Lappeenranta-Lahti University of Technology LUT
LUT School of Energy Systems
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# Mechanical Design of a Telepresence Robot for Instructional Use

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Examiners:
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# ABSTRACT

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**Mechanical Design of a Telepresence Robot for Instructional use**

Master’s thesis

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86 pages, 37 figures, 7 tables and 17 appendixes

Examiners: Professor Aki Mikkola, D.Sc. (Tech.) Kimmo Kerkkänen

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Telepresence robots are a well-established way to enable communication and in person contact between one or multiple people over distance. Compared with more common telecommunication methods a physical device presenting the operator in the location allows more established and natural communication and interaction with the environment. Some of the main limitations in the use of telepresence robots are the costs associated and the lack necessary functionality for some intended use cases. Multiple available solutions offer cost-effective way for communication in business and event-oriented situations but leave lot to be desired in aspects requiring physical interaction capability with the surroundings or in social gesturing. This can be solved by the addition of a manipulator to the robot construction.

Availability of budget-oriented telepresence robots including the ability to manipulate objects is sparse and lack functionality required in a prototyping laboratory and academic use. Additional aspects such as modularity, modifiability and transportability are wanted from such robot and can be realised with a new design.

In this thesis a solution for affordable and self-assembled telepresence robot platform is designed concentrating on the mechanical design and prototype manufactured based on requirements and wishes presented by the JHC staff. Security aspects concerning such telepresence robots and small mobile manipulators are evaluated and discussed to allow inherently safe mechanical design. A construction based on plywood and commonly available components is realized and the manufacturability and the assembly of the required components discussed.

# TIIVISTELMÄ

Lappeenrannan-Lahden Teknillinen yliopisto LUT

LUT School of Energy Systems

LUT Konetekniikka

Perttu Juvonen

**Mechanical Design of a Telepresence Robot for Instructional use**

Diplomityö

2021

86 sivua, 37 kuvaa, 7 taulukkoa ja 17 liitettä

Tarkastajat: Professori Aki Mikkola, Tekniikan tohtori Kimmo Kerkkänen

Hakusanat: telepresence-robotti, lämpömuovattava vaneri, mekaaninen suunnittelu, luontainen turvallisuus, turvallisuusstandardi, mobiilimanipulaattori

Telepresence-robotit ovat vakiintuva tapa mahdollistaa viestintä ja yhteys yhden tai useamman ihmisen välillä. Verrattuna yleisempiin kommunikaatiomenetelmiin fyysisen operaattoria edustavan laitteen läsnäolo sallii luonnollisemman viestinnän ja vuorovaikutuksen ympäristön kanssa. Huomattavimmat rajoitukset telepresence-robottien käytössä ovat kustannukset ja mahdollisten toivottujen toimintojen puute. Useat saatavilla olevat ratkaisut tarjoavat kustannustehokkaan tavan kommunikoida liiketapaamis- ja tapahtumapainotteisissa tilanteissa, mutta jättävät toivomisen varaa tilanteissa, jotka edellyttävät fyysistä vuorovaikutusta ympäristön kanssa tai sosiaalisten eleitten välittämistä. Tämä voidaan ratkaista sisällyttämällä manipulaattori robotin rakenteeseen.

Edullisten telepresence-robottien, varsinkin manipulointiin kykenevien, saatavuus on rajattua ja näillä tuotteilla ei usein ole prototyyppilaboratoriossa ja akateemisessa käytössä tarvittavaa toiminnallisuuskokonaisuutta. Tämänlaisessa ympäristössä robotilta vaaditaan ominaisuuksia, kuten modulaarisuutta, muunneltavuutta ja kuljetettavuutta. Nämä tarpeet voidaan toteuttaa suunnittelemalla uusi ratkaisu, joka ottaa ne huomioon.

Tässä opinnäytetyössä suunnitellaan telepresence-robotti päämääränä edullisen ja itse koottavan ratkaisun mekaaninen suunnittelu ja sen pohjalta prototyyppi, joka valmistetaan JHC:n henkilöstön vaatimusten ja toiveiden perusteella. Tällaisten telepresence-robottien ja pienikokoisten liikkuvien manipulaattoreiden turvallisuusnäkökohtia käydään läpi työn ohessa, jotta mahdollistetaan luonnostaan turvallinen mekaaninen suunnittelu. Vaneriin ja muihin yleisesti saatavilla oleviin komponentteihin perustuva rakenne toteutetaan työssä ja valmistuksessa tarvittavien komponenttien valmistettavuutta ja laitteen kokoonpanoa käydään läpi.

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## SYMBOLS AND ABBREVIATIONS

AGV – Autonomous Guided Vehicle
BOM -Bill of Materials
FOV – Field of View
FDMI – Flat Display Mounting Interface
HRI – Human-Robot Interaction
HRC – Human-Robot Collaboration
HSR – Human Support Robot
IMU – Inertial Measurement Unit
NO – Normally Open
PU - Polyurethane
ROS – Robot Operating System

# 1 INTRODUCTION

Telepresence robots and robotics are paving the way for globalised communication and interaction between people. Uses of virtual meetings in the form of video and voice calls are common but lack certain elements of human interaction. These parts can be alleviated by using robotics to allow free movement and interaction between people working on a project needing and greatly benefitting from physical presence. Small telepresence robots like Double 3 by Double robotics shown in Figure 1a are commonplace sight in many modern work environments. On other hand manufacturing industry has started working towards autonomous and mobile manufacturing technologies to increase the effectiveness and agility of manufacturing various products. Mobile manipulators have been a recent part of this development process allowing more dynamic manufacturing environment. KUKA Iiwa project (Figure 1b) is one example of these mobile platforms.

**Figure 1.** a) Double 3 telepresence robot (Double Robotics, 2020) b) KUKA KMR Iiwa mobile manipulator (KUKA, 2017)

Lappeenranta-Lahti University of Technology (LUT University) has created environment in its premises for students to create and develop different projects to support their studies or hobbies called J. Hyneman Centre (JHC). In some cases, projects created in these premises have been delayed by the lack of interaction between instructors and students for reasons preventing local presence of the instructor. A telepresence robot with omnidirectional movement and basic manipulation ability has been deemed to be a functional and applicable solution for these problems allowing presence over distance with no costly and time-consuming travel. Other problems arising from situations like for example the COVID-19 pandemic in progress during this work could be alleviated with suggested telepresence robot.

Most of the commonly available solutions for telepresence robotics often are not suitable for the requirements presented for the intended use case. The commercial solutions available fitting or applicable with minimal modifications to the presented requirements for a telepresence robot including a manipulator would be costly or unnecessarily hard to obtain. This has led to the project to create more affordable and easily manufactured telepresence robot in-house. Self-implemented solution would also enable further development of the telepresence robot concept to allow better suitability for LUT University and possible partner usage. Certain company has shown interest to the project and has agreed to finance the designed telepresence solution and is providing supplies for robot manufacture.

Previous work on this project has been done mostly on the electronic and conceptual basis and this thesis will concentrate on the mechanical requirements and implementation of the robot including design and manufacturing of prototype. Safety and safety standards are one of the main driving guidelines during the design process in addition to the manipulation and movement requirements. The implemented design includes functionality and design elements to allow fluid and natural interaction between the robot and humans.

Significant amount of research has been done on the Human-Robot interaction (HRI). In many cases the lack of human-like gestures between robots and humans has been deemed to reduce the effectiveness and eagerness to interact with the robot and or robot operator. Addition of manipulator imitating human arm gestures and head movement is not applied in many of the current commercial solutions even when recent research has noticed the advantages. Safety standards have been catching up with the recent advantages of HRI, solutions implementing these standards in situations where robots function in areas designed mainly for people have been less discussed.

For some use cases current robotic solutions are not providing enough flexibility or are not economically feasible for the intended use case. In addition, many of the current solutions are proprietary design locking users down to the product manufacturers implementation. A solution based on common materials like standardised electrical components and plywood construction that anybody with enough interest and resources could build and use, adding their own modifications to the design if needed.

## 1.1 Background literature

Multiple academic journals have been discussing the use of telepresence robots and the advantages and challenges of HRI:

Heenan et al have discussed the use of hand gestures in robot interaction to help communication and establishing a social bond between a robot and a human (Heenan *et al.*, 2014). Additionally Watanabe et al. have discussed the use of visual cues in presenting the robot intentions (Watanabe *et al.*, 2015). Additionally social gestures in robotics have been discussed by Li and Chignell (Li and Chignell, 2011). Neudstaeter et al. have done extensive research on the use of telepresence robots in academic conference setting noting social interaction nuances in such setting (Neustaedter *et al.*, 2018). Similar study in university study setting is made by Fitter et. al. (Fitter *et al.*, 2020) and in high schools by Darling-Aduana and Heinrich (Darling-Aduana and Heinrich, 2020). The environment and use in these papers can be compared with the one intended for the designed robot and the results in these articles are of interest during the design process.

Tuli et al. have done research on the design process and interaction for a small telepresence robot (Tuli *et al.*, 2020). Parameters presented are useful in the design. The methods and social interaction models presented in these articles can be used as a guideline and support for the system movement and interaction requirements for the mechanical design of the robot in this thesis.

Multiple sources have done work on the omnidirectional movement capability and development of omnidirectional robotic solutions: Taheri and Zhao have done extensive research and comparison between different solutions for omnidirectional movement. They note and compare the multiple advantages and disadvantages of each solution. (Taheri and Zhao, 2020)

Oetomo et al. have done research on the kinematics of powered caster wheels. The research is a good basis for implementing solution based on the idea of similar designs (Oetomo et al., 2005). Mooney and Johnson have researched the applicability of omnidirectional movement solution in rough terrain conditions and briefly discuss the disadvantages of more common solutions in such conditions (Mooney and Johnson, 2014). The capability required for intended environment and specifications needs to be evaluated. Thomas and Vantsevich have conducted equations to determine a wheel diameter required for climbing obstacles. (Thomas and Vantsevich, 2010)

Omnidirectional movement has multiple advantages that have been realized and used in industrial mobile robots. The method of movement for the designed robot is based on the journals and information discussed in them, as every different solution has its own advantages and disadvantages the best solution for this specific case needs to be researched before implementation.

Safety standards and technical specifications concerning machine design, industrial -, collaborative and autonomous robotic solutions discussed in this thesis: in paper from 2008 the need for specific standards for service robots not belonging to the same group as industrial and manufacturing equipment is noted (Virk *et al.*, 2008). Additionally, the lack of a category in standardization for specific robotic solutions is discussed by Barattini et al. (Barattini, Federico, Gurvinder Sigh Virk, *et al.*, 2019). It is to be noted that there is no single standard for the mechanical design of the manually controlled telepresence robots and/or small mobile manipulators.

The most important standard concerning the machine design the best practice is the ISO standard 12100 specifying the risk evaluation criteria and process (SFS, 2020). The standard is intended for industrial equipment and as such is not fully applicable in the context discussed. The planned standard addition ISO/TS 15066 discussed by Mathieu (Mathieu, 2016) and Björn and Reisinger (Björn and Reisinger, 2016) in their respective works specifies limitations and guidelines for industrial solutions functioning in collaborative environment similar but not fully applicable to the one intended for the device designed during the thesis. Other standards discussing machine safety which are to be evaluated and discussed in the design process are the standard for personal care robots ISO 13482:2014 (SFS, 2014). ISO 10218 parts one to three specify requirements for the machine safety and safety mitigation and are to be used in conjunction to the ISO 12100. Bogue has done review and discussion on the standards concerning robots interacting with humans (Bogue, 2017). Work can be used to reliably note more important aspects in safety with telepresence robots.

Most of the standards available are not designed for the specific use case and thus cannot be applied specifically. Therefore, different aspects of standards on industrial manipulators, helper robots and autonomous vehicles are discussed and applied where best suited for this specific use case.

## 1.2 Objectives of the work

The objective of the thesis is to find out the most important aspects for the mechanical design of the telepresence robot with a manipulator and to continue the design progress based on previous work. The goal is to implement a prototype for the specific use case and environment. Commercial solutions for telepresence and mobile manipulator solutions are evaluated and safety and safety standards for the use case are evaluated and applied in the design process.

The research problems of the thesis are:
The availability of low-cost mobile manipulators is lacking and often not suitable for instructional use. Implementation of a low-cost telepresence robot capable of manipulation has requirements that need to be assessed and implementation planned.

The research questions of the thesis are the following:
What mechanical functionality and elements are required for the implementing of a cost effective and safe telepresence robot?
How can effective and human-like movement and manipulation be achieved?
How can plywood be effectively used in the construction of a telepresence robot?

The thesis work is done on the premises of LUT University and JHC. The work is done over a time span of six months from September 2020 until March 2021 and includes work on the background research, mechanical design and documentation and prototype build of the designed robot. The project will be continued later based on this work. The work is conducted by the writer of this thesis in the supervision of JHC representatives. The progress of the work is discussed with the supervisors whenever deemed necessary in addition to the Meetings and deadlines that have been agreed upon at the beginning of the project. Resources needed during the thesis are discussed and realised with the University staff responsible for the project.

In the first chapters, literature review on the current commercial solutions is conducted and different implementations compared, the literature review realises the need for your own implementation based on functionality and costs. In addition, the most important safety standards concerning the implemented telepresence robot are discussed. Second chapter contains the mechanical design and design process of the robot are discussed. Third chapter contains the implementation of the robot prototype and basic testing of the prototype functionality. In the final chapter the results of the thesis and suggestions for project continuation are discussed.

# 2 BACKGROUND AND METHODS

## 2.1 Telepresence, distant presence, and mobile manipulators

Telepresence is a term used for virtual technologies allowing control, interaction, and participation over distance using telecommunication technologies. The advances and spread of network infrastructure, streaming technologies and capable hardware availability have allowed the spread of more affordable solutions for telepresence. Video streaming is largely integrated part of modern daily life and video conferencing has been adopted all over the world. In addition, research and development on mobile robotics has allowed mobile telepresence machines to arrive on the market, with increasingly affordable prices as the technology is readily available and use more familiar to the users. The most prominent use of telepresence is the use of voice and video calls over the internet.

Mobile manipulators are robotic solutions capable of moving around in their surroundings freely. Robots that are not limited to specific area mechanically like by rail or a platform compared with conventional industrial robots. In the industry mobile manipulators have become more common as automated flexible and modular solutions are added to the manufacturing environment. Mobile manipulators are capable of manipulating objects with tools or a grabber to modify or transfer the object in question. In many cases, the manipulators function outside human range and such are isolated from human contact in current manufacturing environments. Collaborative solutions are being developed to allow more flexible interaction with humans and robots allowing more flexible environment.

### 2.1.1 Effective human robot interaction

HRI is an important aspect of effective robot design. Research done on HRI allows us to determine and implement functionality that enables efficient and safe collaboration between robots and humans. In the case of the mobile telepresence robot with manipulation capability ensures that the social and physical interaction with the robot is established.

Social cues, for example hand or head gestures help the communication between the local people and distant user to feel more natural. Research has been done on how to help robots be more human and socially engaging. (Li and Chignell, 2011)

For the currently designed robot it was decided to enable the movement of the screen and camera on three axes: height, tilt and pan to enable screen orienting and giving the user more freedom to look around. Additionally, the movement of the “head” of the robot allows an addition of humane head gestures; looking at the other person you are communicating with or showing intention to turn around by turning the robot head assembly.

Additional gesturing could be achieved using the grabber of the robot for pointing, waving or even handshaking. Hand gesturing is natural for human interaction and enables more engaging communication with robots that are capable in comparison with the ones without. (Slack et al., 2018) In the scope this thesis the arm is included in the build, but further development of possible hand attachment and gesture implementation are left for further research.

### 2.1.2 Robotic solutions available on the market

In this chapter available commercial solutions for telepresence and mobile manipulators are listed and evaluated for the specific use environment. These solutions will be used as an outlier for the design created in this thesis.

On the market there are multiple telepresence solutions offered for conferencing and marketing use. Few good examples of commercial telepresence robots are Kubi, Temi, Double and Beam robots. All companies have developed relatively similar build consisting of two to three wheels and a screen or a tablet and audio equipment for communication. This basic compact design is well suited for communication applications and easy transfer of the unpowered robot.

Some of the solutions discussed are capable of both two-way communication and manipulation. These are the Mantaro TeleTrak (MantaroBot, 2017) , the Origibot 2, the new Stretch bot, Toyota HSR and TIAGo by PAL robotics.

Nevertheless, all four solutions have their disadvantages in the presented use case:

TeleTrak has only one Degree of Freedom (DoF) in its manipulator and is mostly capable for pointing and pushing tasks. Additionally, the tracked movement is more suitable for outdoor use as noise and friction are not desirable in indoor use.

Origibot 2 is lightweight and low-cost solution. Unfortunately, the availability of the system is questionable as at the current time there has not been updates on the bot manufacture or sales after the robot has been published in 2016.

The Human Support Robot (HSR), TIAGo and Fetch Mobile manipulator are the only solutions in the comparison that fulfil most of the presented requirements and wishes. Even though HSR is designed for autonomous assistive function for human needs some of the ideas implemented could be applied to a human controlled or a semi-autonomous telepresence robot. (Toyota, 2015; Yamamoto et al., 2018, 2019) The presented platform has the high price of 60000 dollars and has a subscription model attached, so unfortunately is out of scope for many use cases. TIAGo does not have monthly fee but the cost for the hardware is high exceeding 50 000 dollars. The pricing for the fetch is not available but can be assumed to be like the previous solutions.

**Figure 2.** Toyota Human Support Robot (Yamamoto *et al.*, 2019)

Appendix II contains the main specifications of different telepresence robots on the market. Similar comparison between robots capable of manipulation and mobile manipulators found during the literature research is in appendix III. Information that are not provided by the manufacturer or seller of the product are left blank. Specifications that are not applicable to the specific appliance are marked with non-available (NaN) status.

From the specifications, we can deduct that the most inspected solutions on the market have similar functionality and construction overall. However, the divide between the robots meant for telepresence and the commercial mobile manipulators is notable: telepresence robots with manipulation functionality are sparsely accessible. Additionally, the solutions combining the functionality of these two groups available are not fulfilling the requirements specified earlier: the functionality or the costs limit these out. This means that there is a need for a novel solution and design to allow more affordable mobile manipulation and communication.

### 2.1.3 Safety standards concerning the project

In the implementation of the telepresence robot there are multitudes of standards that can be applied for efficient and inherently safe design. As there is not one standard for the specific use intended standards for industrial and personal care robots will be applied where deemed necessary. These standards and main concerns are discussed in this chapter.

A basic standard concerning the safety of manufacturing equipment and inherently safe design is the ISO 12100:2013 – Safety of machinery - General principles of design, risk assessment and risk reduction. This standard determines the hazards and guides in the risk assessment and reduction process. The main hazards concerning the telepresence robot and a grabber are related to the kinematics and maintenance. The mechanisms used to drive the robot and parts of the robot should be guarded using fixed protective covers whenever possible, even though in normal operation user should not be near the functioning machine.

A more specific standard defining the safety of industrial robots is the EN ISO 10218:2007. Most of the standards are concern industrial manufacturing equipment where the function is limited to specific area. In the case of freely roaming robots, these standards are currently not applicable exactly.

Other area where safety standards are of importance is the medical (IEC 80601-2-77:2019) and personal care robotics (EN ISO 13482:2014). Robots specified in these standards function in close collaboration with medical personnel and thus the standards defining the use in these cases are. Take the human contact into account much more broadly.

These standards are not defining the exact use and functionality required from the robot to be designed. Therefore, a set of standard practices from both sets must be applied during the design process. An example of a similar use case in semi-autonomous cleaning robots are presented in the book “Human-robot Interaction” chapter 8: use case for an “orphan robot” not applicable to each category (Barattini, Federico, Gurvinder Sigh Virk, *et al.*, 2019). Therefore, adapting standards for similar applications is necessary for this project.

The main way of preventing the robot from causing injury by collision during movement is to determine inherently safe movement speeds for the robot functionality. Inherently safe speeds are low enough to reduce the possibility of impact by allowing longer reaction times and in the case of collision have low enough impact force not to cause a hazard. Limits for safe impact forces are presented in the proposed technical specification ISO/TS 15066 which is planned to be included in the main standard concerning industrial robots in the year 2021. The technical specification can be applied to implement a predictive control system, examples have been discussed in the works of Bogue discussing the standards themselves (Bogue, 2017). Rosenrstauch, Pannen and Krüger have discussed the use of RGB-D cameras for human detection (Rosenstrauch *et al.*, 2018) and Shin et al. the pressure and impact algorithms allowing safe interaction with humans (Shin *et al.*, 2019).

In this project the safety of the designed robot is implemented into a level where the possibility of the semi-autonomous function of the robot is possible in the future. The robot will be used mainly in Hand Guided (HG) operation mode at least soon, but the limited observation and reaction capabilities of the remote operator and the robot needs to be considered in the design, especially within the limit of robot feedback and control delay.

