely release the ball so that this ball release can be directly observable by any of the referees. After that, the robot can capture the ball again and the center of the circle moves to the new catch position. It is up to the referees to determine if the ball has actually been completely released from the robot. Dribbling with direct contact between the robot and the ball outside this circle will be considered ball holding. It is up to the referee to decide if the robot dribbling the ball has complied with the above rule, namely in what concerns the three meters radius. The referee decision on this is final and non disputable.

- Dribbling the ball backwards, that is, dribbling while the robot is moving towards the opposite direction of its relative position to the ball is allowed for a maximum distance of 2 meters. During the backward dribble the ball must also be rolling in its natural direction. Once any particular robot has dribbled the ball backwards for more than 1 meter, it can not repeat the same backward dribbling again before the ball has been completely released by that robot or until the robot has engaged a new ball struggle against an opponent robot (i.e. the ball is actively disputed between the two opponent robots for more than 2 seconds).

- Violating any of the above rules is considered ball holding.

(Asada et al., 2021)
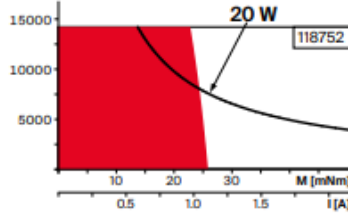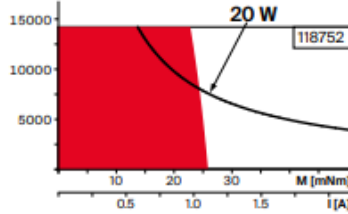
34

# B   Data sheets

**M 1:2**

| | Stock program |
| :-: | :-- |
| ☐ | Standard program |
| | Special program (on request) |

**Part Numbers**

| | | | 118749 | 118750 | 118751 | 118752 | 118753 | 118754 | 118755 | 118756 | 118757 |
| :-- | :-- | :-- | :-- | :-- | :-- | :-- | :-- | :-- | :-- | :-- | :-- |
| according to dimensional drawing | | | 118749 | 118750 | 118751 | 118752 | 118753 | 118754 | 118755 | 118756 | 118757 |
| shaft length 15.7 shortened to 4 mm | | | 302002 | 302003 | 302004 | 302005 | 302006 | 302007 | 302001 | 302008 | 302009 |

**Motor Data**

| | | | | | | | | | | | |
| :-- | :-- | :-- | :-- | :-- | :-- | :-- | :-- | :-- | :-- | :-- | :-- |
| | **Values at nominal voltage** | | | | | | | | | | |
| 1 | Nominal voltage | V | 9 | 15 | 18 | 24 | 30 | 42 | 48 | 48 | 48 |
| 2 | No load speed | rpm | 10000 | 9660 | 10200 | 9560 | 9860 | 11100 | 10300 | 8240 | 5050 |
| 3 | No load current | mA | 110 | 60.8 | 53.9 | 36.9 | 30.5 | 25.2 | 20.1 | 15.2 | 8.52 |
| 4 | Nominal speed | rpm | 8970 | 8430 | 8850 | 8330 | 8640 | 9920 | 9160 | 7040 | 3830 |
| 5 | Nominal torque | mNm | 11.1 | 20.5 | 22.9 | 26.3 | 26.7 | 27.1 | 27.7 | 28.7 | 30 |
| 6 | Nominal current (max. continuous current) | A | 1.5 | 1.5 | 1.46 | 1.16 | 0.968 | 0.784 | 0.653 | 0.536 | 0.343 |
| 7 | Stall torque | mNm | 232 | 225 | 220 | 243 | 249 | 283 | 264 | 209 | 129 |
| 8 | Stall current | A | 29.1 | 15.8 | 13.5 | 10.4 | 8.72 | 7.94 | 6.03 | 3.81 | 1.44 |
| 9 | Max. efficiency | % | 76 | 82 | 83 | 85 | 86 | 87 | 87 | 86 | 84 |
| | **Characteristics** | | | | | | | | | | |
| 10 | Terminal resistance | $\Omega$ | 0.309 | 0.952 | 1.33 | 2.32 | 3.44 | 5.29 | 7.96 | 12.6 | 33.4 |
| 11 | Terminal inductance | mH | 0.028 | 0.088 | 0.115 | 0.238 | 0.353 | 0.551 | 0.832 | 1.31 | 3.48 |
| 12 | Torque constant | mNm/A | 7.96 | 14.3 | 16.3 | 23.4 | 28.5 | 35.6 | 43.8 | 55 | 89.6 |
| 13 | Speed constant | rpm/V | 1200 | 670 | 586 | 408 | 335 | 268 | 218 | 174 | 107 |
| 14 | Speed/torque gradient | rpm/mNm | 46.5 | 44.7 | 48 | 40.3 | 40.4 | 39.8 | 39.6 | 39.8 | 39.7 |
| 15 | Mechanical time constant | ms | 5.68 | 4.87 | 4.77 | 4.55 | 4.47 | 4.4 | 4.37 | 4.37 | 4.35 |
| 16 | Rotor inertia | gcm² | 11.7 | 10.4 | 9.49 | 10.8 | 10.6 | 10.6 | 10.5 | 10.5 | 10.5 |