**Table 1.** Main hazards for telepresence robots identified in the standards discussed

| **Hazard type** | **Hazard** |
|---|---|
| Mechanical | Pinching between arm joints |
| | Pinching between arm and body |
| | Pinching between linear axis moving parts |
| | Pinching to steering/drive mechanism |
| | Getting run over by robot |
| | Dropping carried item |
| | Robot losing stability |
| **Electrical** | Electric shock |
| | Loss of battery power |
| **Thermal** | Component Overheating |
| | Material Degradation |
| | Material combustion |
| **Noise** | Loud noises from audio equipment |
| | Motor noises |
| | Noise caused by EMF |
| **Vibration** | Loosening fasteners |

The intention is to implement the mitigation of the hazards in the design inherently as ISO 12100 suggests. Otherwise, the hazards will be addressed in the software implementation and use guidance for the robot. In this project, the suggested step by step risk assessing and mitigation process is left out because of the large amount of time needed and the relatively low hazard severity level compared the industrial machines the standard is discussing. The assessing process was noted to be laborious in the case presented to us by Barattini et al. concerning semi-autonomous vacuum cleaners. (Barattini, Federico, Gurvinder Singh Virk, *et al.*, 2019)

## 2.2 Used tools and software in design and build

Computer Assisted Design (CAD) software package Solidworks 2020 Student edition is used to create and present the robots' models and manufacturing drawings. The version used for the modelling prohibits the use of the models commercially and thus the licences of the software should be updated if the design will be used commercially as planned at the time.

In the manufacturing of the prototype Fusion 360 Computer Assisted Machining (CAM) software is used to generate the required toolpaths. The software was chosen because the tool library was easily available for use with the machinery available at JHC. In addition, the team has previous experience in using the Fusion for CAM application.

Necessary calculations for the design parameters were conducted using Matlab r2020b software. Mathworks Simscape package is used to generate URDF (Universal Robot Description File) for the designed robot model.

## 2.3 Design methodology

In the design, the design process is conducted applying the Systematic Approach of Pahl and Beitz (SAPB) methodology established by Pahl and Beitz. In Figure 3, the basic workflow of the systematic approach is presented. The process is highly iterative and thus backtracking and redesigning is integral part of the process.

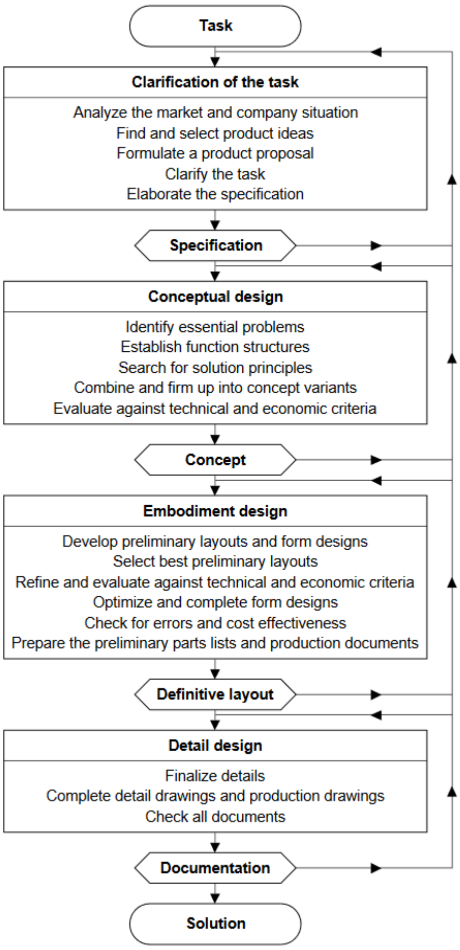

**Figure 3.** Systematic Design Approach (simplified) (Malmqvist *et al.*, 1996; Pahl *et al.*, 2007, p. 4)

The design will be conducted followingly: Finding and listing the main requirements and wishes for the design is don first. These are used to map the most important functionality and design elements required in the design progress. The main goal is to fulfil all the requirements presented and reasonable implementation complexity and cost. In the design use of standard solutions is preferred to novel concepts to allow easier implementation.

Brainstorming and comparing of different ways of implementing the requirement concepts is the basis of the design process. After different solutions have been established the applicability and functionality will be further evaluated and compared. Improved or alternative designs are evaluated, and the best overall solution implemented based on the design criteria. The design is verified so that the functionality can be ensured.

# 3 MECHANICAL DESIGN PROCESS

In this chapter, the design background and the design process are discussed.

## 3.1 Requirements for the proposed design and function description

Requirements for the robot designed are collected and evaluated in this chapter, the comparison of requirements and literature research on available solutions is realised.

For the project in hand there is a need to specify exact requirements and wishes before starting the design process. The requirements are used to guide the progress and help choosing the best solutions for the project. The required solution is a teleoperated presence device with capability to interact with the environment.

Some of the main specifications had already been realised on the previous work. For a more effective presentation and use of these requirements, a table is created and presented in the appendix I. Most important aspects for the mechanical design are presented in table 2 below. In addition to the requirements specified in the previous work more specifications regarding the functionality were gathered from the JHC personnel and people working on the electronics in the previous project phase. In addition, some aspects are specified for the design modularity and standard practices to allow the continuation of the project in the future and applicability for different use environments. The basic functionality the use of plywood in the construction has advantages in the material availability and modifiability compared with common plastic or metallic solutions and thus integral part of the product design. The main idea in the use of Baltic plywood in the construction is to allow the packing of the robot more effectively for shipping. There are possible environmental and functional advantages following the use of plywood that need further evaluation.

**Table 2.** Main requirements for the telepresence robot

| Wish/Requirement | Description |
|---|---|
| **R** | Ability to traverse smooth, carpeted or paved surfaces |
| **R** | Ability to go through doors 90 cm wide |
| **R** | Ability to climb over thresholds of 2 cm |
| **R** | Ability to point and grasp |
| **R** | Ability to push buttons and switches |
| **W** | Ability to lift 1kg load from 0,5 m away |
| **W** | Ability to reach on tables/work surfaces |
| **R** | Clear visibility to surroundings for the operator |
| **R** | Collision prevention with expected surrounding objects and surfaces |
| **W** | Disassembled robot can be packed |
| **W** | Total material cost under 5000 dollars |
| **R** | Screen or rubber head mounted for interaction |
| **R** | Audio equipment for communication |
| **R** | Camera with sufficient ability to perceive surroundings |
| **W** | Camera focusable to objects (height, rotation, tilt movement) |
| **R** | Robot is capable of normal walking speeds |
| **R** | Robot can't cause serious harm to surroundings |
| **R** | Batteries for at least 2 hours of use |
| **W** | Natural/easy movement cabability |
| **R** | Recharging should not need special training (simple recharging) |
| **W** | Ability to initiate charging remotely (docking) |
| **R** | Compliant with necessary standards for robot safety and movement |

In the table any changes and comments regarding the requirements were noted. For example, the arm and camera have gone through a design change even before this project was started, these changes had not been marked in the previous work and came up during the discussion with the personnel. In addition, some aspect regarding the practical use were brought up by Jamie Hyneman in a meeting, working on a similar robot project with his own team. Additions like ease of use with the computer and practical difficulties with the movement discussed and specifications were changed accordingly.

### 3.2 Hardware specified in previous project

Some of the hardware used for the robot have been researched and determined before current work. In this chapter, this hardware is listed, and the functionality discussed.

In the previous work, the basis for the electronics of the telepresence robot is specified. The parts having the most impact on the mechanical design process are the grabber and the camera system. Additionally, the prototype platform created in previous work is not used in the current design. Parts sourced for the prototype will be reused where applicable.

During the requirement specification process for the mechanical design, it came up that the specified arm and camera specifications have been changed: The arm had been changed from Bend 3D Moveo to DORNA arm by DORNA Robotics.

**Figure 4.** DORNA 2 robotic arm and control unit (DORNA Robotics, 2020)

The DORNA arm specified for the project is not currently listed for sale on the manufacturer’s website (DORNA Robotics, 2020). The second generation DORNA 2 is available, but the specifications and price differ from the first version significantly. The project was modified to accommodate the newer version even though the costs and control box specifications were significantly different.

Dorna 2 allows the attachment of different tools using standard screws. The control box allows the attachment of an additional axis to the arm and control with the Dorna framework. In this work the specification of the grabber is left out and left for later as the form of the gripper or tool is changed according to each use case. Different tools, grippers and their attachment systems will be designed and specified later based around 3D printed or other available manufacturing means.

The RIOCH V camera was specified in the previous project to be used as the visual aid for the controlling. The specified camera has a FoV of 360 deg. During previous research work, the camera was deemed inoperable as the specific communication protocols were not working during the implementation and testing of the product. The manufacturer has not provided information to proceed with the use of the camera.

### 3.2.1 First prototype/testing platform

The telepresence robot project had been established earlier. A course work for an electronics course at LUT University has been done surrounding the subject. In this work the aspects of requirements and electronic design of the robot have been discussed and designed. Some of these aspects are included in the table of requirements presented earlier.

In Figure 5, the prototype platform created in the previous project is presented. The platform is not capable of omnidirectional movement. The prototype platform consists of a standard 2020 aluminium profile and has 210 mm wheels. Basic steering mechanism and a single BLDC drive motor are attached to the platform. The steering is implemented using servo and steering linkages.

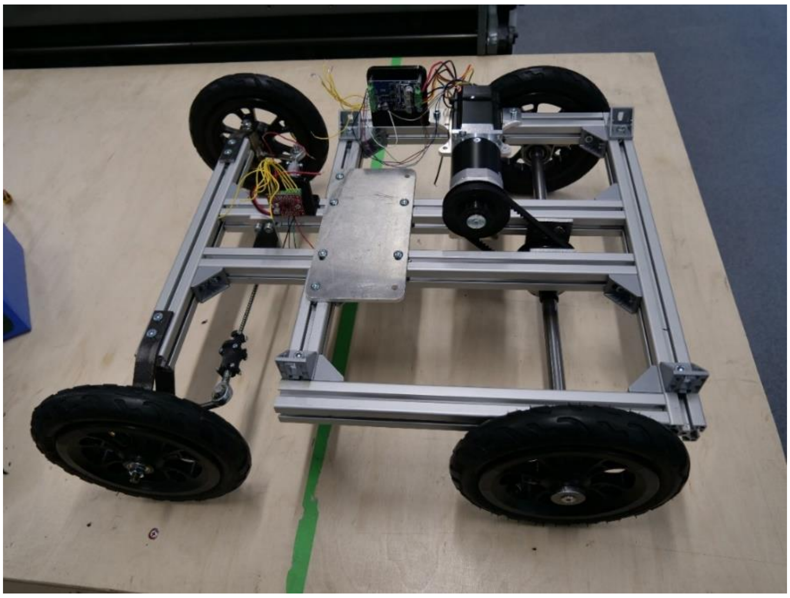

**Figure 5.** Assembly of the first prototype robot (JHC team, 2020, p. 8)

The previous project was made as a part of an electronics course at the LUT University. The main goal of the project was to design and determine electronics for the robot under discussion. The prototype is created mainly for testing the electronics. As such the previous prototype does not fulfil the requirements discussed: The platform is too small to accommodate wanted functionality and the platform is not omnidirectional. Therefore, fully new implementation is designed and built. Similar construction using an aluminium profile is a possibility for the new platform.

### 3.3 Safety in semi-autonomous robots and robot construction

Safety is one of the important aspects when designing a robot for use in environment, where people are working. Even though the implemented robot will mainly be controlled by a human operator over distance, the safety of humans and objects around the robot should be ensured whenever possible. Therefore, the safety system of the robot should be on the level of semi-autonomous robots even in situation where the robot does not have autonomous operating capabilities.

The main intent is to have the robot designed to have inherently safe operation principles. This means that the robot is not capable causing significant harm. This can be achieved by creating covers for parts having the possibility of causing harm to humans or surroundings.

Another way of implementing safety is to provide social safety with audiovisual feedback to the surroundings of the robots' functions before they are executed. Ways of implementing this have been discussed with the use of hand and head gestures (Li and Chignell, 2011) or with the use of a visual representation of the intended movement with the projector (Watanabe *et al.*, 2015). In the design it is decided to use gestures implemented in the software further in the project. Head assembly will include the possibility in movement which will allow gesturing to be done. Additional safety can be implemented with the use of predictive algorithms limiting the speed of the robot when the possibility of contact with the surroundings is apparent.

The robot is to have sensors in the design preventing the possibility of collisions due to the operator error. This means that the robot needs to sense if an object is near, and the operator control would cause collision if continued. This is relatively easily implemented using basic sensors and software.

The fire safety of the intended plywood construction needs to be evaluated. Compared with a fully metallic construction the fire hazard is increased significantly. The flammability and heat degradation properties of birch plywood according to the Handbook of Finnish plywood (Koskisen Group, 2002) are good enough for the intended use case. Problems may arise if there is open flame in or near the robot construction. Therefore, open fire and high heat situation should be avoided. Most probable fire hazard in the construction is the battery. As it is situated under the robot in the case of fire the flame should self-extinguish relatively fast as there is a little change for the smoke to escape from under the robot baseplate.

## 3.4 Robot base assembly

The frame base of the robot is used to attach and contain the most important functional elements for the robot. Solution using aluminium extrusion and Birch plywood were evaluated.

A plywood base is realised to be better solution in this case as it can be routed easily from one piece needing no assembly and construction requires inherently less attaching equipment compared with an aluminium profile; wood screws can be widely used instead of T-slot nuts, bolts, and washers. More positional freedom is also achieved which increases the modularity of the system for possible future additions. Material properties needed in the design process for the plywood components come from the Handbook of Finnish plywood by Koskisen group (Koskisen Group, 2002).

Formed side panel/skirt assembly consisting of two thermoformable plywood panels is attached to the sides of this base using wood screws. Additional support is provided by plywood pieces screwed to the sides keeping two halves together and resting the sides on the base frame. The rest of the system is built over this base frame and the sides bent around it, base frame assembly with the wheel modules provides basic movement capability.

### 3.4.1 Control and I/O

The main computing and control unit of the robot is Intel NUC BXNUC10FNH mini-PC. The NUC is used to run software that determines the robot functionality, control schemes and audio-visual communication. The NUC was left over from the previous project, for future builds other alternatives such as the lower spec intel NUCs, Simply NUC Aspen, Ruby and Topaz can be discussed. Differences between the current NUC and these alternatives are the main processor, expandability, and connectivity.

Additional peripherals are attached to the NUC: these include Arduino in general IO, Electromen EM-356A BLDC motor controllers for drive motor control through a RS485 USB adapter and Trinamic TMCM-6214 stepper controller for controlling the robot steering, head movement and height adjustment. The screen and RGB-D camera are attached to the computer using HDMI and USB cables.

The Dorna arm provides additional IO if deemed necessary further in the project. Future grabber attachment to the arm could use the outputs in the controller to achieve an integrated control of the whole arm with one controller and software package. The controller outputs are only 3,3 V which is important when deciding the connected components; the servos should be capable of 3,3 V input or the level should be shifted to the 5 V logic level common to the hobby servos.

### 3.4.2 Omnidirectional movement

Most commercial telepresence robots discussed earlier are not usually capable of omnidirectional movement instead relying in most cases in the use of two driving wheels with additional castor wheels to support the weight. For the usage in specific environment, the omnidirectionality was deemed to have significant advantages, especially in more restricted areas. For example, in an elevator the ability to turn at place and move sideways enables the fluid pressing of a button for the elevator usage.

Omnidirectional movement with omnidirectional wheels is a solution for natural movement in the environment in the most general cases and in all use-cases specified for the current robot.

Research on the omnidirectional movement and solutions enabling has been well established. Solutions including Omni-, Mecanum-, Powered Castor drives are further discussed.

Many commercial solutions requiring omnidirectional movement achieve it with the use of Mecanum or Omni wheels (Figure 6). These solutions are commonly available and the kinematic modelling for the system is relatively easy. Additionally, omnidirectional movement can be achieved with only 2 to four motors in the system as the direction is controlled by driving the motors in predetermined direction combinations. For these wheel types, the most notable problems are the complexity of the wheel itself and the non-continuous contact between the ground and wheel. When in theory the wheel contact is circular the wheel causes vibration when rotating (Park *et al.*, 2016; Taheri and Zhao, 2020). Additional problems mentioned in the literature are the low ride height and slippage of wheels, especially in the case of omnidirectional wheels that allow free movement perpendicular to the wheel drive direction. (Taheri and Zhao, 2020)

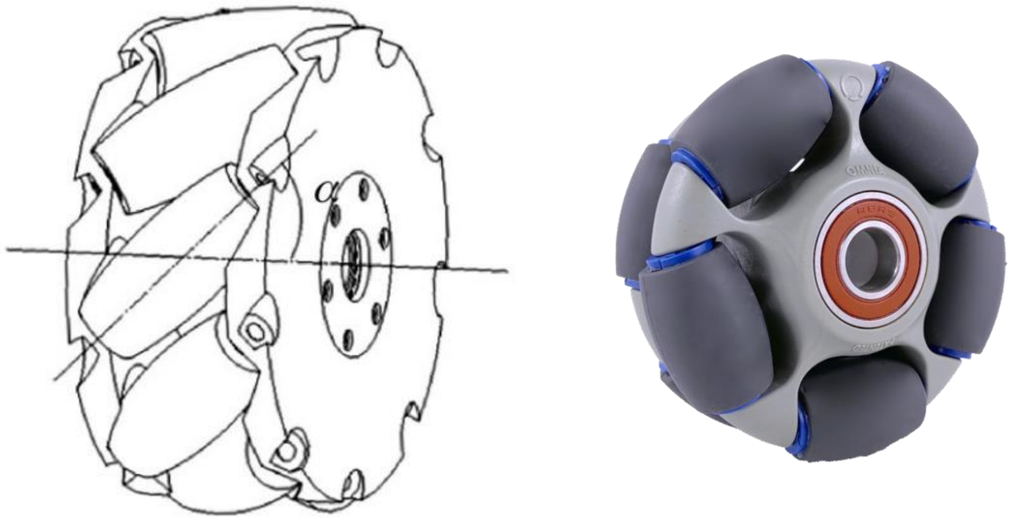

**Figure 6.** A) Mecanum wheel (Guo *et al.*, 2016) b) Omni wheel (Rotacaster, 2021)

A solution using two BLDC motors attached to a freely swivelling configuration were noted to be a possible solution to implementing omnidirectional movement. In this configuration, the two motors when driven at the same speed go straight and if driven differently rotate around the swivel axis. Use of three of these allows movement in every direction. The lack of research, a need for electric contactor assembly and difficulties obtaining the specific type of motors with sufficiently short length compared to torque required were the main reasons to abandon this drive method. Six drive motors would be needed for implementation therefore increasing costs. Future research should be considered for the use of this method in robotic solutions.

A swerve drive or a powered castor wheel is a solution that allows omnidirectional movement and eliminates the shortcomings of Mecanum and Omni wheels in the regard of vibrations and slipping, still allowing the installation of the motors to be installed inside the main body. The main disadvantage being the increased complexity in the mechanical implementation and the need for additional steering motors. These kinds of powered castor wheel solutions are used in the industry in Autonomous Guided Vehicles (AGVs) where supported loads are often much higher than in our use case.

During the design it was realised that commercial solutions made for AGVs are often not applicable in this case. Most available solutions were designed for greater carry capacities requiring heavyweight construction and powerful motors, usually over 250 W. An additional disadvantage of the modules was a low wheel diameter possibly causing difficulties climbing obstacles or vibrations on uneven surfaces. Therefore, it was decided to design and create a wheel module for this use case.

**Figure 7.** Powered caster wheel module for Automated Guided Vehicles (Kelvin Elettromeccanica, 2020)

The type of module allowing locating the motors inside of the robot frame is deemed to have more appealing construction and visual properties for the intended use case. A version of swerve drive with both drive and steering motors situated vertically on top of the module is available on the market but has the same sizing and pricing problems as the module presented previously.

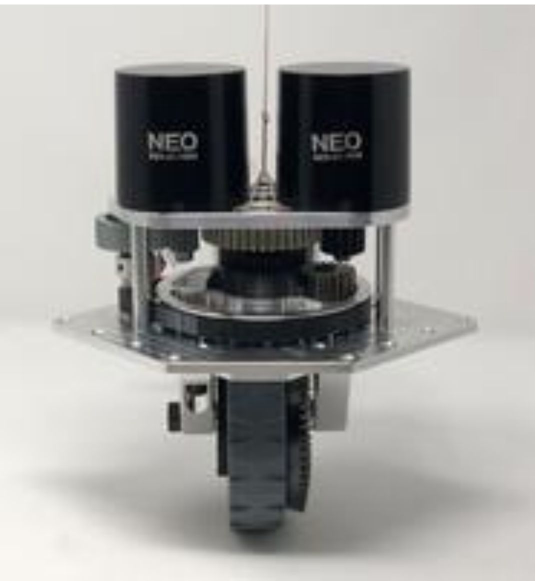

**Figure 8.** Swerve drive module with motors on top of the module (Swerve Drive Specialties, 2021)

To realize the exact mechanical requirements for the base frame two aspects needed to be established: The robot physical weight and dimensions in addition to the environmental challenges to determine the carry capacity and the power in the drive system.

The requirements for the drive motor and wheels were calculated using preliminary Bill of Materials (BOM) to calculate the weight of the final robot. The robot weight is estimated to reach up to 50 kg including all the components.

The environmental worst cases were determined with the use of guidelines for accessibility by Finnish Environmental Ministry which are followed in the building all around Finland. Similar guidelines for accessibility are in use in other European countries. In these guidelines, accessibility ramps are specified to have at least a width of 900 mm and maximum incline of 8% (Ympäristöministeriö, 2018, p. 14). In the design process incline of 10% (5,71 deg) was used to include some factor of safety in the calculations.