**Specifications**

**Thermal data**
| | | |
| :-- | :-- | --: |
| 17 | Thermal resistance housing-ambient | 14 K/W |
| 18 | Thermal resistance winding-housing | 3.1 K/W |
| 19 | Thermal time constant winding | 12.5 s |
| 20 | Thermal time constant motor | 612 s |
| 21 | Ambient temperature | -30...+100°C |
| 22 | Max. winding temperature | +125°C |

**Mechanical data (ball bearings)**
| | | |
| :-- | :-- | --: |
| 23 | Max. speed | 14000 rpm |
| 24 | Axial play | 0.05 - 0.15 mm |
| 25 | Radial play | 0.025 mm |
| 26 | Max. axial load (dynamic) | 3.2 N |
| 27 | Max. force for press fits (static) | 64 N |
| | (static, shaft supported) | 800 N |
| 28 | Max. radial load, 5 mm from flange | 16 N |

**Other specifications**
| | | |
| :-- | :-- | --: |
| 29 | Number of pole pairs | 1 |
| 30 | Number of commutator segments | 11 |
| 31 | Weight of motor | 130 g |

Values listed in the table are nominal.
Explanation of the figures on page 90.

**Option**
Preloaded ball bearings

**Operating Range**



n [rpm]

20 W

118752

M [mNm]
I [A]

**Comments**

| | **Continuous operation** |
| :-: | :-- |
| | In observation of above listed thermal resistance (lines 17 and 18) the maximum permissible winding temperature will be reached during continuous operation at 25°C ambient. = Thermal limit. |
| ☐ | **Short term operation** The motor may be briefly overloaded (recurring). |
| — | **Assigned power rating** |

**Modular System**                                                           Details on catalog page 44

**Gear**
416_GP 26 A
418_GP 32 BZ
419_GP 32 A
422_GP 32 C
429_KD 32
452-460_GP 32 S

**Sensor**
510_Encoder MR 128-1000 CPT
515_Encoder Enc 22
518_Encoder HEDS 5540
520_Encoder HEDL 5540
527_DC-Tacho DCT 22

**Accessories**
565_Brake AB 28

**Motor Control**
532_ESCON Module 24/2
532_ESCON 36/2 DC
533_ESCON Module 50/5
535_ESCON 50/5
541_EPOS4 Micro 24/5
542_EPOS4 Module 24/1.5
542_EPOS4 Module 50/5
543_EPOS4 Compact 24/5 3-axes
544_EPOS4 Compact 24/1.5
545_EPOS4 Compact 50/5
547_EPOS4 50/5