A minimum wheel radius to achieve the desired climbing ability is calculated according to equations presented by Thomas and Vantsevich (Thomas and Vantsevich, 2010). All the three wheels in the construction function in the driving mode described as they are driven by motors.

The minimum radius for wheel $r_{min}$ capable of climbing over an obstacle with known height $h_0$ is calculated with equation (1). The desired threshold height is 2 cm.

$$r_{min} = \frac{(h_0 + h_{zs})\sqrt{1 + (\mu_p W_w - \frac{F_{frame}}{W_w} + \mu_p F_{frame})^2} - h_n}{\sqrt{1 + (\mu_p W_w - \frac{F_{frame}}{W_w} + \mu_p F_{frame})^2} - 1} \tag{1}$$

where $h_{zs}$ is the ground deformation set at 5 mm to increase the safety margin in case of softer terrain, $h_n$ is the wheel deformation estimated to be around 5 mm for the softer TPU wheel hitting the obstacle, $W_w$ is the weight of the vehicle set at 50 kg, $\mu_p$ is the factor of gripping in the contact with the value of 0,6. $F_{frame}$ is longitudinal force acting on the wheel caused by the frame and in the worst possible case is 0 N.

It was determined that the minimum wheel radius to allow climbing over the specified threshold is 25,1 mm. Standard wheel solutions exceeding this theoretical minimum were therefore further researched. Larger wheels have additional advantages over small wheels such as smoother ride over rough terrain and reduced wear. Therefore, larger wheels are preferred in the design.

It was determined that wheels with a diameter of 100 or 110 mm are readily available for the use in skating and kick scooter applications with affordable prices. These wheels have common standard installation with the width of 24 mm and often the standard 608-ZZ bearings are integrated into the wheel. Possibility of choosing the hardness of the polyurethane (PU) tread is additional advantage in these wheels allowing specifying the needed hardness and grip according to the use environment. If the wheels for some reason are not available, it is possible to cut an alternative wheel in the same size from plywood and use an O-ring for the tread. The theoretical threshold climbing capabilities with wheels with a diameter of 100 mm and 110 mm are 39,9 and 44,9 mm respectively.

Wheels with a diameter of 110 mm and with the PU hardness of A85 were ordered for the prototype. The TPU hardness affects the grip, rolling resistance and noise of the wheels. The hardness of TPU should be determined individually for the main use environment, but any hardness between A85-A90 should be good for general use. The wear resistance of the wheels is good in the used relatively slow speeds.

Preliminary requirements for the drive motors were calculated using an online tool (‘robotshopmascot’, 2013). The parameters were determined as described for three drive wheels and an incline of 10%. The speed and acceleration were set at 1 m/s and 0,2 $m/s^2$ respectively. The robot is specified to have a mass of 50 kg. Results indicate that the drive motors with power of 50 W are sufficient and nominal rotation speed at wheels should be around 180rpm. The results are used to search for motor models fit for use.

With these parameters, a Brushless DC motor commonly known as BLDC is specified. A solution using standard NEMA mounting pattern for the motor is preferred to allow better modularity in the future if the motors need to be changed. The required power of around 50 W can be commonly found in standard NEMA size of NEMA17 that has 42 mm flange width. Originally use of bigger NEMA23 or 60 mm BLDC motors were planned, but later it was determined NEMA 17 have better suited dimensions and properties for the use case.

The Nanotec DB43M024030-A 53W motor and a planetary gear GP42-S1-4-SR with a gear ratio of 1:3.93 were determined to be feasible solution for the current prototype. The main limiting parameter for a motor-gearbox combination is the maximum combined height of 132 mm in the current design. In the future, the frame height can be adjusted to accommodate longer motor-gear combinations if necessary.

A bevel gear pair with module 2 and gear ratio of 1:4 was deemed fitting for the drive. The main driving parameter is the geometry of the gear pair: Larger gear attached to the wheel allows the use of shorter drive shaft and smaller driving gear allows for less offset for the wheel from the steer axis. These are desirable properties to allow more compact design with less undesirable forces caused by longer engagement distance in use.

Injection moulded plastic bevel gears are used in this situation as they are relatively inexpensive in comparison with brass or steel gears and have self-lubricating properties. Gears manufactured from Polyacetal, Polyketone or Nylon are available on the market. The final gear ratio from the drive motor to the wheel is therefore 1:15,92. with the nominal rotation speed of 3000 rpm at the motor the nominal rotation speed for the wheel is 188,5 rpm. This means a nominal velocity of 1,09 m/s for the robot using 110 mm wheels which is close to normal walking speed specified in the requirements.

The drive shaft is routed through the rigidly attached main axle with the use of two MR128-ZZ miniature ball bearings. These bearings support the tangential loads caused by the geometry of bevel gearing. Axial loads caused by the gears are supported by the motor gearbox in the other end of the shaft while the axle and the smaller bevel are resting on the upper bearing when in rest. Main driving characteristic of choosing the bearing type in this case was the size requirement when implementing an axle inside another construction.

The forces in the bevel gear pair need to be assessed to determine if they are sufficient for the use case. Additionally, the bevel gear pair causes the axial and tangential forces of the drive shaft which is to be assessed to determine load on shaft bearings. The maximum drive torque at the bevel gear can be evaluated using the tables and calculators provided by the manufacturer: Norelem specifies the maximum torque for the smaller gear to be 80,4 Ncm which is higher than the nominal output of the specific drive motor is at 60,8 Ncm.

The radial load on the bearings is calculated according to the following equations given for standard bevel gear pair in the technical handbook (Valtanen, 2016, pp. 924–925). The bearings are not carrying axial load. Axial load is supported by the planetary gearbox bearing.

The radial force $R_n$ in bearing for a shaft supported by two bearings can be calculated using equation (2).

$$R_n = \sqrt{P_n^2 + U_n^2} \tag{2}$$

The radial force component caused by axial force is defined with equation (3)

$$U_1 = \frac{S_1 r_1}{b_2} \tag{3}$$

where $r_1$ is the contact radius of the gear $b_2$ is the distance from bearing 1 to bearing 2 at 56,5 mm. The radial force component $P_1$ caused by tangential force $F_{t1}$ is defined by equation (4)

$$P_1 = \frac{F_{t1} a_1}{b_1} \tag{4}$$

where $a_1$ is the distance from a gear contact point to bearing 2 being 91,65 mm and $b_1$ is the distance from a gear contact point to bearing 1 being 35,15 mm. The axial force $S_1$ in the drive axle caused by the bevel gear geometry is calculated in equation (5)

$$S_1 = F_{t1} \tan(\alpha) \sin(\beta) \tag{5}$$

where $\alpha$ is the pressure angle of the gear pair chosen at 20 deg and $\beta$ is half of the reference cone angle of the smaller bevel gear with value of 17 deg. The resulting axial force is 2,10 N which is under the static rating of 545 N for the planetary gearbox of the motor (Nanotec Electronic GmbH, 2021). The tangential force $F_{t1}$ caused by drive torque is calculated using equation (6) where $T_{max}$ is the maximum drive torque at the smaller gear specified by the manufacturer at 0,81 Nm.

$$F_{t1} = T_{max}/r_1 \tag{6}$$

In the second bearing the radial force can be calculated using the same equation (2) the radial force component $P_2$ is calculated with equation (7)

$$P_2 = \frac{F_{t1} b_1}{b_2} \tag{7}$$

and the component $U_2$ caused by axial force is equal to $U_1$ defined with equation (3). The resulting radial forces at the bearings are $R_1 = 51{,}38$ N and $R_2 = 31{,}67$ N. The specific basic dynamic load rating $C_r$ for the bearing is 545 N (NSK, 2011). The dynamic equivalent bearing loads $P_{r1}$ and $P_{r2}$ are equal to the radial load ratings $R_1$ and $R_2$ calculated previously as the bearings are not supporting the axial load. The life rating $L_{10}$ for the bearings is calculated according to standard ISO 281 with equation (8).

$$L_{10} = (\frac{P_{rn}}{C_r})^3 \tag{8}$$

The life ratings $L_{10}$ for bearings are $1.19 \cdot 10^3$ and $5.09 \cdot 10^3$ million revolutions respectively. This value means infinite rating in practice as the maximum speed of the drive shaft is around 660 rpm.

The steering motor is attached to the wheel module with a 3M timing belt and with pulleys 12T and 72T providing a reduction of 1:6. Standard NEMA17 motors with a position encoder are used. The encoder with 400 steps can effectively follow if the motor is losing steps during use. The chosen controller does not support closed loop control; therefore, corrections should be made in software if necessary. In the future, the requirement of encoders should be further assessed. The required torque at the motor is 1,2 Nm and no additional gear reduction is required. This is enough to hold the wheel steady during acceleration or braking. Standard PNP-type Inductive sensor and sheet metal tab are included to allow sensing of the zero position in addition to the encoder integrated into the motor. The sensor provides a signal to the stepper controller when the tab is under it.

The components specified are mounted into module frame laser cut from 2 mm structural steel sheet. 2 mm sheet was chosen to avoid excess bending in the module during use. The same thickness is used for all the components manufactured from sheet metal to avoid an unnecessary addition of different material thicknesses or types. A riser mount for the drive motor is cut and bent and attached to the main plate using M5 rivet nuts and M5 bolts. A part manufactured from sheet metal is used to attach the wheel to the bearing housing made of plywood. The bent flanges are providing additional stiffness for the part and allowing the precise attachment of components. A mount plate for the bevel gear is also cut and uses rivet nuts. The plate ensures correct placement and spacing for the screws used attaching the bevel gear to the wheel. The manufacturing drawings for these four components are in appendixes IV-XI.

Bearing is needed to allow rotation around the steering axis. These bearings are carrying the robot weight on their axial direction. Additional torsional loads are to be expected during normal use. Solutions using multiple bearings were discussed but a solution using one dual row angular ball bearing was realised. The bearing can support all forces in the use case simultaneously allowing shorter construction for the steering axle. The bearing is oversized for the design load as the drive axle needs to be routed through the steering axle. This at the same time reduces the compression load of the bearing surface in the plywood part used for the bearing housing.

In the designed implementation there are some drawbacks that are addressed in the design. Most of the drawback are associated with the wheel contact point offset of 28 mm from the drive axis which can be seen in Figure 9.

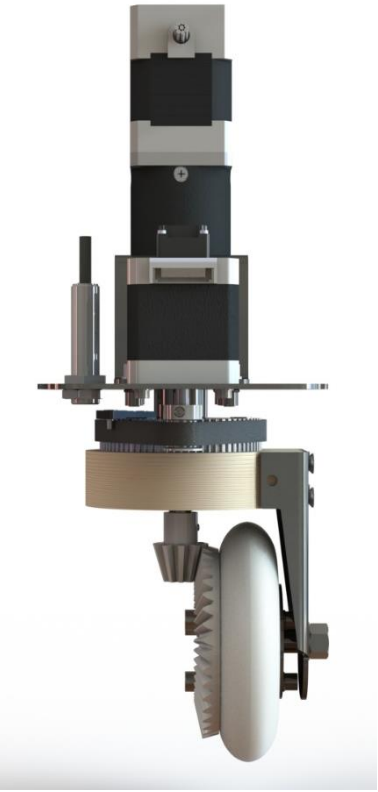

**Figure 9.** Wheel contact offset from main axis in implemented module

The offset $r_s$ of 28 mm causes additional torsional torque for the wheel assembly relative to the robot mass. This is supported by the steer bearing. Additional load for the steering motor is caused by the drive torque which might cause a loss of steps and steering errors. The effect of the drive torque is calculated to check if the steering motor can handle this load. The maximum load torque for the steering motor at the wheel axis $T_{smax}$ is calculated with equation (9). $T_{wmax}$ being the maximum drive torque at the wheel of 3,24 Nm and $r_w$ the wheel radius of 55 mm. The torque at the motor is one sixth of this due to the drive ratio.

$$T_{smax} = r_s \frac{T_{wmax}}{r_w} \tag{9}$$

The maximum torque $T_{smax}$ at the steering axis is 1,65 Nm which means that the steering motor is under a load of 0,275 Nm in case where full drive torque is applied. This is well below the hold torque specification of 0,48 Nm for the motors used and allows possibility for driving the motors with lower current when stationary to increase efficiency.

In Figure 10, the exploded view of the wheel module is presented. The exploded diagram helps to visualise the wheel assembly part locations and assembly direction.

**Figure 10.** Exploded wheel module assembly

### 3.4.3 Robot battery, power distribution and charging

A battery is specified to have at least 2 hours of functional run time. This can be achieved with a battery having the capacity of larger than 300 Wh assuming average power consumption between 100 and 150 W. A battery with capacity of 510 Wh is chosen for the first prototype, the battery can be changed if capacity is deemed unsatisfactory. The frame provides room for larger ones. The battery is capable supplying continuous 900 W and should therefore be safe to use even in extreme situations. The battery has a protection circuit to prevent damage to the Li-Ion cells. The battery voltage is specified so that used components can use it effectively. Seven cell Li-ion batteries are available for use in electric bicycles. These batteries have voltage range between 22,1-29,4 V depending on the charge state. This voltage range is suitable for most components having the nominal voltage of 24 V. During the design process, the components were checked to have the maximum continuous voltage of at least 30 V. components with lower nominal voltage will be powered using isolated DC-DC power converters. Mean Well units SD-100B-12 and SD-15B-5 are used to provide 12 V and 5 V the rails of 100 W and 15 W respectively. RSD-60G-5 can be used if more 5 V power is desired for the servos and Dorna controller. Additionally, TDK i6V converter is used for providing 19 V for the Intel NUC, which has the power requirement of 120 W. The output voltage of the TDK can be adjusted to this level using 680 Ω set resistor according to the TDK datasheet.

The robot will house a Li-Ion battery under the base plate. The battery will be attached using belts screwed to the bottom of the plate. The battery is connected to the charging circuit using XLR plug installed by the manufacturer and main power with XT-60 plug. The main power is routed through a fuse box with six fuses. The power distribution and fuse values are shown in Table 3. The Power values are calculated using the maximum peak power consumption of appliances and includes the efficiency losses of said components.

**Table 3.** Fuse values and circuits

| **Circuit** | **NUC + 12V** | **Dorna + 5V** | **Stepper driver** | **Drive mtr L** | **Drive mtr R** | **Drive mtr F** |
|---|---|---|---|---|---|---|
| **Fuse** | 15A | 15A | 10A | 5A | 5A | 5A |
| **Max Power** | 300W | 300W | 230W | 50W | 50W | 50W |

The fuse box is situated between the battery positive and positive terminal of appliances. The negative terminal of the battery is connected to appliances using a ground rail made from aluminium U-profile which is situated to the bottom of the robot. Cables are connected using crimped ring connectors, screws, and nuts.

A Panasonic AHS power relay is used to electronically disconnect the battery from electronics to avoid sparking when connecting or disconnecting the battery and allow disabling the power from the robot without disconnecting the battery. The relay can disconnect 30 V DC 30 A power according to the datasheet. The relay is actuated using a power switch situated in the back of the robot and allows disconnecting the battery from all the electronics except emergency stop and main power switch. A 68 Ω resistor is added between the coil and switch to limit the input voltage to a safer level for the relay in continuous use.

Possibility for a docking station for the robot is included in the prototype plans but is not manufactured in the scope of this thesis. The main function of the docking station will be to charge the robot through contact points included in the robot construction. Possibilities for additional functionality in the docking for example tool changing is left out of the scope of this project.

Spring contacts manufactured by MillMax are included in the construction attached to the front of the robot using screws. The threads in the contacts were drilled and tapped for metric M3 thread instead of the original thread.

A docking capability was wished in the specification phase. A simple docking station with appropriate contacts connected to a charger is sufficient to implement the functionality. The more difficult part of docking is the guidance of the robot to the docking station for charging. Solutions to guiding the robot to the charging station will be left for future work. Implementation could be achieved using the RGB-D camera and a target point. Work done Cassinis et al. on the docking navigation approach could be used for the ground work (Cassinis *et al.*, 2005).

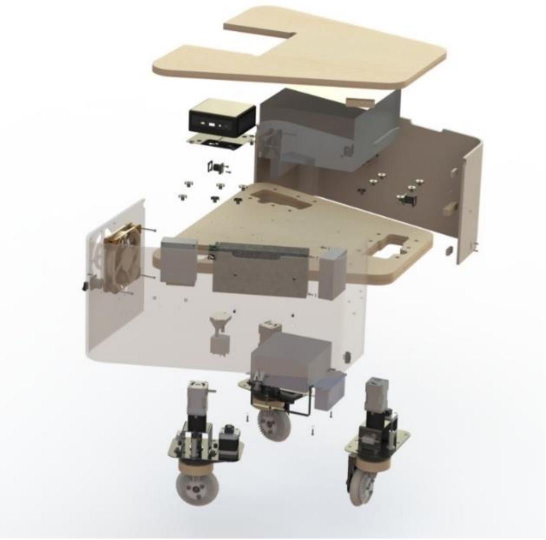

**Figure 11.** Exploded view of robot base assembly

## 3.5 Body of the robot

The robot body construction is attached to the base consisting of the main plate and wheel modules. The body includes the tower and other functional components required for the robot.

Most of the components listed are relatively self-explanatory. The components are mounted into the frame with the use of expanding screw inserts and machine screws. Threaded screw inserts are an alternative to the used ones if available.

For obstacle avoidance MaxBotix MB-1010EZ sonar sensors are added to each side of the robot base. Maxbotix has sensors with different detection pattern if 1010 model is deemed to be unsuitable for the intended use problems. These sensors are attached to Arduino for distance measurement. Sensors can be chained together to avoid crosstalk and interference. Chained the sensors will measure distance one at a time taking 50 ms each, so for 4 sensors the overall poll rate is 200 ms.

The sensors are attached to the inside of the side assembly with two M3 bolts and the sensor element is put through a 16,8 mm diameter hole. A 3D printed spacer is designed to protect the components in the front of the PCB from being compressed during the attachment. Header rows or screw terminals with the spacing of 2,56 mm are soldered to the sensors to allow an easy connection and disconnection of the cables when necessary.

Alternative sonar sensors HC-SR04 should be tested for future use as the cost is around one eight compared with the MaxBotix model line. Unfortunately, the documentation is lacking for these sensors and thus for the first prototypes easier solutions to implement and troubleshoot are desired. For the use of HC-SR04 solutions chaining multiple sensors together are available (Octosonar, 2020) and should be tested in the future for use in place of the more costly MB10xx sensors.

In current prototype design three additional HC-SR04 sensors are attached to the tower assembly to allow the detection of tables or other objects around the same height. These sensors allow the increased reliability of the collision detection. The sensors are attached using 3D-printed case screwed to the outside of the tower. Cables for the sensor are routed through a 12 mm hole drilled through the sides and service hatch.

The acoustic performance of the robot body cannot be trivially evaluated. Therefore, the possibility of excessive noise generation is there, even if hazardous noise levels are not expected. Possibility to add dampening material to the inside of body panels could alleviate problems if they arise during robot usage.

Most of the components installed inside the robot generate heat in use. Therefore, it is necessary to design active cooling for the system to avoid overheating the components (CPU, Motors, Controllers, PSU). The cooling of these components is achieved with the addition of two 120 mm computer fans to the back of the body. The airways are cut to the plywood during the routing process.

Fans are to be connected to the 12 V power to limit the amount of noise. Additionally, the fans purchased for the prototype have the maximum allowed voltage of 27,6 V (Sunon, 2008) and thus cannot be powered safely straight from the battery. Possibility of adding a control circuit for the fans can be done in the future if deemed necessary for more effective cooling and less fan noise is desired.

### 3.5.1 Component mounting

The control electronics are mainly mounted into the walls of the body using M3 threaded inserts to enable the use of standard M3 machine screws and to ensure the longevity of mounting in the case of multiple reattachment cycles of the components. Expanding type of thread inserts can be used if threaded models are not available.

Most of the PCB’s have surface mount components and leads on the side of the board going against the wall. For these components, plastic risers with the height of 3 mm are used to lift all the components and component leads off the wall. In theory plywood has high enough isolation capability to allow the powered traces or lads touching without problems but it is good practice to ensure that short circuits are not happening even in adverse conditions.

In some locations where the mounted component is light and under no stress the M3 screws can be tapped straight to the plywood. For example, in the current design the end stop micro switches are mounted using M3 screws tapped to 2,5 mm holes in the plywood. In future revisions the necessity of inserts in the attachment of PCB: s should be further evaluated.

### 3.5.2 Tower and linear assembly

Tower assembly accommodates the linear axis built from plywood components to allow the height adjustment of the manipulator and the screen assembly. The plate which accommodates the components has four LV201 track rollers guiding it on rails manufactured from plywood. The rollers are mounted using standard M12 bolts. The linear movement is drive with a NEMA 17 motor and 12 mm trapezoidal lead screw situated at the top of the tower. The lead screw nut is situated to a plywood block attached to the main plate. It was determined that separate brake is not needed as the lead screw has sufficiently low efficiency to prevent back driving.