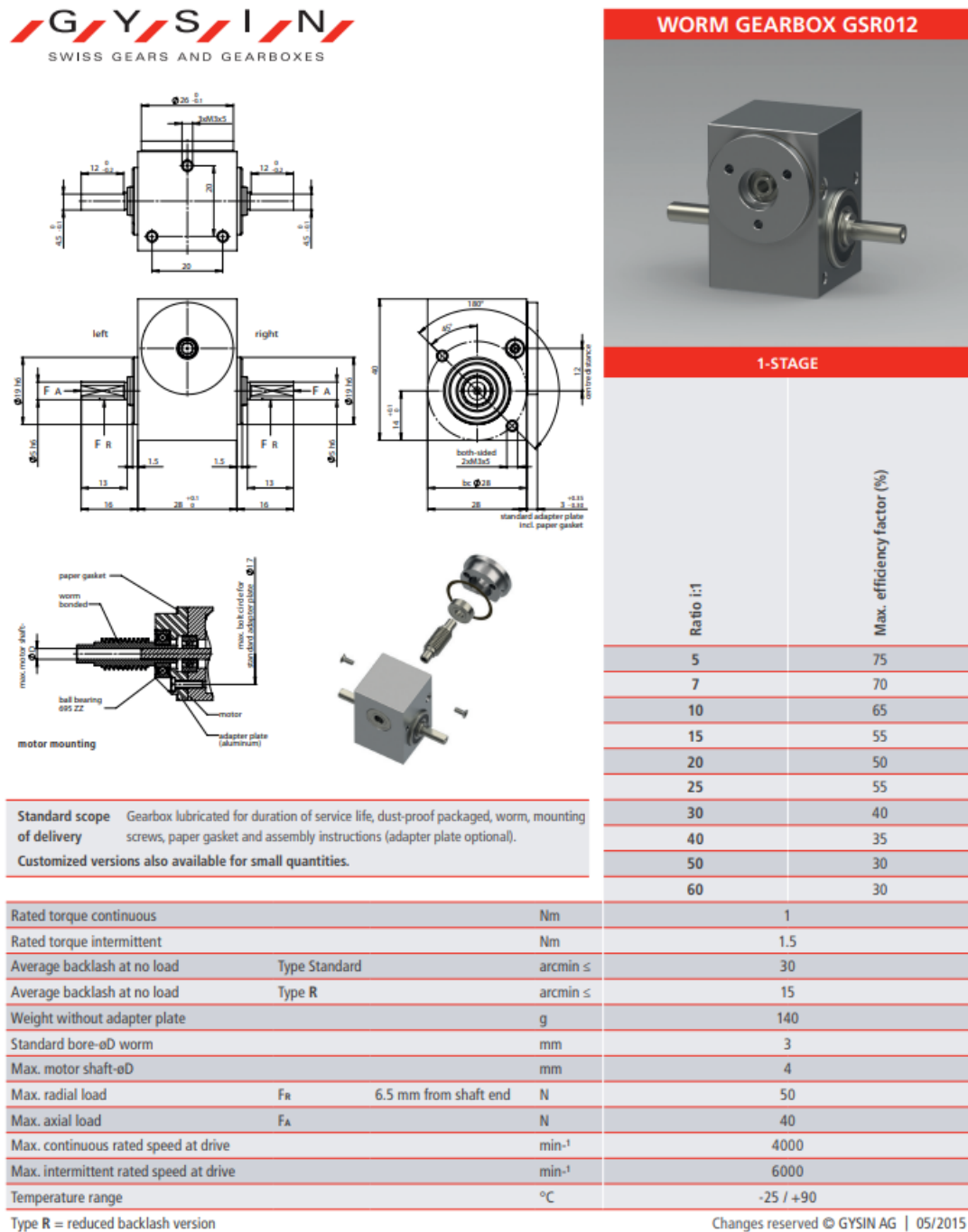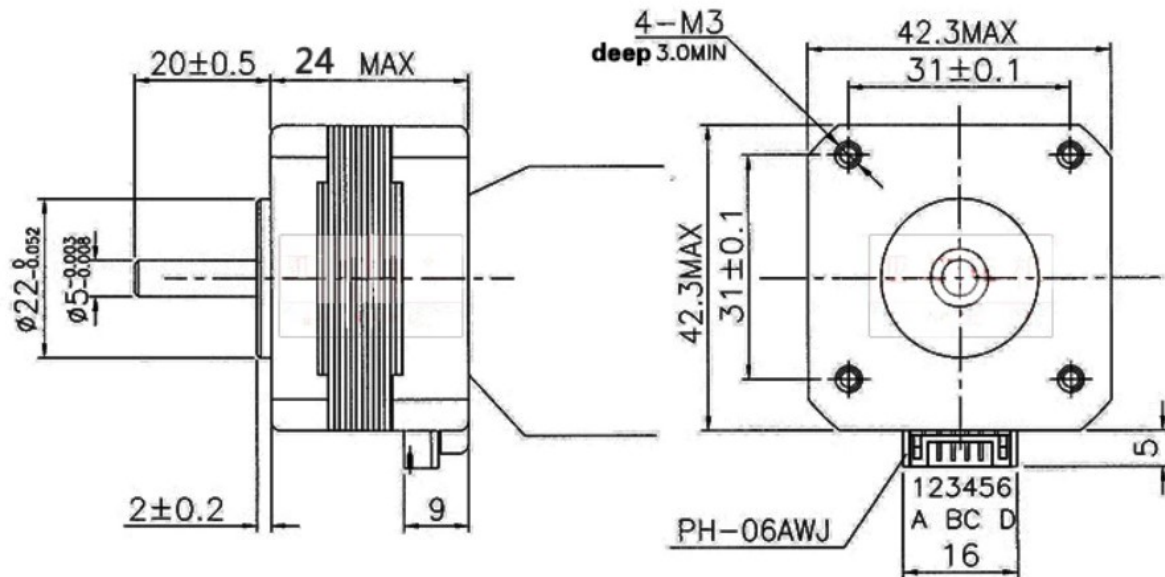Figure B.1: Datasheet of Maxon Motor RE25