Aluminium U-profiles are situated to the sides of the tower assembly to guide bellow covers used for the visual and touch cover of the parts not covered by the linear plate. The two bellow covers are 140 mm wide and 5 mm thick. The closed length is 50 mm and maximum opened length is 350 mm allowing the full designed movement. Covers are attached to the linear plate using velcro tape. Other ends are attached with velcro tape and 3D printed plastic stops glued to the rail ends.

Cabling for the electronic components situated in the linear assembly is routed through a cable chain to allow safe movement. Cable chain with the inner size of 15x20 mm was deemed large enough to accommodate the cables. The cables include the HDMI-, USB- and audio cables to the screen and RGB-D camera, head movement motor cables and power for these components. Cables going to the screen assembly are routed through a hole made to the bellow cover. The necessary length for the chain was calculated using equation (10)

$$L_K = \frac{S}{2} + \Delta M + K \tag{10}$$

Where $L_K$ is the required length of power chain $S$ is the maximum movement length of the linear assembly being set at 400 mm. $\Delta M$ is the deviation of 280 mm from the fixed end from movement mean point in the direction of movement. The constant K is calculated using equation (11). $R$ being the bend radius of the power chain specified at 18 mm in this case and $T$ is the chain thickness of 10 mm.

$$K = R\pi + 2T \qquad (11)$$

The required cable chain length is determined to be around 460 mm. Cable chain up to 500 mm can be used with the cables used the first prototype. One of the ends of the cable chain is attached to the wall of the tower assembly and another is attached to a plywood part sticking out of the linear plate assembly. The cable chain width is 20 mm and depth 10 mm. The bend radius of the cable chain is 20 mm, but this can be increased in the future to reduce stress on the cables inside the chain.

The cables from the Dorna control box to the arm are routed separately due to the short length and thickness of the cables. These cables are hanging freely from the bottom of the linear plate assembly. Enough clearance is provided in the tower to allow the free movement of the cables.

A T10x2 lead screw would have been sufficient for the use case, but as the screw is supported only from one and the other end is free. According to chart shown in Figure 12 the critical rotation speed of T10 screw of around 850 rpm is deemed too close to the desired velocity range of the linear movement. A standard T12x3 screw is therefore used which has a critical rotation speed around 1500 rpm, which allows sufficient linear speed for the axis with enough factor of safety. The maximum speed should be kept under 80% of this in use. Additional advantage is the 3 mm pitch that allows faster linear movement with the same rotation speed.

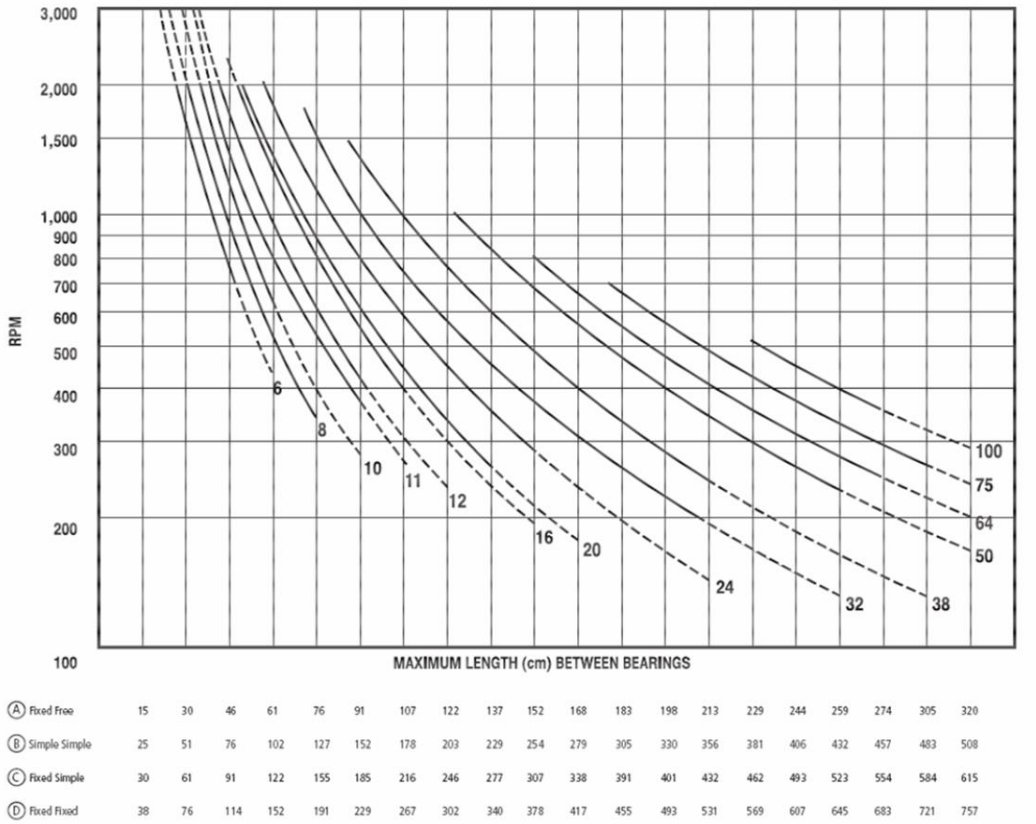

**Figure 12.** Lead screw critical speed chart (Huco Dynatork, 2020)

In Figure 13 the exploded view of the tower assembly is shown to visualize the assembly and parts.

**Figure 13.** Exploded view of the implemented tower assembly

### 3.5.3 Head/visual instruments assembly

Robot head is implemented to allow gesturing and a free view to the environment. Originally a RIOCH V camera with a 360-degree Field of View (FoV) was to be provided for the guidance of the robot remotely. During the previous work it was determined that the camera is not allowing necessary functionality to be effectively use. Therefore, RIOCH V is left out of the current prototype plan. An additional camera can be added in the future if deemed necessary for effective visibility for the operator.

An RGB-D camera was a deemed cost-effective addition to the robot construction, allowing depth data to be collected of the surroundings. RGB-D cameras measure depth in the environment using visual technologies. This enables safety and manipulation assistance for the control of the robot. Intel D435i was deemed good solution for the prototype as it has relatively low MSRP of 200 dollars and allows a broad array of software control for the user. Vit and Shani have done the comparison of performance of RGB-D solutions available on the market in agricultural use(Vit and Shani, 2018). An additional survey has been done by ROS-Industrial project (ROS-Industrial, 2020) and by Halme et al. concerning all visual safety systems available (Halme *et al.*, 2018). The camera has an integrated Inertial Measurement Unit (IMU) Integrated in the construction that provides data for robot movement correction and collision detection purposes. The head assembly is attached to equally linear assembly as the arm, this way the distance between the arm and screen is constant.

The mount is specified to have three degrees of freedom: height, pan and tilt. These allow relatively broad look into the environment and flexibility to allow the implementation of human gestures for more efficient interaction during use. Both axes have a microswitch to provide a zero-point signal to the stepper controller. The microswitches are wired in Normally Open (NO) arrangement.

The screen is attached using standard Flat Display Mounting Interface (FDMI) mount points also commonly known as VESA standard. The plate cut from plywood is specified to include mount points in 75x35, 75x75 patterns specified in the standard in part C and small displays in part D with flat or raised mount type and that weight under 4,5 kg (VESA, 2006). The plate allows the mounting of the screen horizontally or vertically. The FDMI allowable weight of 11 kg for bigger screens specified in part D is deemed unnecessarily heavy to effectively implement for this use case. Misuse of the mount should be prevented with warnings in the quick start guide of the robot.

The vertical movement of the screen and camera is made with the aid of standard hobby servo attached to the plywood plate. The servo was used for this use case as they are relatively compact and affordable in comparison with a custom solution using a standard stepper motor. The torque requirement for the servo was calculated with the maximum load of 4,5 kg on the assembly. A servo with the torque of 1,1 Nm was deemed sufficient but a higher torque servo was chosen to allow sufficient unpowered torque. This way the screen will not drop down freely in case of unexpected power loss.

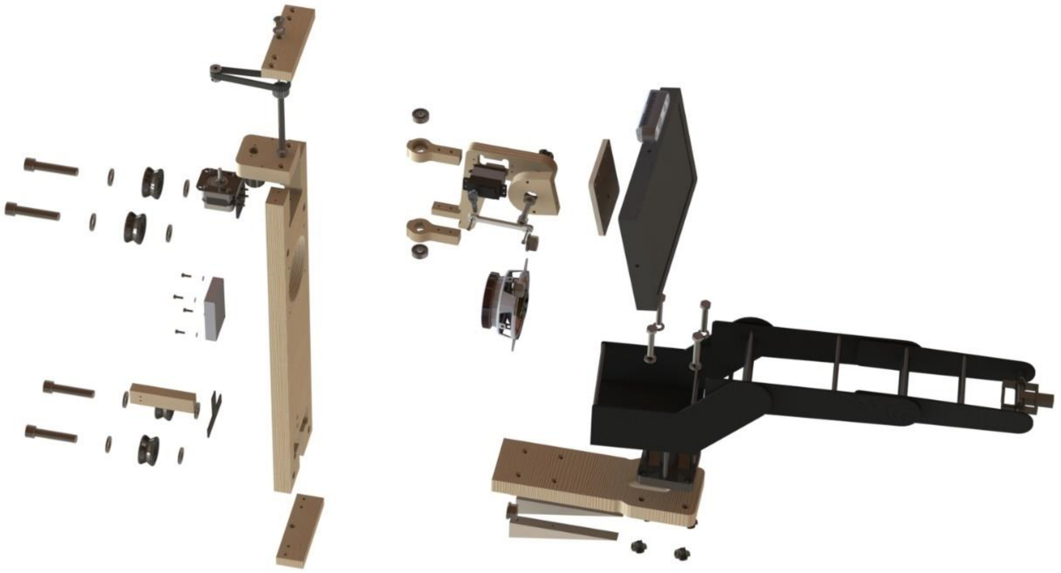

**Figure 14.** Exploded linear- and screen assembly

## 3.6 Robot Stability Evaluation

The stability of the design needs to be evaluated. The main parameters affecting the stability are the environmental effects, mainly the maximum incline/climb. The robot centre of mass and acceleration of the robot and parts of the robot causing the inertial shift during movement.

The stability in static situation is evaluated using the maximum incline angle determined by the recommended maximum ramp angle of accessibility ramps in Finland. The incline of accessibility ramps should be under 8% which is equal to an angle of 4,76 degrees. The robot should be stable when on such incline.

The robot centre of mass is determined using the 3D model created. The maximum shift in the centre of mass is determined mainly by the orientation of the arm holding a load and the screen position. 9 separate positions causing a maximum shift in the centre of mass were determined according to Figure 15 the values output by Solidworks for this case are shown in appendix XII. Note that in Solidworks the Y and Z axis are swapped in comparison with the coordinates used in elsewhere in this report.

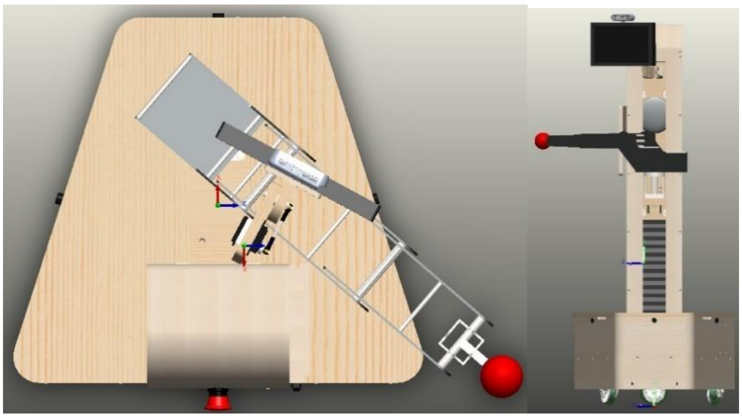

**Figure 15.** Example of determining centre of mass static limits

A spherical model created of the limits of the mass centre shift seen in Figure 16. If the angle of line drawn between wheel support points situated in the circles marked blue and this sphere has an angle greater than the inclination angle, the robot should stay stable in the incline. In the figure red points show the wheel centre axis, contact points of interest and centres of mass measured using the 3D model. The red star shows the worst-case centre of mass possible in our case.

The support points of wheel change according to the orientation of the wheel as the steering axis is different from the wheel point of contact.

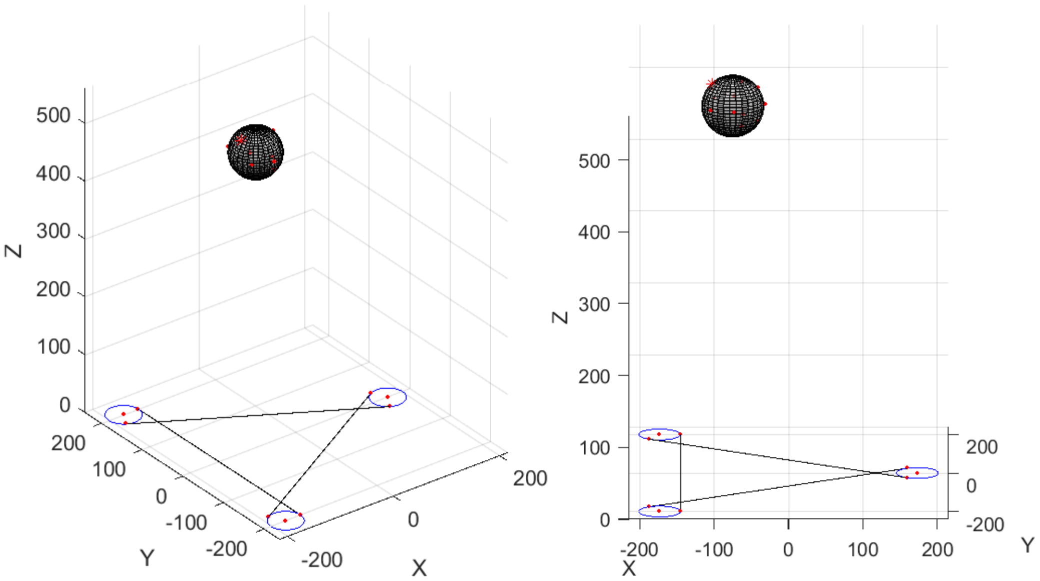

**Figure 16.** Stability inspection in Matlab a) Isomeric view b) from right side

The absolute worst case the robot will fall backwards when the back wheels are both oriented sideways in a way where the contact points are as far forward as possible. In this case if the fully loaded arm is pointed straight back the incline that causes the robot to fall would be 4,46 degrees. This does not exceed the requirement specified, but it is to be noted this situation would require three individual actions to happen simultaneously:

1. The robot is on an incline over 4,5 degrees
2. The robot back wheels are oriented sideways so that the contact points are as forward as possible
3. The controller of the robot reaches blindly as far back and up as possible with full load

The probability of all three happening simultaneously is low and can be avoided by the controller or with software limitations. Second worst and more likely situation where the robot loses stability when driving straight up the ramp. In this situation, the contact point is 28 mm further back compared with the previous situation. In this case the angle where stability is lost is 7,40 degrees. This allows the climbing of accessibility ramps even in situation where the arm is fully loaded and pointing back, which in their own case are relatively uncommon use cases. As the absolute worst case is well in the design specification other situations need no further inspection.

The stability during acceleration needs to be evaluated. The acceleration causes inertial force F that is relative to the mass and acceleration of the robot. With the high acceleration of 0,5 $m/s^2$ and robot mass of 50 kg, the force is 15 N. This causes the previously calculated fall angle to decrease to 2,92 deg. This means that the stability is lost if the robot is accelerating up a slope with an angle of 4,47 deg. The designed maximum robot acceleration is lower than this and the previously mentioned assumptions of the situation still apply. Therefore, the situation where this loss of stability happens is minimal and can be accepted in the design.

## 3.7 Prototype manufacturing and assembly

The prototype manufacturing is started by sourcing the required components and materials. The components were sourced from online retailers shipping from Europe. Components were ordered mainly from bigger multinational distributors who have warehouses in Europe, disregarding single items not available from these that needed to be individually sourced. Plywood was provided by the company interested in acquiring telepresence robots and structural steel required available from JHC or LUT Voima which manufactures the sheet metal and axle components for the prototype out of structural S355 steel. Most of the plywood parts were CNC routed or laser cut with the tools available on JHC premises.

Assembly of the prototype was started with the components first available for use. The first components manufactured were for the screen arm and tower assembly as most components for the full assembly arrived first. In Figure 17, the screen arm assembly can be seen with the 10,1” screen installed in the plywood plate using M4 screws. The Intel D435i RGB-D sensor is installed on the screen using ¼” to ¼” camera adapter fitting the standard camera stand screws in both components.

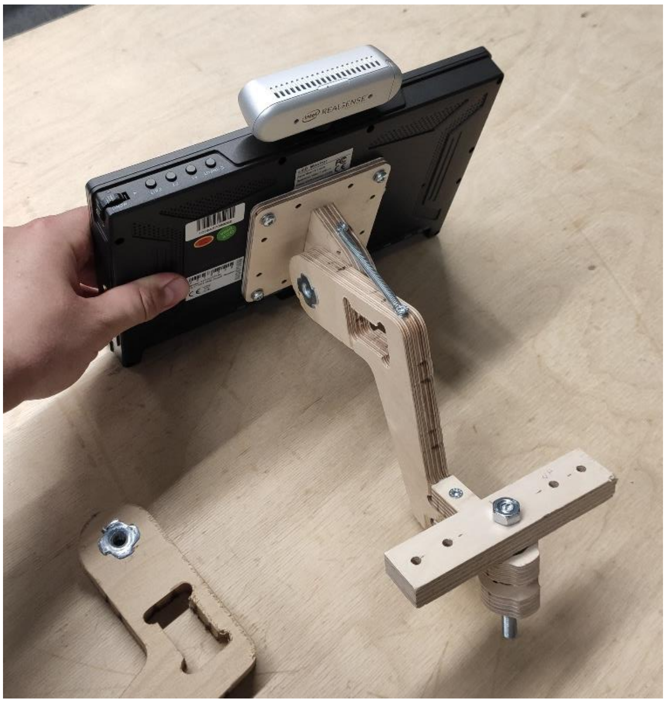

**Figure 17.** Beginning screen arm mechanical assembly

The tower sides were marked using a laser and cut manually using rip and band saws. Finishing was done with a belt sander. Attachment holes for components were drilled with a battery-operated drill. The limit switches were tapped straight to the wood blocks. In future revision, more robust attachment should be discussed. The limits' switches are wired in NC configuration.

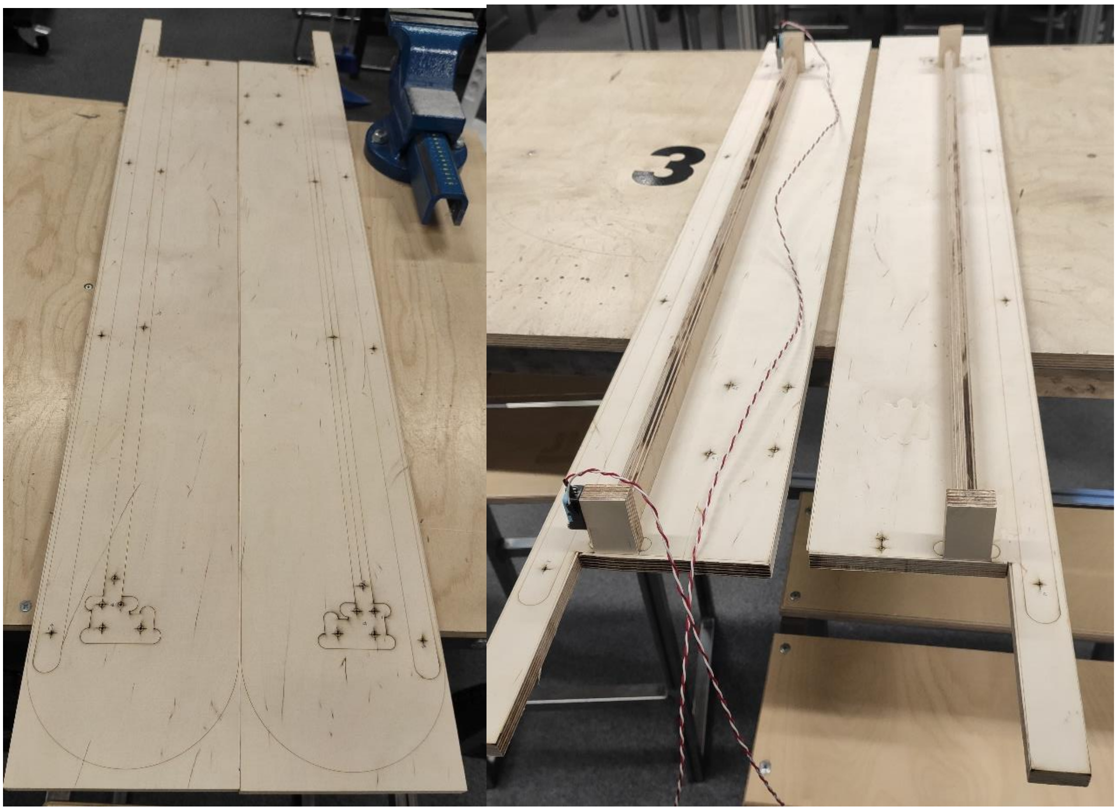

**Figure 18.** Tower assembly walls a) unfinished blanks laser marked and partly cut b) finished, rails and end stop switches attached

The 3M timing belt pulleys needed to be machined and drilled for use. The 72T pulleys and one 24T pulley were provided to LUT Voima to be machined. The rest of the pulleys were centre drilled for 5 mm axle (12T pulleys) and 6 mm axle (24T pulley). Threads for two M4 set screws were drilled and threaded to these six pulleys.