| | WORM GEARBOX GSR012 | |
|---|---|---|

| 1-STAGE | | |
|---|---|---|

| Ratio i:1 | Max. efficiency factor (%) |
|---|---|
| 5 | 75 |
| 7 | 70 |
| 10 | 65 |
| 15 | 55 |
| 20 | 50 |
| 25 | 55 |
| 30 | 40 |
| 40 | 35 |
| 50 | 30 |
| 60 | 30 |

**Standard scope of delivery** — Gearbox lubricated for duration of service life, dust-proof packaged, worm, mounting screws, paper gasket and assembly instructions (adapter plate optional).

Customized versions also available for small quantities.

| | | | | |
|---|---|---|---|---|
| Rated torque continuous | | | Nm | 1 |
| Rated torque intermittent | | | Nm | 1.5 |
| Average backlash at no load | Type Standard | | arcmin ≤ | 30 |
| Average backlash at no load | Type R | | arcmin ≤ | 15 |
| Weight without adapter plate | | | g | 140 |
| Standard bore-øD worm | | | mm | 3 |
| Max. motor shaft-øD | | | mm | 4 |
| Max. radial load | F$_R$ | 6.5 mm from shaft end | N | 50 |
| Max. axial load | F$_A$ | | N | 40 |
| Max. continuous rated speed at drive | | | min⁻¹ | 4000 |
| Max. intermittent rated speed at drive | | | min⁻¹ | 6000 |
| Temperature range | | | °C | -25 / +90 |

Type **R** = reduced backlash version

Changes reserved © GYSIN AG | 05/2015

Figure B.2: Datasheet of Worm gearbox GSR012

Figure B.3: Dimensions of stepper motor



| Type | Torque | current | Voltage | line order | Axle diameter | Shaft length | high |
|---|---|---|---|---|---|---|---|
| 17HS0423 | 0.42N.m | 1.5A | 12V | ABCD | 5mm | 23mm | 23mm |
| technical parameter | | | | | | | |
| Characteristic | | Specifications | | Characteristic | | Specifications | |
| Phase number | | 2 | | Step pitch | | 1.8°±0.09° | |
| Rated voltage | | DC 9.6V | | Rated current | | DC 0.3A/phase | |
| Phase resistance(20℃) | | 4 × ( 1±10% ) Ω/phase | | Phase inductance | | 38×(1±20%)mH/phase | |
| Holding torque | | ≥200mN.m | | Positioning torque | | 20 mH.m REF. | |
| Steering ( axle extension ) | | A-AB-B-clockwise | | Maximum no-load startup frequen | | ≥1200PPS | |
| ximum no-load operating freque | | ≥1400PPS | | insulation resistance | | ≥100MΩ (dc 500V) | |
| Electrical strength | | AC600V/1mA/1S | | Insulation grade | | Level B | |
| Rotational inertia | | 31.6g.cm² | | Quality | | 158g REF. | |