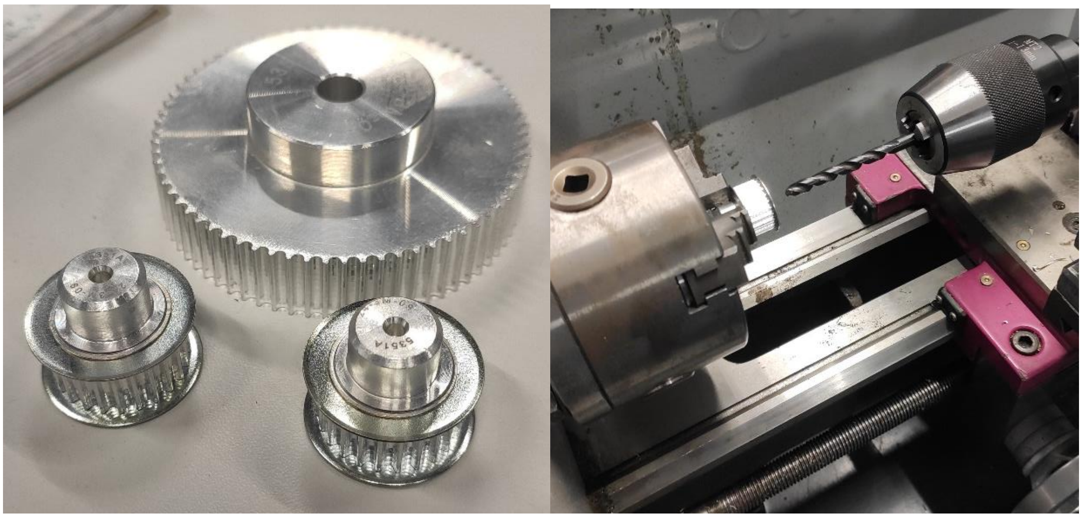

**Figure 19.** Timing belt pulleys and pulley centre hole drilling setup

A motor flange is attached to the lead screw plate using thread inserts and M3 screws. The attachment allows the belt to be tightened for use. Lead screw bearing unit FK08 is attached to the lead screw and to the plate. Plate is attached between the two walls using wood screws and provides support for the tower structure. The upper end stop switch of the linear movement can be seen below the leadscrew plate.

**Figure 20.** Lead screw assembly joining walls

Figure 21 shows motor for the head horizontal movement is attached to the lead nut flange similarly as in previous assembly. The lead screw will go through the belt loop when the plate is inserted into the tower assembly. In the Figure 21 one of the four attached LV201 track rollers can be seen.

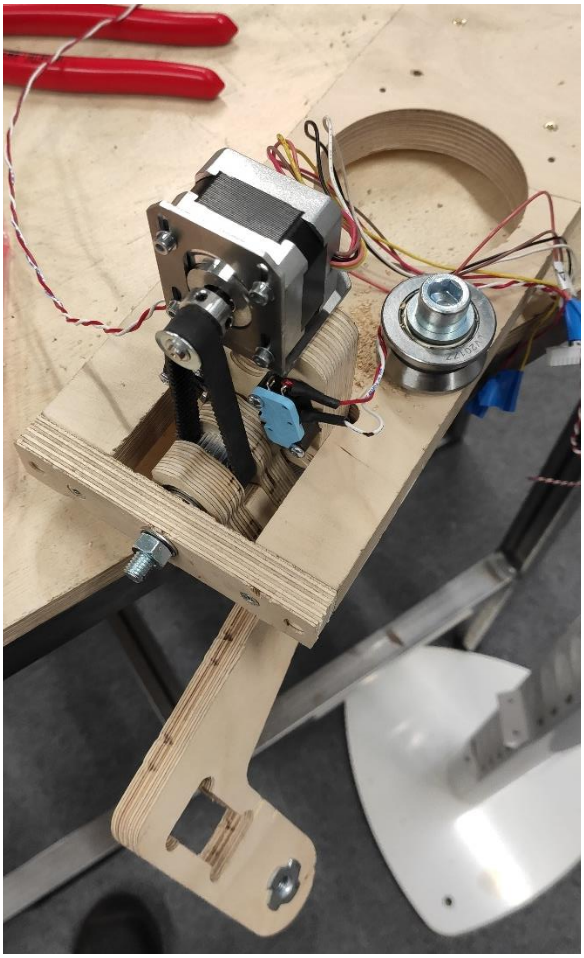

**Figure 21.** Linear plate assembly

The Visaton DX-10 speaker with included cover is installed in the front of the linear plate in Figure 22. The linear assembly is installed in the tower and is sliding between the rails attached to the walls. The lead screw is driving the assembly up and down.

**Figure 22.** Linear plate assembly inside the tower assembly

For the first prototype thermoformable plywood is not available. Alternative design using laser cut slits is used for the tower top (Figure 23. ) The emergency stop is installed in the hole cut to the top part before attaching it to the walls using wood screws.

**Figure 23.** Tower top a) Laser cut to include flexibility as thermoformable plywood is not available b) In the tower assembly

A partially assembled wheel module is presented in Figure 24. Motors and an inductive sensor are attached to the main plate. The drive axle attached to the drive motor with shaft coupling. The drive shaft is supported inside the steer axle using two RM128 ball bearings. The steering stepper is driving the wheel with a 3M belt.

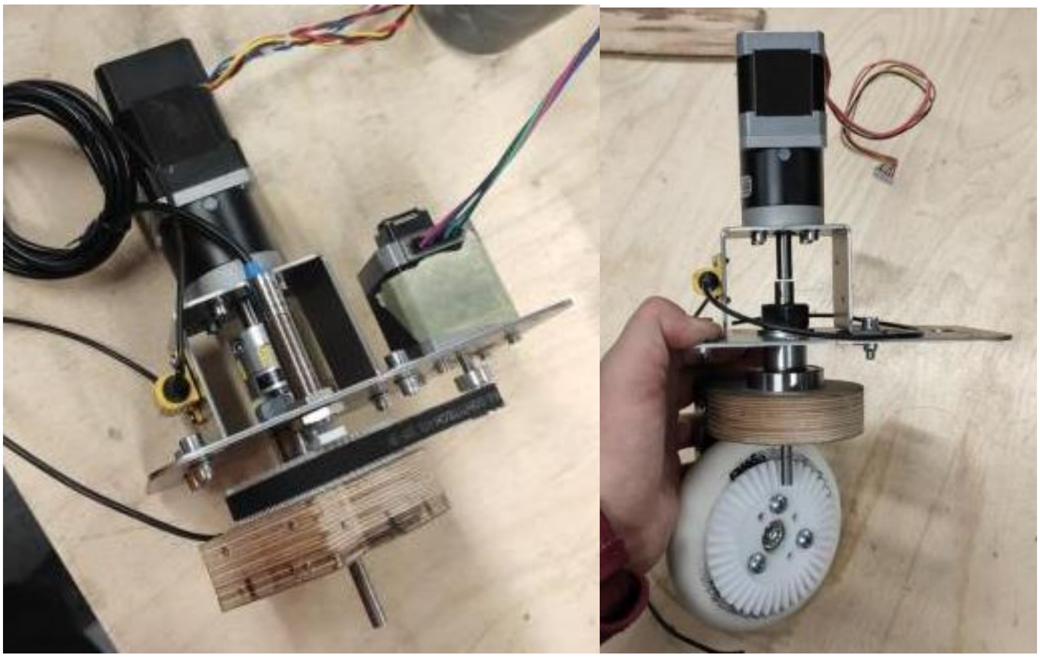

**Figure 24.** Partially assembled wheel modules

In Figure 25 a finished module can be seen from the bottom. The bevel contact, steering belt and the zero-position detecting inductive sensor can be seen. Additionally, the M16x1,5 thin nut is holding the assembly together. It is good to note that a 23 mm socket is needed in the assembly of the wheel modules.

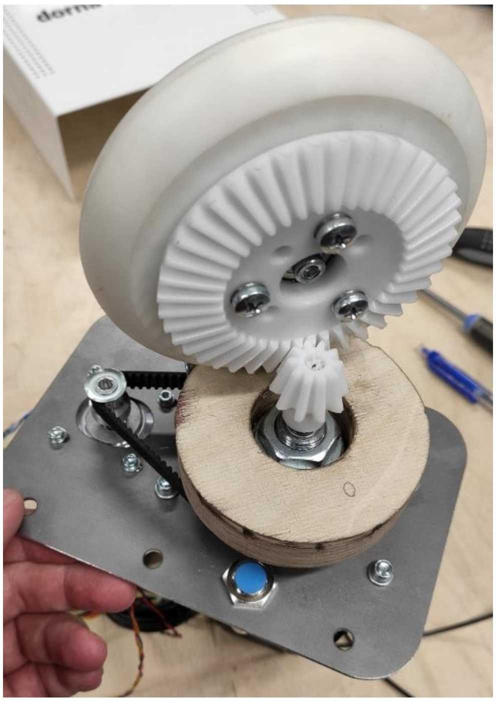

**Figure 25.** Finished wheel module from bottom

The test assembly of the wheel modules to the base plate is shown in Figure 26. All the components for final assembly have not arrived yet and thus two of the three modules are unfinished.

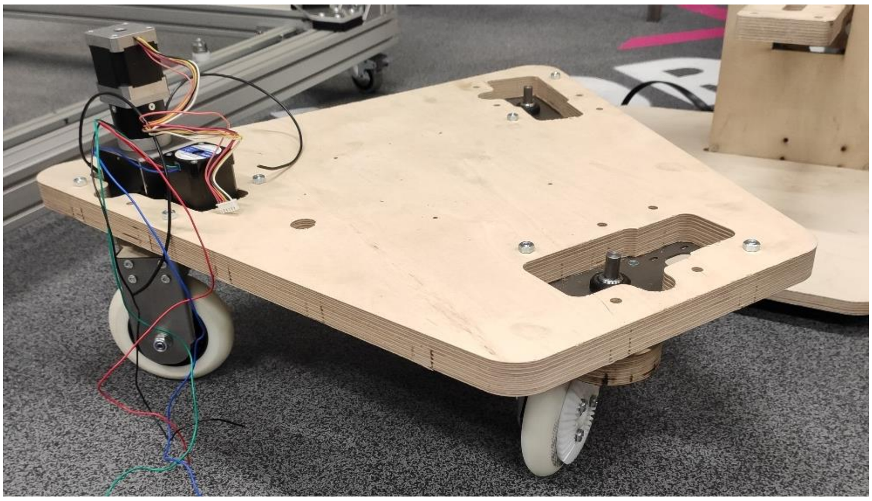

**Figure 26.** Propped up (unfinished) baseplate assembly

In Figure 27. Laser cut slits to bend the right-side plate are shown. The components can be attached before assembly as shown in b- figure. Advantage regarding the assembly of the laser cut design instead of one bent using thermoformable plywood is that the bends are not rigid which allows easier manipulation and installation due to the orientation of the components. Downside is slightly reduced rigidity in the full assembly. Additionally, the laser cut bends are susceptible to damage if bent multiple times or under the designed bend radius.

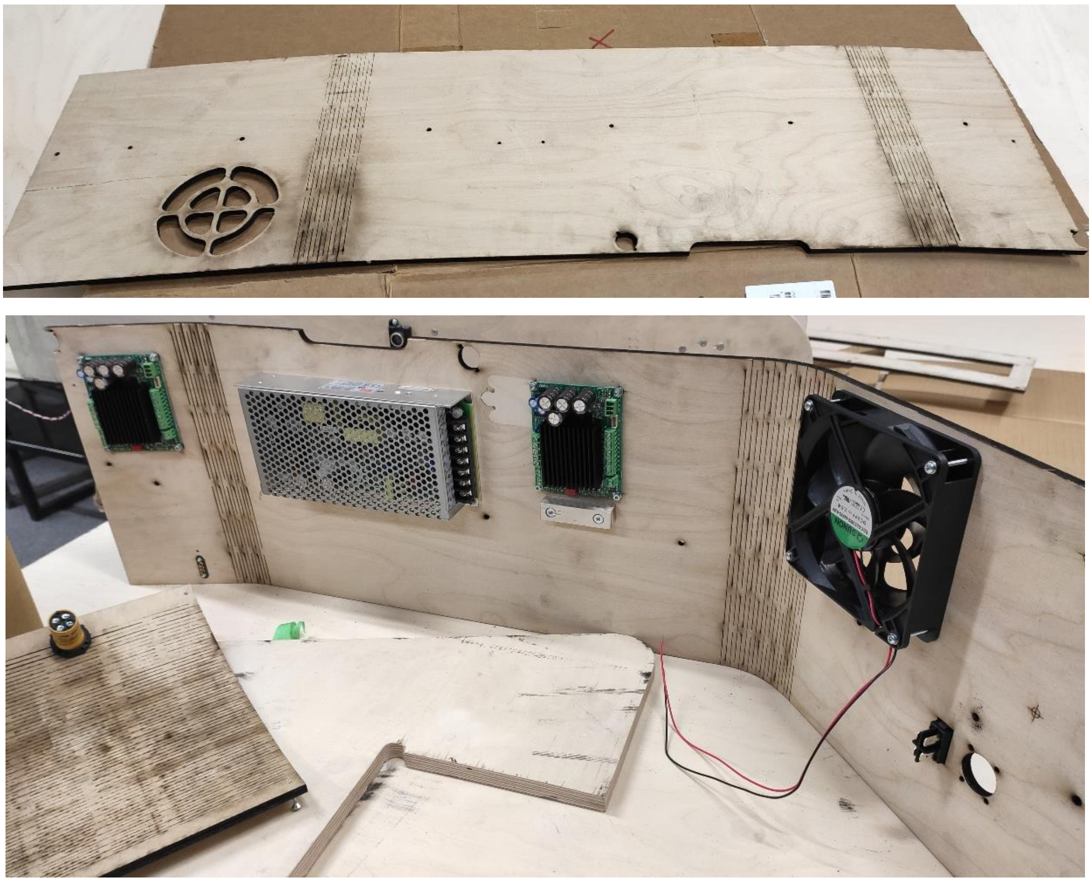

**Figure 27.** Laser cut side plate a) flattened b) with components attached

In Figure 28. The almost finished prototype is shown firstly without side panels installed and secondly without wheel modules. Wheel modules were added later to the system when the rest of the parts arrived.

**Figure 28.** Robot frame propped up a) with wheels and no side plates b) with side plates, top plate and no wheels

All the electronic components are installed inside the robot frame and cabled together according to the block diagram presented earlier. Plastic cable clips are attached to the frame using double side tape to keep the inside of the robot more accessible. Cables handling the IO signals are shielded and the shielding grounded to prevent unnecessary noise in the signals. The cabling inside can be seen in figures 29 and 30.

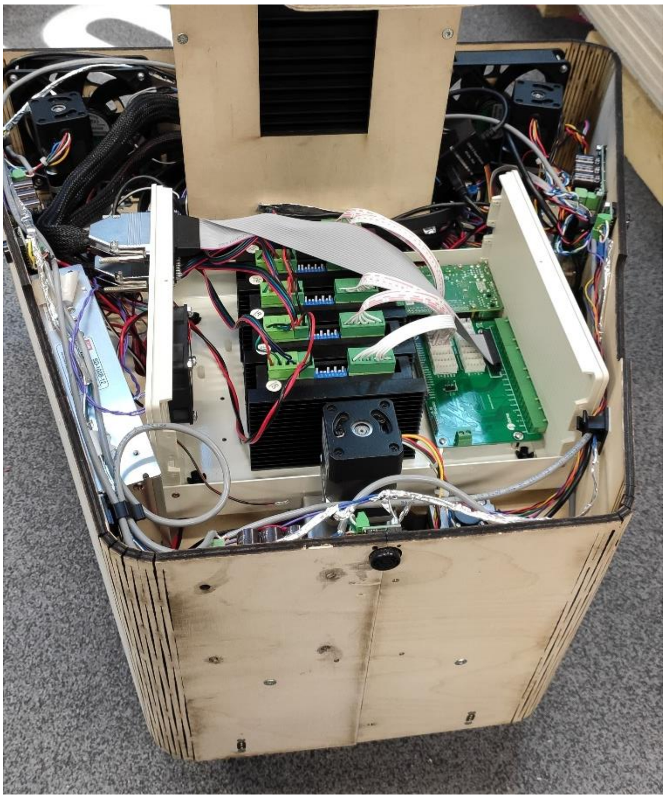

**Figure 29.** Robot components and cabling inside

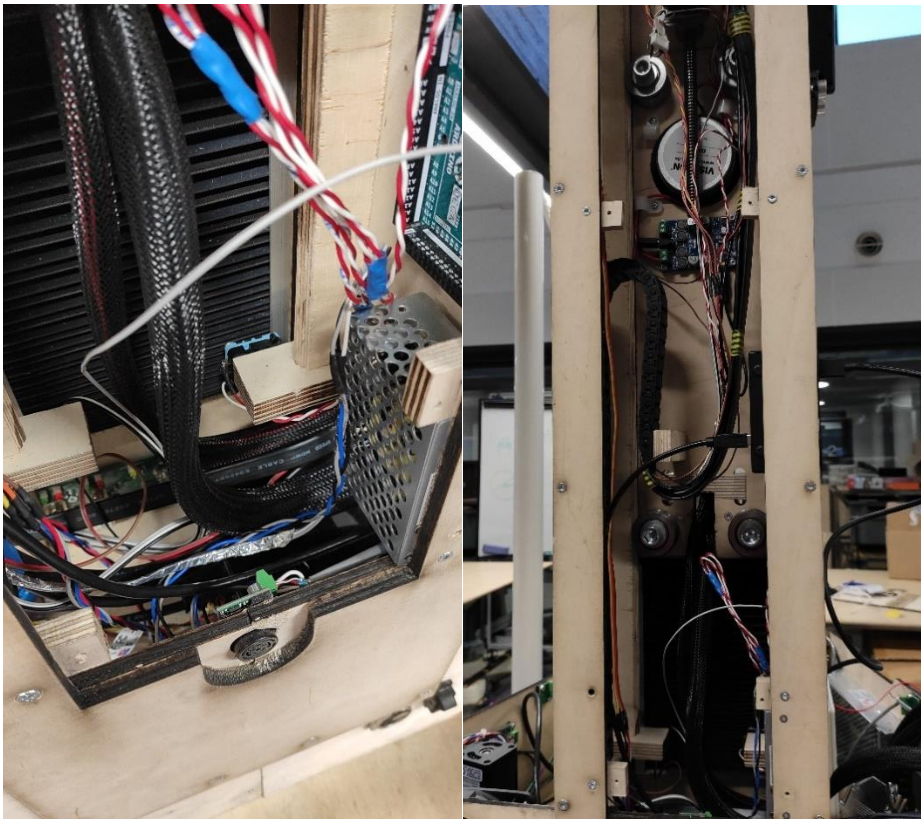

**Figure 30.** Cabling in the back of the robot

The power cables of components are routed to the bottom compartment of the robot through a hole drilled to the plate. The battery, fuses and ground rail are situated at the bottom of the robot in addition to the power switch circuit. The cable charging the battery is separate and is connected to the charging connector at the back of the robot and to the docking connectors in the front. It is important to route the cables so that they are not interfering with the wheel movement or touch the ground.

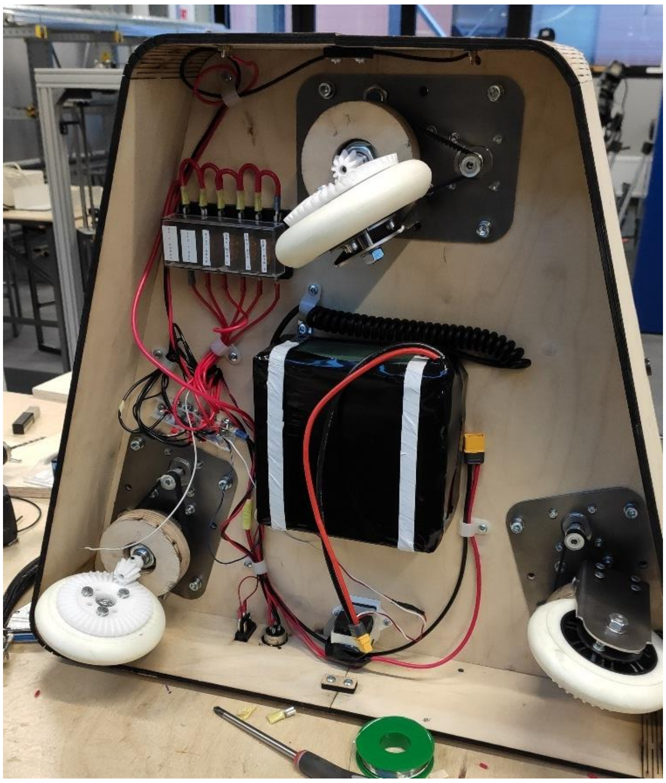

**Figure 31.** Battery and fuse box in the bottom compartment

The electronic components' connection block diagram is presented in Figure 32. The multitude of different voltage levels is provided by DC-DC converters. Separate voltage levels are presented with different colours and the arrow direction shows which component provides power/signal to another.

Data signals are shown with brown arrows, these include low level and USB connections. RS-485 bus is separated and shown with green lines, connecting the CPUs and motor controllers together providing control signals and sensor feedback.

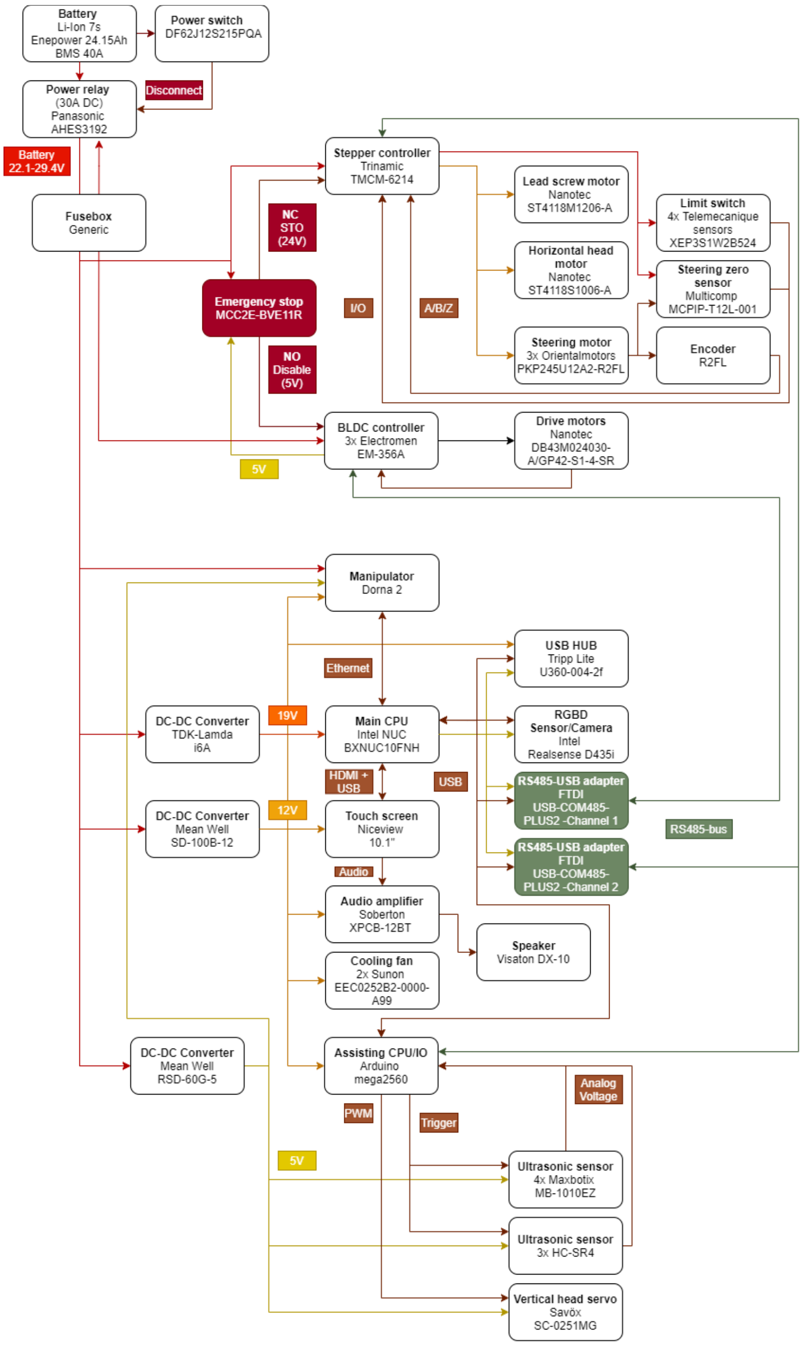

**Figure 32.** Electronics connection diagram

The finished prototype is shown in Figure 33. The electronics are enclosed with the top plate resting on the sides and the service hatch is screwed closed in the back of the tower. The HC-SR04 sensors can be seen on the three sides of the robot allowing the detection of obstacles on the tabletop-level. The prototype is left natural coloured in this case but could be stained or painted. Additional possibility of using plastic foil with a custom printout for example containing logos is possible if using thermoformable plywood for the tower and side panels.

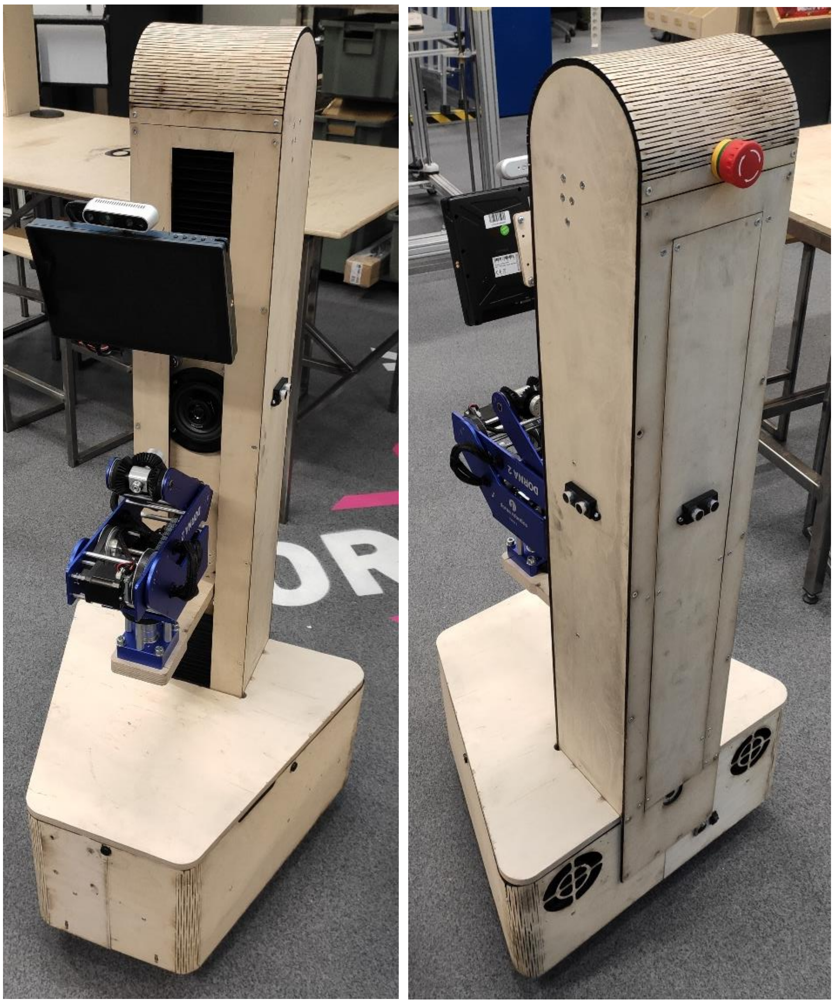

**Figure 33.** Finished prototype

# 4 RESULT ANALYSIS

The designed robot has omnidirectional movement and manipulation capabilities according to the specifications determined.

The kinematic diagram of the designed robot prototype is presented in Figures 34 and 35. The diagram is based on URDF (Universal Robot Description Diagram) created with Solidworks add-on SW2URDF. URDF file is useful in the development of robot software and kinematic analysis in the future development, the current model might need to be simplified for more efficient use.

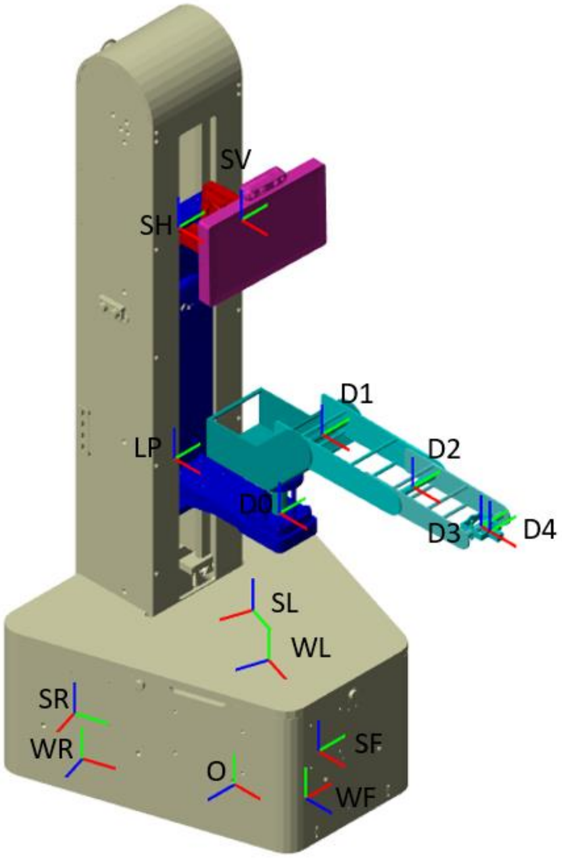

**Figure 34.** Prototype Kinematic Diagram

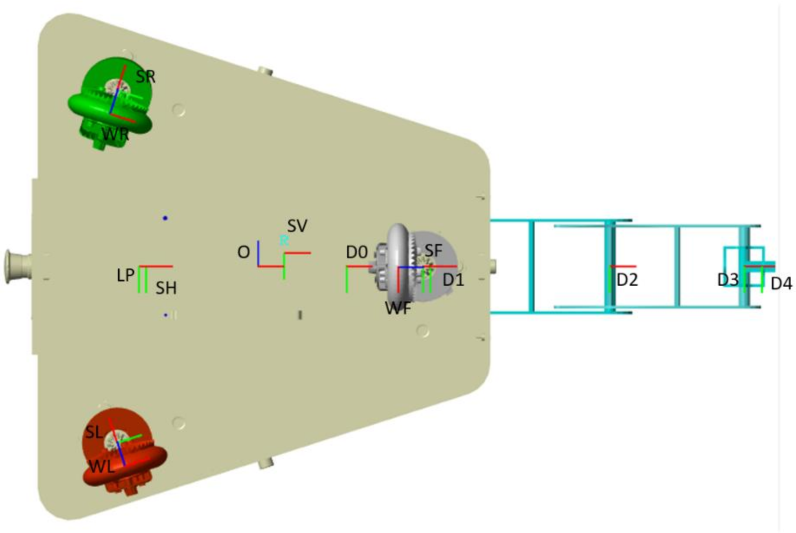

**Figure 35.** Kinematic diagram bottom view

The joints and their positions in relation to the robot origin are shown in the kinematic diagram are listed in the Table 4.

**Table 4.** Kinematic diagram joint specification

| Joint | Joint type | Local Axis | Pos X [mm] | Pos Y [mm] | Pos Z [mm] | Range of motion [deg]/[mm] | Lower | Upper | Joint description | Notes |
|---|---|---|---|---|---|---|---|---|---|---|
| **O** | Fixed | NaN | 0 | 0 | 0 | NaN | NaN | NaN | Bot origin | Centre of wheel connection points, ground level |
| **SR** | Revolute | Z | -159 | 158 | 200 | Inf | NaN | NaN | Right wheel steering | |
| **SL** | Revolute | Z | -159 | 158 | -200 | Inf | NaN | NaN | Left wheel steering | |
| **SF** | Revolute | Z | 187 | 158 | 0 | Inf | NaN | NaN | Front wheel steering | |
| **WR** | Revolute | Z | -168 | 55 | 173 | Inf | NaN | NaN | Right wheel drive | |
| **WL** | Revolute | Z | -150 | 55 | -230 | Inf | NaN | NaN | Left wheel drive | |
| **WF** | Revolute | Z | 159 | 55 | 0 | Inf | NaN | NaN | Front wheel drive | |
| **LP** | Prismatic | Z | -135 | 564 | 0 | 335 | 0 | 335 | Linear Plate | Origin at plate back and top of Dorna attachment plate |
| **D0** | Revolute | Y | 101 | 576 | 0 | 272 | -136 | 136 | Dorna j0 | Limited by the tower assembly (355, -175, 180) |
| **D1** | Revolute | Y | 196 | 776 | 0 | 270 | -90 | 180 | Dorna j1 | Limited at some orientations! |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **D2** | Revolute | Y | 0,399 | 0,776 | 0 | 284 | -142 | 142 | Dorna j2 | Limited at some orientations! |
| **D3** | Revolute | Y | 0,551 | 0,776 | 0 | 270 | -135 | 135 | Dorna j3 | |
| **D4** | Revolute | X | 0,571 | 0,776 | 0 | Inf | NaN | NaN | Dorna j4 | |
| **SH** | Revolute | Z | -0,127 | 1,016 | 0 | 70 | -35 | 35 | Screen Horizontal movement | |
| **SV** | Revolute | Y | 0,03 | 1,116 | 0,015 | 160 | -80 | 80 | Screen vertical movement | |

## 4.1 Safety in the designed prototype

The safety aspects and standards discussed earlier are considered in the prototype design. A safety level of the design is not on the level of industrial or automatic solutions but will allow increased safety in situations where mild hazards are possible. A table of the main hazards possible in current situation and the mitigation implemented is shown below in Table 5.

**Table 5.** Hazard mitigation implemented in design

| Hazard | Mitigation | Mitigation in design |
|---|---|---|
| **Mechanical** | | |
| Pinching between arm joints | Limit motor force and speed, impact detection | Motor controller, sensor (force/distance/proximity) |
| Pinching between arm and body | Limit motor force and speed, impact detection | Motor controller, sensor (force/distance/proximity) |
| Pinching between linear axis moving parts | Limit motor speed, Limit access | Motor controller, covers |
| Pinching to steering/drive mechanism | Limit access | Cover (side assembly) |
| Getting run over by robot | Visual cues, Limit speed, avoid collision | Sensors (distance, proximity, camera) |
| Dropping carried item | Ensure good grip from item<br>Prevent/avoid access below the carried item<br>Limit movement speed when carrying load | Sufficient motors, motor control, warning light |
| Robot losing stability | Inherent design to avoid destabilization<br>Avoid high acceleration of movement<br>Avoid pushing the robot | Wheelbase wide and long enough, low centre of mass, acceleration limits, use guidance |
| **Electrical** | | |
| Electric shock | Limit access to live wires and appliances (enclosure)<br>Isolate hazardous components/connections<br>Use of safe voltage level | Design of electronics placement and cover<br>Voltage level is under 60V DC |
| Loss of battery power | Warn of low battery<br>Ensure safe stop in case of loss of power | Warning system implementation in software<br>Inherently safe design in case of power loss (robot stops movement safely) |
| **Thermal** | | |
| Component Overheating | Ensure cooling airflow<br>Isolate heating elements from touch | Ensure enough airflow (fans, fan placement) |

| | | |
|---|---|---|
| Material Degradation | Isolate heating elements from compustible materials<br>Limit heating of components | Ensure enough airflow (fans, fan placement)<br>Ensure safe component positioning |
| Material combustion | Isolate heating elements from compustible materials<br>Limit heating of components | Ensure enough airflow (fans, fan placement)<br>Ensure safe component positioning |
| **Noise** | | |
| Loud noises from audio equipment | Limit output of audio components | Design software limitations |
| Motor noises | Dampen noice sources | Add dampening material, ensure no resonant components |
| Noise caused by EMF | Isolate audio equipment from EMF | Add grounded screens to cabling/PCB: s |
| **Vibration** | | |
| Loosening fasteners | Ensure fasteners stay tight | Add locking combound/lock washers to vibrating elements |

Many of the safety features enabled by the specified hardware need to be implemented at the software level. Most notable being the use of the included RGB-D 3D sensor and the ultrasound sensors. Some safety elements like force limiting can be enabled at hardware level.

The design is relatively safe in its’ implementation. The hardware allows safe semi-autonomous operation with correct software. For the current prototype, the main intended use is remote controlled operation with local monitoring by nearby people. Additional safety can be added by providing information of the possible hazards. A warning light and sound cues can be implemented in the future to aid warning the environment of the robot operation.

## 4.2 Bill of materials

The components and materials previously discussed and sourced for the prototype manufacture are listed in the BOM (Bill of Materials) shown in appendixes XIII-XVI. The BOM is divided into four parts:

Appendix XIII contains the electronic and standard mechanical components selected and accommodated in the construction. Appendix XIV includes the cabling and connectors required for connecting the electronic components together. Additional connectors are included for external functionality like charging.

The appendix XV includes the manufacturing times for all the components manufactured during the project. Components are manufactured using CNC milling, drilling, sawing, turning, and 3D-printing. Plywood with high thickness tolerance specifications is suggested for use in the parts specified to be manufactured from 15 or 24 mm thick plywood. These plywood grades have necessary dimensional, structural, and surface quality specifications for the intended application. In the design of these parts the possible variation in the plywood thickness is considered and functional dimensions are ensured during the manufacturing process where possible.

Appendix XVI includes the fasteners and materials used for fastening in the robot construction. Standard fasteners available from a local supplier are used wherever possible. The main exception being the thread inserts used for the component mount points.

The combined costs for all the needed components for the prototype are shown in the Table 6. The individual cost summary can be seen in the appendixes mentioned.

**Table 6.** Prototype component cost summary

| **Costs total** | |
|---|---|
| **Components** | 7253,85 |
| Cables + Connectors | 137,93 |
| Fixing gear | 47,87 |
| Materials | 55,66 |
| **Total** | 7495,31 |

The costs exceed the budget set for the project for about 150% margin. Main contributing factors being the availability of more cost-effective solutions from reliable distributors and time constraints set on the project for the implementation of more cost-effective solutions. Future work should be done reducing the costs. Some suggestions for future iterations have been discussed already in this thesis.

### 4.3 Prototype manufacture costs

The manufacture of the robot is done mainly with the use of CNC routed plywood. Most of these parts are designed to allow routing without flipping the part during the process. Therefore, most of the parts can be routed at the same time from one plywood sheet if a sufficiently large router is available.

Some of the standard components, mainly the ones in power transmission need some work before they can be used. The larger bevel gears are modified to sit flat against the side of wheels by machining the back of the bevel gear. Holes for mounting screws are drilled through the gear. The smaller gear is drilled and tapped for two M3 set screws.

The various pulleys are modified followingly:
The 72-tooth 3M pulley is machined flat and mount screw holes are drilled. Mount holes for zero sense plate are drilled and tapped. One of the 24 teeth pulleys is machined flat, and two 3 mm holes are added to lock the rotation in relation to the screen arm assembly which the pulley will be turning. The rest of the pulleys are drilled and tapped to include 2 M3 set screws to lock their orientation on the axles.

Appendix XV includes the mechanical components manufactured or modified from standard components. The required manufacturing times are based on toolpaths created in Fusion 360 CAM. The times are calculated using tool parameters for CNC machining and laser cutting presented in the table 7 for the JHC machinery. The parameters were determined by determining safe base values and adjusting them during the manufacture to acquire good quality and sufficient speed. No significant tool wear is encountered during the manufacture of parts for the robot using these parameters. Further optimisation could be done to increase the manufacture speed further.

**Table 7.** Manufacturing parameters for machines used at JHC

| Machine | Tool | Use | Spindle speed [rpm] | Feed [mm/min] | Plunge feed [mm/min] | Max. Stepdown [mm] |
|---|---|---|---|---|---|---|
| **Bodor BCL-1309XU** | 100W Laser | Cut 6,5mm plywood | Power: 100% | 1st pass: 480<br>2nd pass: 1440 | NaN | NaN |
| **Rensi Reu 900** | 7-8 mm flat upcut HSS | Roughing/ outline cutting | 14000 | 3000 | 400 | 12 |
| | 4 mm flat upcut HSS | Screw through holes/Mountpoints | 18000 | 2200 | 500 | 7,50 |
| | 3 mm flat upcut HSS | Fine details | 19000 | 2200 | 500 | 7,50 |
| | 2,5 mm drill | Wood screw prehole | 16000 | NaN | 400 | NaN |

A constant manual tool change time requirement of 2 min is estimated for parts using CNC routing and multiple tools as the CNC were used during the project does not accommodate automatic tool change ability.

The manufacturing time calculated gives a rough estimation of the work required for the manufacture. Exact costs for the manufacture time are not calculated as they are highly dependent from multiple aspects such as the supplier chosen and the tooling available.

Tasks needing manual work including drilling, sanding, and sawing are not evaluated in the manufacturing time estimate as they depend highly on the proficiency of the user doing these tasks. Additionally, these can be left as a task to be done as a part of the robot assembly done at the receivers end if a lower cost is desired.

## 4.4 Prototype functionality

As software is excluded from this thesis because of the time constraints only basic test were run to test the prototype functions to ensure the components installed work as intended.

The stepper driver and steppers were briefly tested to test the speeds and noise when using default parameters set according to the specifications of the motors. The stepper driver software and computer connected with USB cable were used to drive the steppers. Additionally, the functionality of the end stops, encoder signal and home positions sensors for each axis were ensured to be functional.

The drive motor and the motor controller were tested by driving the motor in a closed loop mode with light load applied by. The controller provides some basic data of the function through the USB-serial adapter. The system responded to the load well and the motor and controller are working as intended. In the final application, the motors are driven in open-loop mode as the speed adjustment is done in real time by the driver.