Figure B.4: Datasheet of stepper motor

# C  Flat patterns
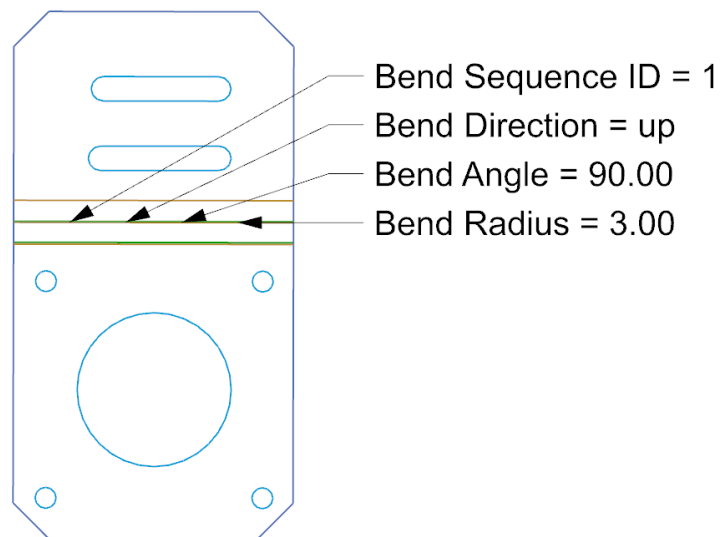


Figure C.1: Flat pattern of ball receiver arm
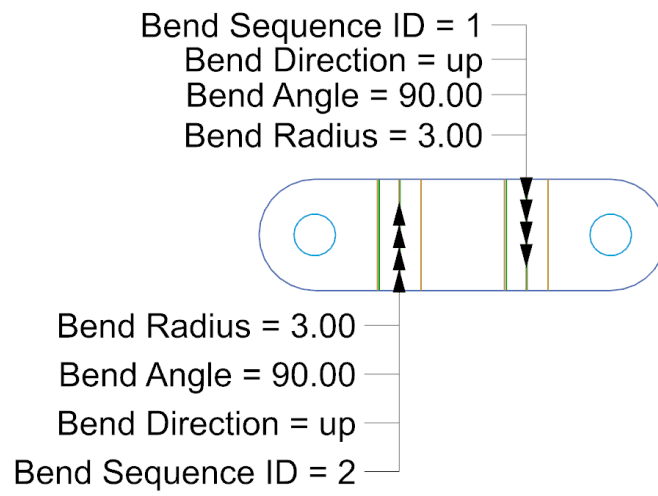


Figure C.2: Flat pattern for attachment piece for motor

Bend Sequence ID = 1
Bend Direction = up
Bend Angle = 90.00
Bend Radius = 3.00

Bend Radius = 3.00
Bend Angle = 90.00
Bend Direction = up
Bend Sequence ID = 2

Figure C.3: Flat pattern for spring attachmet

# D   Extra final design figures
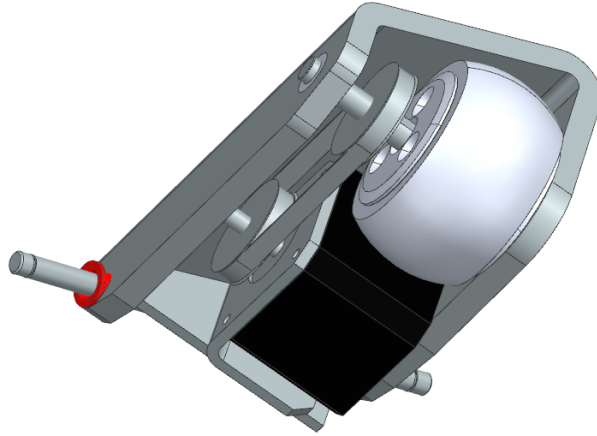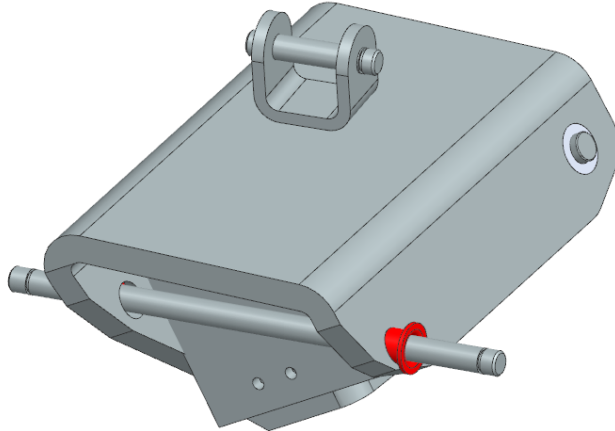


Figure D.1: Total arm bottom view


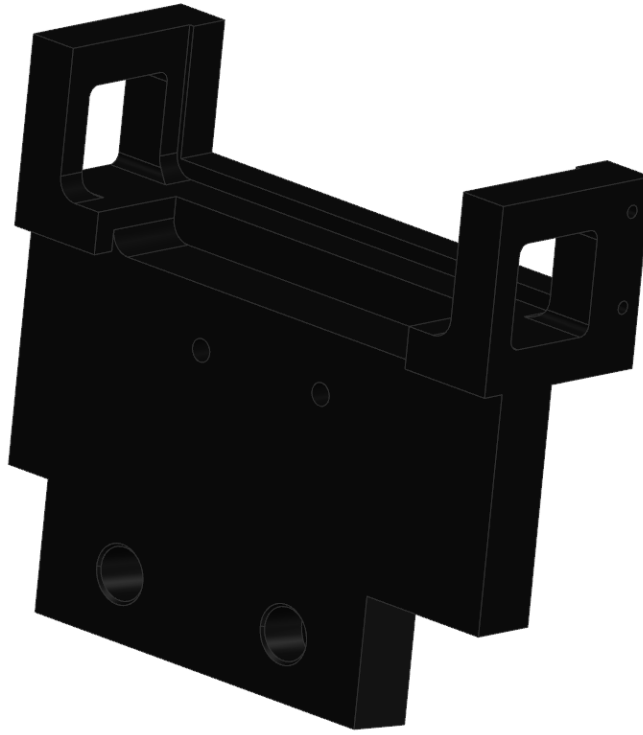
Figure D.2: Total arm back view

# E    Additional figures



Figure E.1: Addapted housing piece

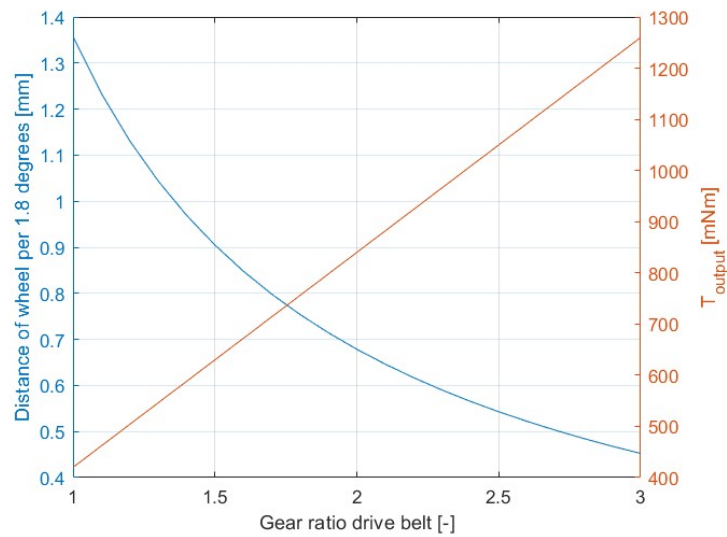

Figure E.2: Gear ratio influence on distance of wheel and torque output

# F    Matlab scripts

## F.1    Motor placement effect on inertia of arm

```
1  clear;
2
3  L=1;
4  d=0:0.1:1;
5  I = (d.^2)./L;
6  Ld = d./L;
7
8  plot(Ld,I)
9  grid on
10 xlabel('I_{current}/I_{new} [-]')
11 ylabel('L_{arm}/d_{motor} [-]')
```

## F.2    Effect of drive belt

```
1  clear;
2
3  gearratio = 1:0.1:3;
4  r_wheel = 26.6;
5  torque = 420;
6
7  distancedegree = 1.8 * pi/180 * r_wheel;
8  improveddistance = distancedegree ./gearratio ;
9  improvedtorque = gearratio * torque;
10
11 yyaxis left
12 plot(gearratio,improveddistance)
13 grid on
14 ylabel('Distance of wheel per 1.8 degrees [mm]')
15 xlabel('Gear ratio drive belt [-]')
16 yyaxis right
17 plot(gearratio,improvedtorque)
18 ylabel('T_{output} [mNm]')
```