The computer, screen and audio systems were tested when installed in the prototype. Everything was deemed functional with audio-visual input and output. The RGB-D camera is tested with the use of Intel’s software package, the picture and depth data are deemed functional. Further testing requires software to be developed and is left out of this thesis.

The Dorna arm was tested by manually controlling the arm using Dorna control software and computer attached to the control box using an Ethernet cable according to the instructions of Dorna documentation available online.

The ultrasound sensors used for collision avoidance were tested with simple Arduino test code sending a trigger signal to the sensor periodically and reading the distance value. A piece of paper was moved before the sensor to see if the value changes as expected. Functionality with more than two sensors at once was not tested at this time due to more advanced software required.

These simple functionality tests are a proof that the singular parts of the system are functional. More thorough performance testing of the prototype is to be conducted when the software package required has been further developed. The foldable table is not manufactured during this thesis but will be added to the construction in the future.

## 4.5 Prototyping Notes and Changes for Future Iterations

During the manufacture of first prototype some aspects of design and specific components were deemed necessary to be changed or improved in future iterations. This is a normal part of the iterative design process. In this case some of the modifications were left out of this prototype as they do not cause any significant functional disadvantage and time required for changes would delay the project.

### 4.5.1 Assembly and packaging optimisation

The prototype design should be changed if some assembly elements are deemed inconvenient or aspects of the design can be improved to improve packaging and shipping of the robot. Current design is broadly using wood screws for fastening the wood elements together: alternative methods and reduction in the fastener amount should be a goal in future iterations.

The need for the use of thread inserts for separate components should additionally be evaluated in greater extend. For the prototype, a relatively large number of inserts is used to allow the reattachment of components with no risk of stripped attachment holes. In future revision components that are attached to the robot at most times might not require inserts and could use wood screws or machine screws screwed straight to the wood itself, like with some components in the current prototype.

Some mount points and component orientations were changed according to the first prototype to allow easier routing of cables. Additionally, the robot dimensions will be increased in further iterations slightly to allow more space for cabling and assembly. The base plate width and length will be increased by 10 mm and the tower depth by another 10 mm. Only functional dimension changed additionally is the side length of the equilateral triangle of the wheel mount points increased by 5 mm. This will increase the robot stability slightly.

### 4.5.2 Wheel spoke count and bevel gear attachment

The ordered wheels had 7 spokes in their hub design. This caused a situation where gear attachment with symmetrical 3 or 4 screw design is not optimal. Followingly, the attaching plate on the other side of the wheel was changed to an asymmetric design in addition to broadening some of the gaps between wheel spokes with drill to accommodate the M5 hex screws. In future revisions wheels with spoke count divisible with three should be used to allow symmetrical gear attachment plates.

Furthermore, the bearings and the spacer between the two bearings in the wheel can be ordered ready-made with a minimal cost in the future. For the first two prototypes these spacers were manufactured by LUT Voima. The whole wheel package can therefore be ordered ready-made with minimal cost addition and significant time savings in the manufacture and assembly.

### 4.5.3 Steering motor type

The steering motors ordered for the prototype were 5 wire unipolar motors. The controller used is designed for 4 wire bipolar motors, therefore the motors need to be modified to bipolar type. In case of 6 or 8 wire unipolar motors no modification is needed as seen in the linear movement and screen steppers used in the current prototype. 6 and 8 wire motors can be wired to a bipolar driver with coils in series, with only one coil or the coils parallel. It is important to note that the motor specifications are different for each wiring configuration. These unipolar motors do not have the centre taps of the coils shorted together which is the main reason for the need of modification in 5 wire unipolar motors. The modification might not be possible for all 5 wire motors available on the market and is not recommended by the motor manufacturer.

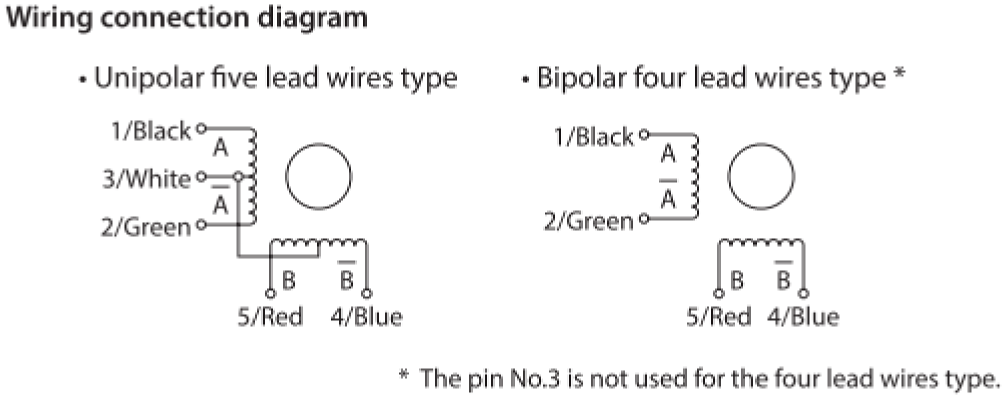

**Figure 36.** 5 wire unipolar coil connection compared to 4 wire bipolar stepper motor (Orientalmotor, 2020)

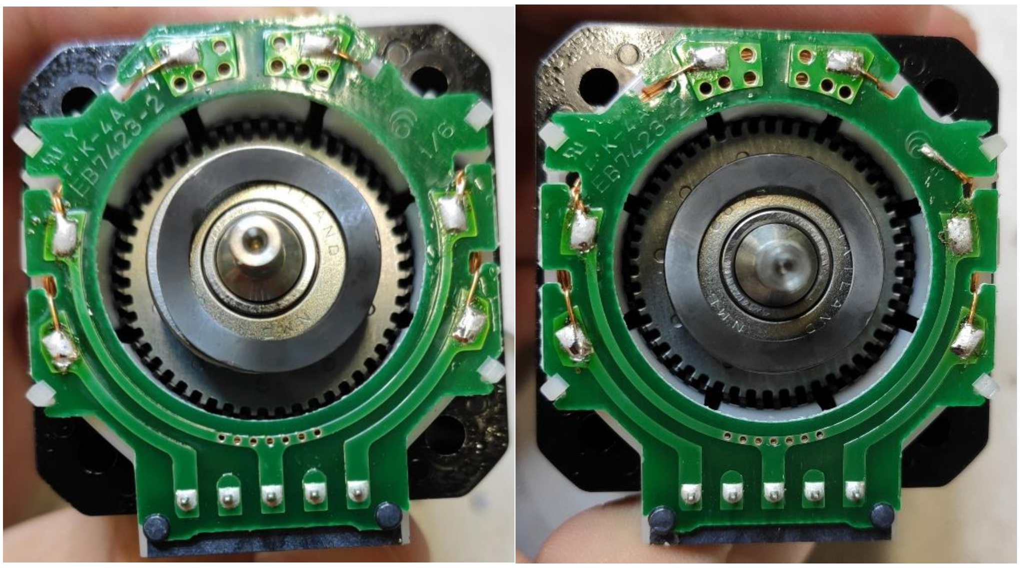

**Figure 37.** PKP245U12A2-R2FL bipolar stepper motor a) Unmodified PCB b) Modified to bipolar wiring by desoldering the centre pin

Prototype testing should be conducted to determine if the encoders are necessary for the use case. In the prototype, encoders are specified to ensure that steps are not lost during more demanding steering manoeuvres. Contrastingly the possibility of a closed loop -control capable stepper controller or controllers can be added if steering is deemed to be unreliable in the current configuration.

### 4.5.4 Manufacture of the plywood and plate components

Further optimisations in the component design should be done to improve the manufacturability and manufacturing times. Features of the current prototype are to be evaluated in use and unnecessary cuts in the part design should be removed. Additionally, if components are deemed too heavy in use lightening cuts in the plywood can be added.

# 5 SUMMARY AND CONCLUSIONS

## 5.1 Main steps for the telepresence robot design

If there is no solution on the market for a specific use case, a custom solution based on one of these designs or a ground-up design is necessary. The main aspects of the design process need to be realised to determine the most optimal design.

It is important to define the main requirements for the design before beginning the mechanical design. It is also important to note that many features even if easy to implement mechanically might require significant amount of work on the software side. Therefore, it is important to allocate enough resources for the project.

The most important aspects to be decided in the design are:
Movement requirements and environmental constraints.
The most common movement type in commercial robots is to have two driving wheels and one or two caster wheels supporting the robot. This is sufficient for most use cases for telepresence robots. In our case omnidirectional movement was deemed beneficial for the use and thus was implemented. There are multitudes of solutions available for omnidirectional movement but each of those have drawbacks. In the design process decision for the used movement needs to be done early in the design process and the drawbacks evaluated in the designed use case. The solution presented in this thesis allows relatively trouble-free mechanical implementation with some drawbacks in build complexity and software implementation.

The requirements for the interaction with environment and people; The telepresence robots natural interaction with people is an important requirement. Human-like movement and gestures help establishing functional communication with the user using the robot. Additionally, personalisation of the robot helps people recognising and keeping up communication with the robot.

Safety in the design to implement necessary requirements.

Telepresence robots should be capable at least of rudimentary collision prevention and collision force should be limited where it is possible. This can be achieved using low-cost ultrasonic or optical distance sensors if the software side is implemented correctly. With sensors capable of more accurate depth and distance detection for example RGB-D sensors or other optical sensors can be used to implement more advanced collision avoidance or route planning. In every case the limitations of sensors should be considered: small, see-through, or angled surfaces being one of the more prominent difficulties for optical and ultrasonic sensors used in these devices. In addition, the latency and determination of the detected object are things that need consideration in software implementation.

## 5.2 Summary of the designed prototype

The prototype of the specific telepresence robot with a grabber was designed and manufactured using standard components and plywood construction. The main goals of the project were achieved and future development in the prototype is to be conducted.

The overall budget specified at the beginning of the project was exceeded by around 50%. The main reason being that the previously specified Dorna arm had become unavailable, and the replacing model had increased the untaxed pricing from 1500 dollars to 3500 dollars. The additional costs of the current BOM can be reduced by utilizing distributors from outside of EU for components not critical for the functionality, for example the bellow covers can be sourced with one tenth of the costs. The current prototype largely uses components sourced from large European distributors to ensure fast shipping and communication during the time-limited project.

The budget for the prototype was exceeded with around 60% margin. Some components are available with reduced prices if longer shipping times and smaller distributors are used. For example, the bellow covers costing hundreds from an industrial manufacturer in Europe can be found from China with a tenfold smaller price. During the prototype build European distributors and better-known components were chosen to allow rapid development and testing of the first prototypes.

## 5.3 Research questions and objectives of research

The main questions concerning telepresence robot features implementation for the specific use case were discussed and realised in this thesis.

More prevalent telepresence robots on the market are listed and compared. Based on this comparison a need for telepresence robot with a manipulator was established and mechanics for a robot designed. Main driving aspects for the design were the intended environment, human-friendly communication, safety, and affordability. Additionally, the robot is intended to be able to be packed tightly for shipping and can be assembled by the end user using common tools.

Objectives concerning the prototype were successfully met: An affordable prototype platform capable of omnidirectional movement, communication and manipulation was designed and created. The requirements and wishes presented by JHC personnel are considered during the design process and final design. The platform uses widely Nordic plywood in its construction and allows possibilities for flatpack -shipping and easy manufacturability. Safety features concerning surroundings and human interaction are considered well established on the hardware level of the design.

The good manufacturability of the robot was achieved: The robot can be manufactured using mainly CNC router for the plywood parts or alternatively water cut if such machine is available. The machine build area should be over 1,2 m long in one direction to allow the machining of all the components. Sheet metal parts can be manufactured by laser cutting or by hand if necessary. Only a couple of parts need to be turned or 3D printed. These parts can be ordered from a manufacturer if machinery is not available.

## 5.4 The possibilities of affordable telepresence robotics

As the market for telepresence robots are growing and the use becomes well established the requirement for development platforms and affordable solutions becomes prominent. The designed prototype functions as a basis for the development of prototypes or platforms using common materials and the idea of self-manufacture and/or assembly of the robot instead of more common moulded plastic construction. This is enabled using plywood, 3D printed and other commonly available components in the construction. The basic modularity of the systems allows the change of the dimensions and mounting of components as needed and provides a basis for further module development.

The availability of affordable and modifiable solutions enables the use of telepresence solutions in new places and situations. Information and ability to provide human-like motion and interaction over distance in addition to the audio-visual interaction together enable more engaging communication and information transit.

## 5.5 Project development and continuation

The full evaluation of the implemented prototype cannot be done before necessary software has been implemented. The development of the prototype should continue with the implementation of ROS package based on the kinematic model of the robot. This allows further development of communication and remote-control software for the robot platform. Additional modules for each element including the sensors and motor controllers needs to be created or modified from ready solutions.

The flatpack-ideology should be further discussed, and packaging and shipping of the robot designed and evaluated. In its current state robot has the basis to enable the flatpack idea as components used could be relatively easily stacked for shipping. The most prominent components in the assembly are the side panels and the docking station that take most volume if pre-formed using thermoformable plywood before packing. Possibility of situating components inside these formed parts could be a solution allowing efficient packaging. These components can be packaged flat if forming is possible in the receiver’s end.

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# APPENDIXES

## APPENDIX I Table of robot requirements and wishes (1/3)

| Category | Wish/ Requirement | Description | Changes (date) | Realization (Y/P/N) | Notes |
|---|---|---|---|---|---|
| **Materials** | **W** | Use of UPM Grada/Other UPM plywood in construction | Possibility for UPM Grada 1000 in addition to 2000 (16.9.2020)<br>Added possibility for other plywood (23.9.2020) | **Y** | Thermoformable plywood MoE drop already at 40C! (17.9.2020) |
| | **W** | Use of only common and easily aquirable components | | **Y** | In other words, avoid custom components where possible |
| **Operation Environment** | **R** | Ability to function everywhere in the JHC prototype area | | **Y** | |
| | **R** | Ability to go through normal doors (90cm wide) | | **Y** | 90 cm is also the minimum width of accessibility ramps (17.9.2020) |
| | **R** | Ability to fit in an elevator with a guardian | | **Y** | |
| | **W** | Functions outside of main use environment | | **?** | |
| | **R** | Needs to be able to climb over treshold of 2cm | | **Y** | Minimum wheel radius can be calculated (18.9.2020) |
| **Functions** | **R** | Ability to grasp and/or point at things | | **Y** | |
| | **W** | Ability to lift 1kg load from 0.5m away | | **Y** | Required height for lifting? (17.9.220) |
| | **W** | Ability to reach on tables/work surfaces | | **Y** | |
| | **W** | Ability to open doors | | **?** | Find out if arm is capable (19.08.2020) |
| | **R** | Ability to push buttons or switches | | **Y** | Arm is capable (19.08.2020) |
| | **R** | Clear visibility to surroundings of the robot for the remote user | | ? | Is ability to turn the camera necessary for clear visuals? (19.08.2020)<br>Requirement for other camera for efficient communication/navigation ? (16.09.2020) |
| | **R** | Collision prevention with surrounding objects | | **Y** | Requirement for edge detection?<br>Is camera picture + AI enough? If not, what sensors required? (22.9.2020)<br>RGB-D cameras are quite affordable (23.9.2020) |

Table of robot requirements and wishes (2/3)

| | | | | | |
|---|---|---|---|---|---|
| **Construction** | **W** | Modular construction (additional components/functions) | | **Y** | |
| | **R** | Total costs under 5000 dollars | | **N** | |
| | **W** | Parametric construction (scalability) | | **P** | |
| | **R** | BCN3D MOVEO Robot arm accomodated in construction | Dorna.ai Robot hand (21.08.2020)<br>Dorna 2 (16.11.2020) | **Y** | Is this available? (19.08.2020) - No, Dorna 2<br>Need for height adjustment for arm? (16.09.2020) - Yes (21.9.2020) |
| | **R** | Screen or rubber head mounted for visual function | | **Y** | |
| | **R** | Ricoh Theta V camera mounted for visual function | | **P** | Possibility of camera change in the future! (21.08.2020)<br>Intel D435i (18.10.2020) |
| | **W** | Camera movement (height, rotation, tilt) | | **Y** | The camera would move with the "Head" of the robot (21.8.2020) |
| | **W** | Camera/Screen able to function similarly as head, height should be around persons face-level | | **P** | Height of the centre of mass? (19.08.2020) Height not on face level, would make unstable robot and difficult manufacture (07.01.2021) |
| | **R** | Main processor (Intel NUC BXNUC10FNH) accomodated within the construction | | **Y** | ~~Which NUC model? (19.08.2020)~~<br>Use vesa standard for mountpoint? (21.08.2020) - Yes, allows for other similar mini computers |
| | **R** | Robot is capable of normal walking speeds | | **Y** | Nominal speed of 1.2 m/s (07.01.2021) |
| | **R** | Robot can't cause serious harm to surroundings in problem situations | | **P** | Software to limit force/avoidance |
| | **R** | Can accommodate batteries for at least 2 hours of use | | **Y** | Find out batteries needed (19.08.2020) - Enerpower 24,5 Ah 7s used |
| | **R** | Robot accomodates motors and actuators to move around Including the control boards | | **Y** | |
| | **W** | Natural and easy movement in the surroundings | | | Are wheels optimal for easy movement? Use of tracks/Multi-directional wheels? (19.08.2020) - Own omnidirectional solution (15.10.2020) |
| | **R** | 2 pc Visaton DX 10-4 speakers accomodated in the consruction | Need for only one (12.11.2020) | **P** | Direction of the speakers? |

Table of robot requirements and wishes (3/3)

| | | | | |
|---|---|---|---|---|
| **Recharging** | **R** | Recharging should not need special training (simple recharging) | **Y** | Plug or docking (07.01.2020) |
| | **W** | Ability to charge remotely/Automatically (docking) | **P** | Positioning to dock not established (07.01.2021) |
| **Other** | **W** | Possibility to use the ROS (Robot Operating System) | **Y** | Component choises could be affected |
| | **R** | Compliant with necessary standards for robot safety and movement | **Y** | ISO 10218<br>ISO 12100<br>ISO 13482<br>ISO 13849<br>ISO/TS 15066 |

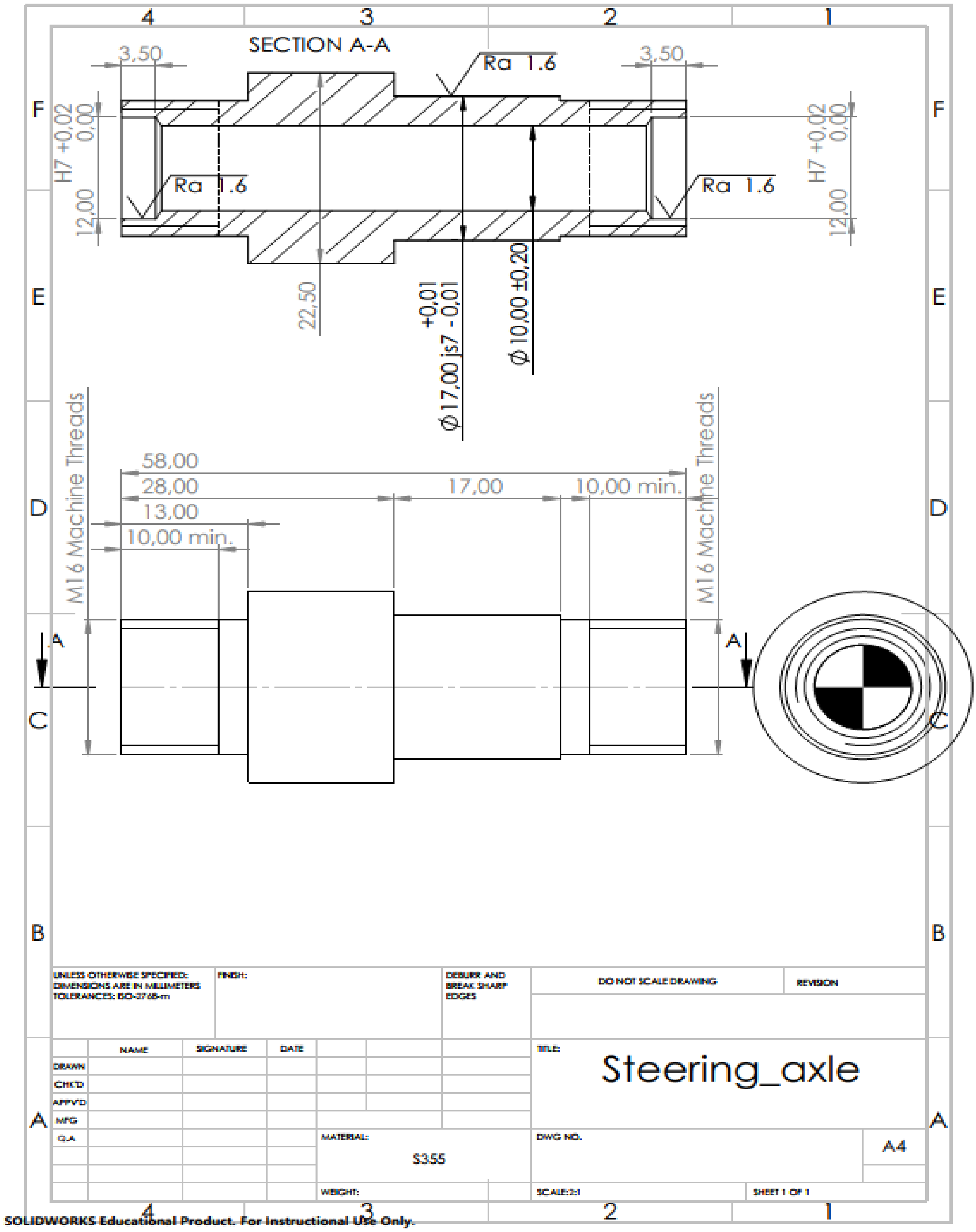
## APPENDIX II Comparison of commercial telepresence robots

| | **Ubbo Maker** | **Ohmni** | **Temi** | **Keylo** | **Double 3** | **Beam** | **Beampro** | **PadBot P2** | **Mantaro Teleme 2** |
|---|---|---|---|---|---|---|---|---|---|
| **Year** | 2016 | 2018 | 2017 | 2017 | 2019 | 2016 | 2017 | 2017 | 2016 |
| **Price** | 1400-2400$ | 2200$ | 4000$ | 24000 $ | 4000$ | ~4000 $ | ~15000$ | 1400$ | |
| **Subscription** | No | No | | | No | | | No | No |
| **Weight [kg]** | 15 | 9,1 | 12 | | < 13 | 13,3 | 40,8 | 6 | |
| **Height [cm]** | 125 | 143 | 100 | 164 | 120-152 | 134,4 | 158,7 | 110 | |
| **Camera** | | 4k wide | 13MP, 2 depth | 3D + wide | wide,zoom+tilt | 2x wide HDR | 2x wide HDR, pan, tilt | | tablet; tilt,pan |
| **Screen** | Tilt | 10,1", tilting | 10,1", tilt | 24" touch | 9,7", touch | 10" | 17" | 10", tilt | Tablet |
| **Audio channels** | Tablet | 2.0 | 2.1 | 1.0 | 1.0 | 1.0 | 1.2 | 2.0 | 2.0 |
| **Sensors** | Ultrasonic | Ultrasonic | Lidar, IMU, ToF | Lidar | Depth, Ultrasonic, IMU | | Optional lidar | Collision, edge | 2x infrared |
| **Wheels** | 4 x mecanum | 2 + 1 caster | 2+1 caster | 2 | 2 | 2+2 caster | 2+3 caster | 2 + 1 caster | 2 + 1 caster |
| **Max speed [m/s]** | 1 | 0,9 | 1 | 2 | | 0,45/0,9 | 0,9 | 0,733 | 0,66 |
| **Run time [h]** | 4-6 | 4-5 | <8 | 2-6 | 4 | 2/8 | < 8 | < 10 | 8 |
| **Other/Notes** | Open Source | Charging dock<br>Foldable<br>Open source | Wireless charging tray | | Charging dock | Charging dock | Charging dock | | Charging dock |
| **References** | (AXYN Robotique, 2018, 2020) | (OhmniLabs, 2020) | (Temi USA Inc., 2020) | (Wyca SAS, 2017) | | (Suitable Technologies, 2017, 2020) | | (Inbot Technology Ltd., 2017) | (MantaroBot, 2016) |

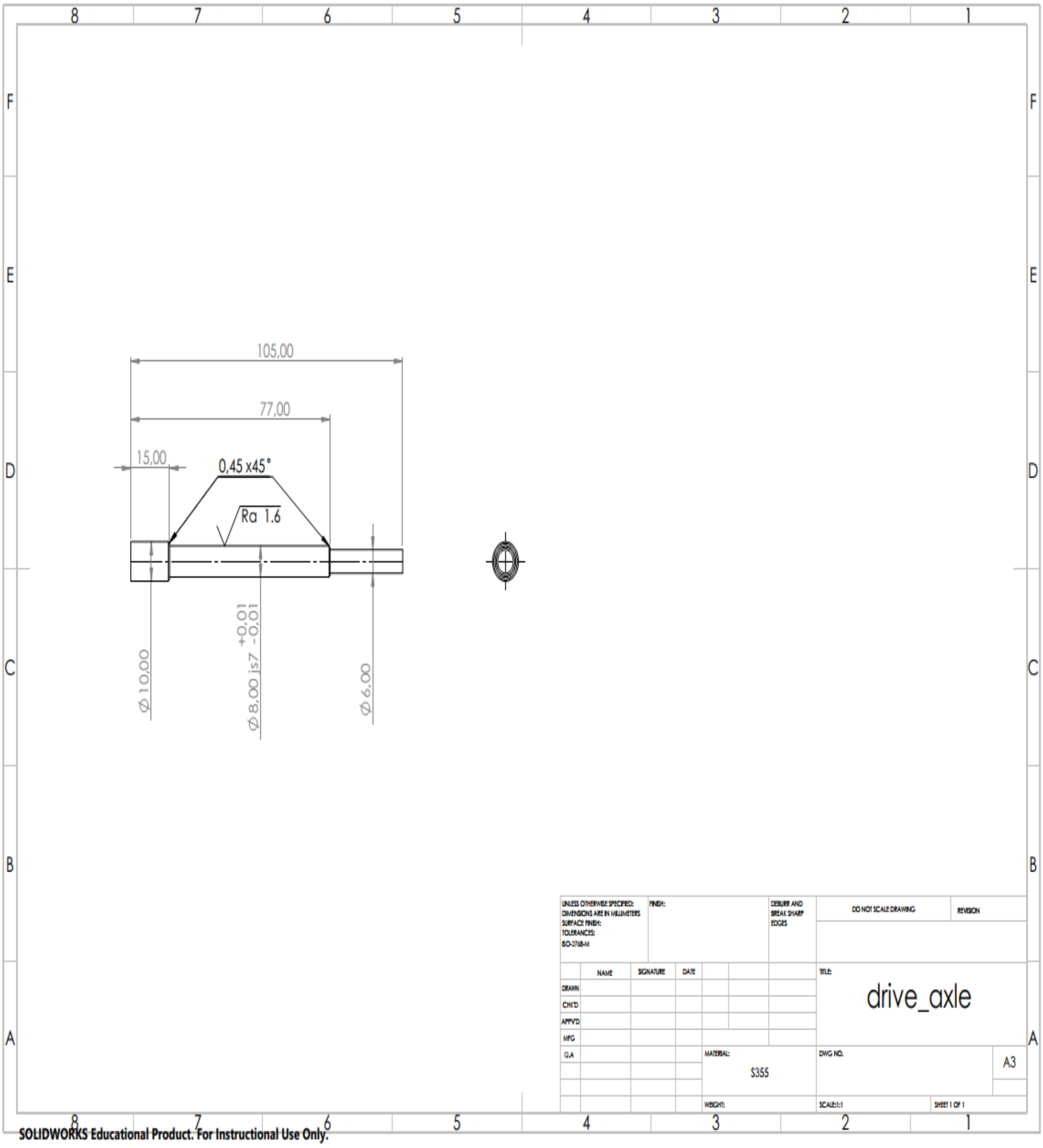
## APPENDIX III Comparison of commercial robots capable of manipulation

| | **Mantaro Teletrak** | **Origibot 2** | **The Stretch robot** | **Toyota HSR** | **TIAGo** | **Fetch MM** | **MuR205** | **Robotnik RB-1** | **KUKA KMR Iiwa** |
|---|---|---|---|---|---|---|---|---|---|
| **Year** | 2016 | 2018 | 2020 | 2015 | 2016 | 2018 | 2018 | 2015 | 2017 |
| **Price** | | ~750$ | 17950$ | ~9000$ | > 40000€ | | | | |
| **Subscription** | No | No | No | 3000$/m | No | | No | No | |
| **Weight [kg]** | 29,5 | <6 | 23 | 37 | 70 | 113,3 | > 90 | 54 | ~420 |
| **Height [cm]** | | 77-90 | 141 | 100-135 | 110-145 | 109,6-149,1 | >35-120 | 103-138 | 196,6 |
| **Camera** | Surface; pan, tilt, arm 720p | | 3D, pan, tilt | 3D + RGB-D + Wide + Hand | RGB-D | NaN | NaN | 2 or 3D | |
| **Screen** | Surface pro 4 | Tilt | NaN | Tilt | Separate module | NaN | NaN | NaN | NaN |
| **Audio channels** | 4.0 | Tablet | NaN | 2.0 | 2.0 | 2.0 | NaN | NaN | NaN |
| **Sensors** | 2x infrared Cliff sensors | | LIDAR | LIDAR, IMU | LIDAR, Ultrasonic,<br>Force | 2D lidar, RGB-D, 6-DOF IMU | RGB-D, Laser scanners, Ultrasonic | RGB-D | Laser scanner<br>Wheel sensor |
| **Wheels** | Tracks x 4 | 2 + 1 caster | 2 + 1 caster | Omnidirectional | 2 + 2 caster | 2+2 caster | | 2+2 caster | 4x mecanum |
| **Arm/Grabber** | 1 DoF | 3 DoF | 3 DoF | 4 DoF | 7DoF | 7 DoF | 6 DoF | 6 or 7 DoF | 7 DoF |
| **Arm carry capacity** | >0 | < 1 | < 1,5 | < 1,2 | <3 | < 6 | < 5 | <2,6 | 7 |
| **Max speed [m/s]** | | | 0,6 | | 1 | 1 | 1,1 | 1,5 | 1 |
| **Run time [h]** | | | | | 4-10 | | | 7 | |
| **Other/ Notes** | | | | | Laptop tray<br>Add-on support | | | | |
| **References** | (MantaroBot, 2017) | | (Hello robot, 2020) | (Toyota, 2015) | (Sataloff *et al.*, 2016) | (Wise *et al.*, 2016; Fetch Robotics, 2020) | (Recker *et al.*, 2021) | (Robotnik, 2020) | (Sorour *et al.*, 2019) |

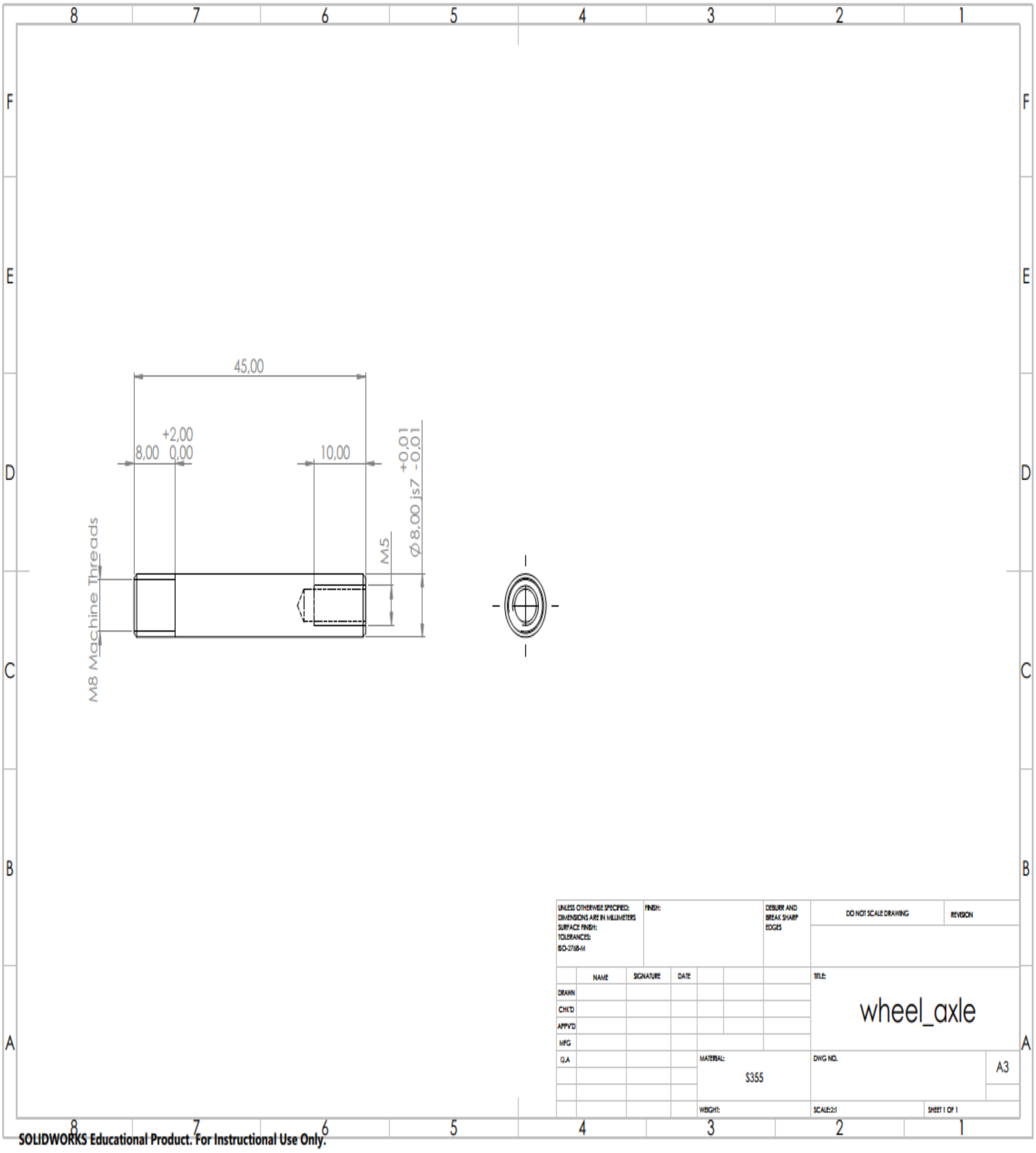
## **APPENDIX IV** Manufacturing drawings – Steering axle



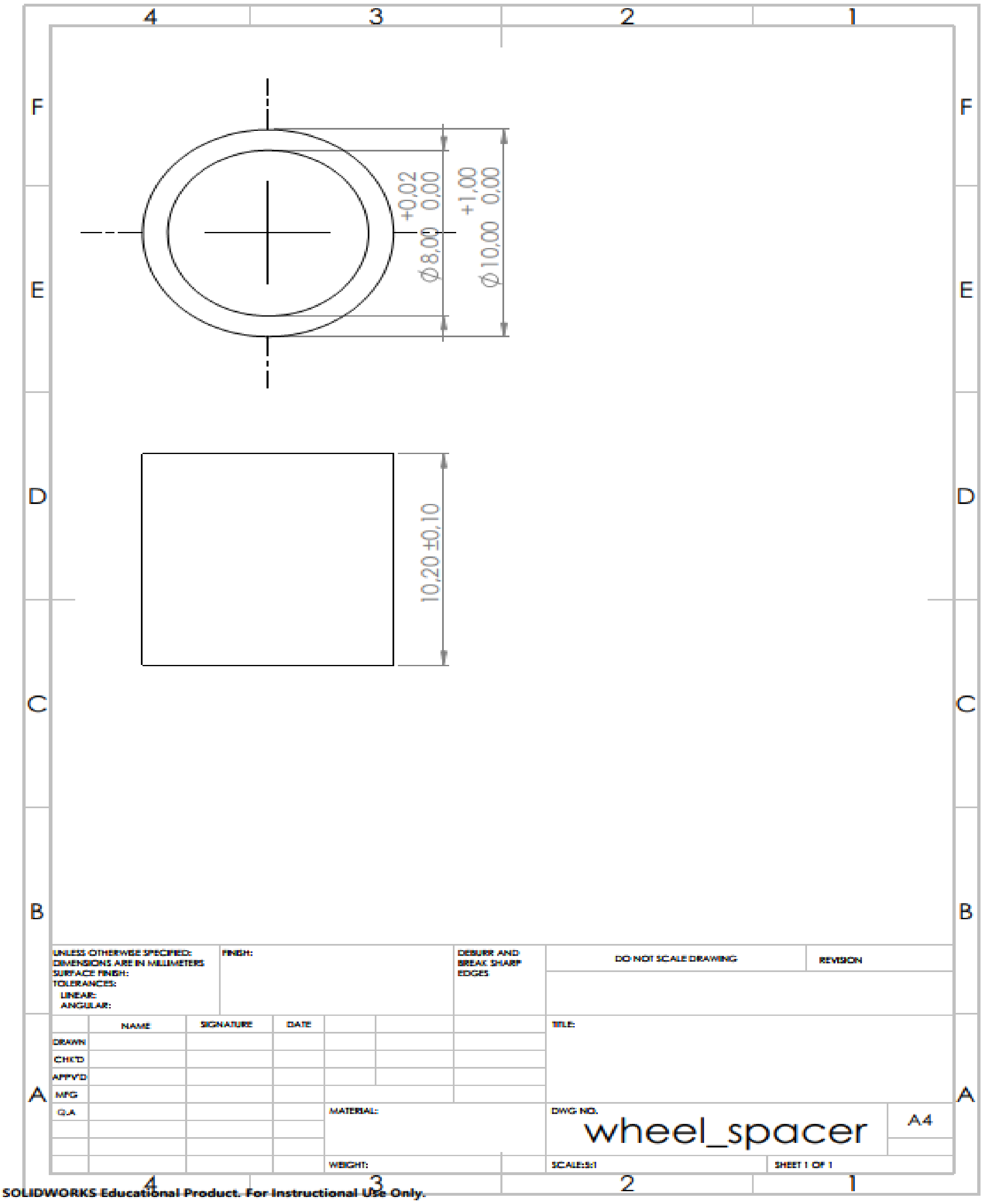
## **APPENDIX V** Manufacturing drawings – Drive axle



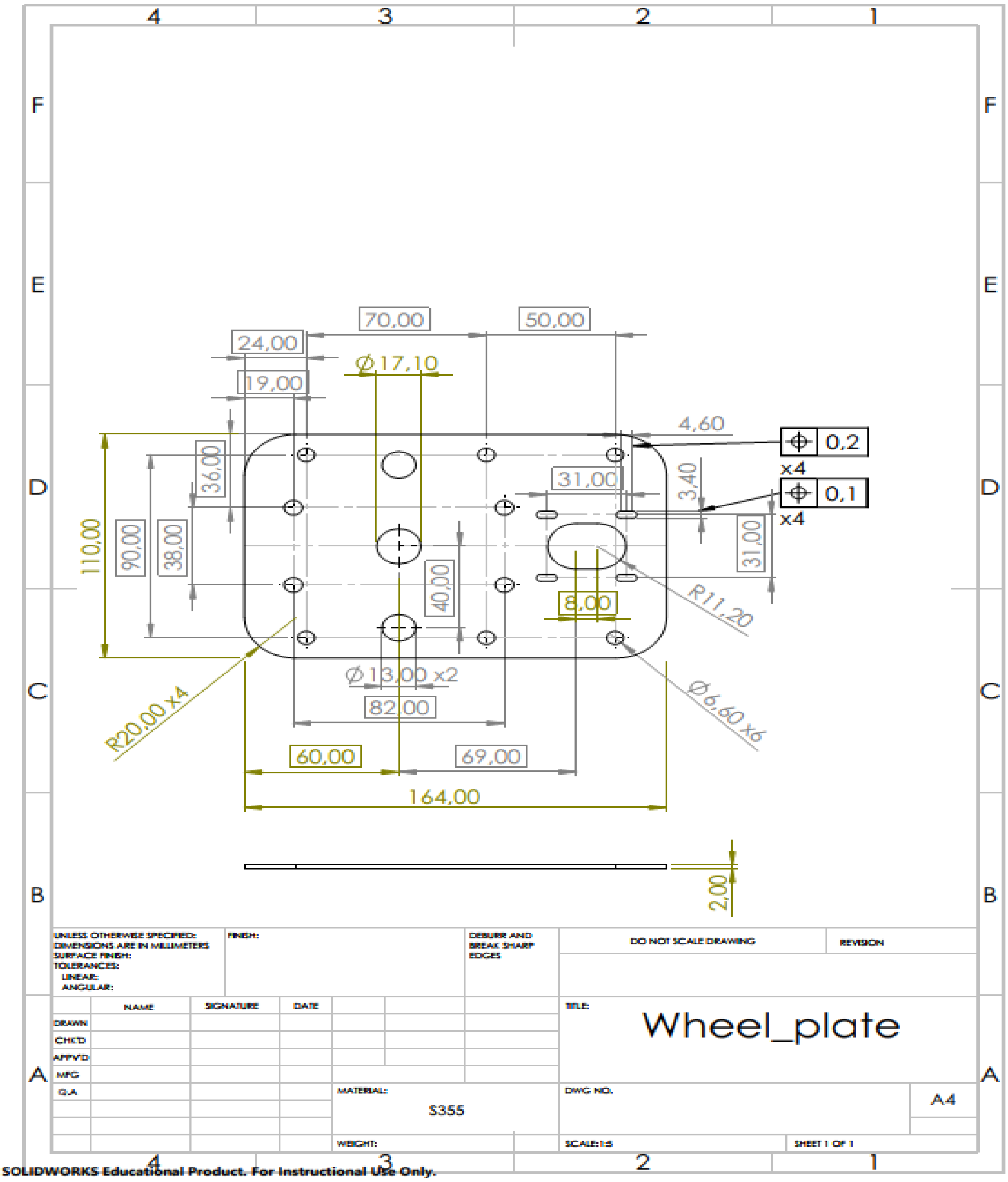
## **APPENDIX VI** Manufacturing drawings – Wheel axle



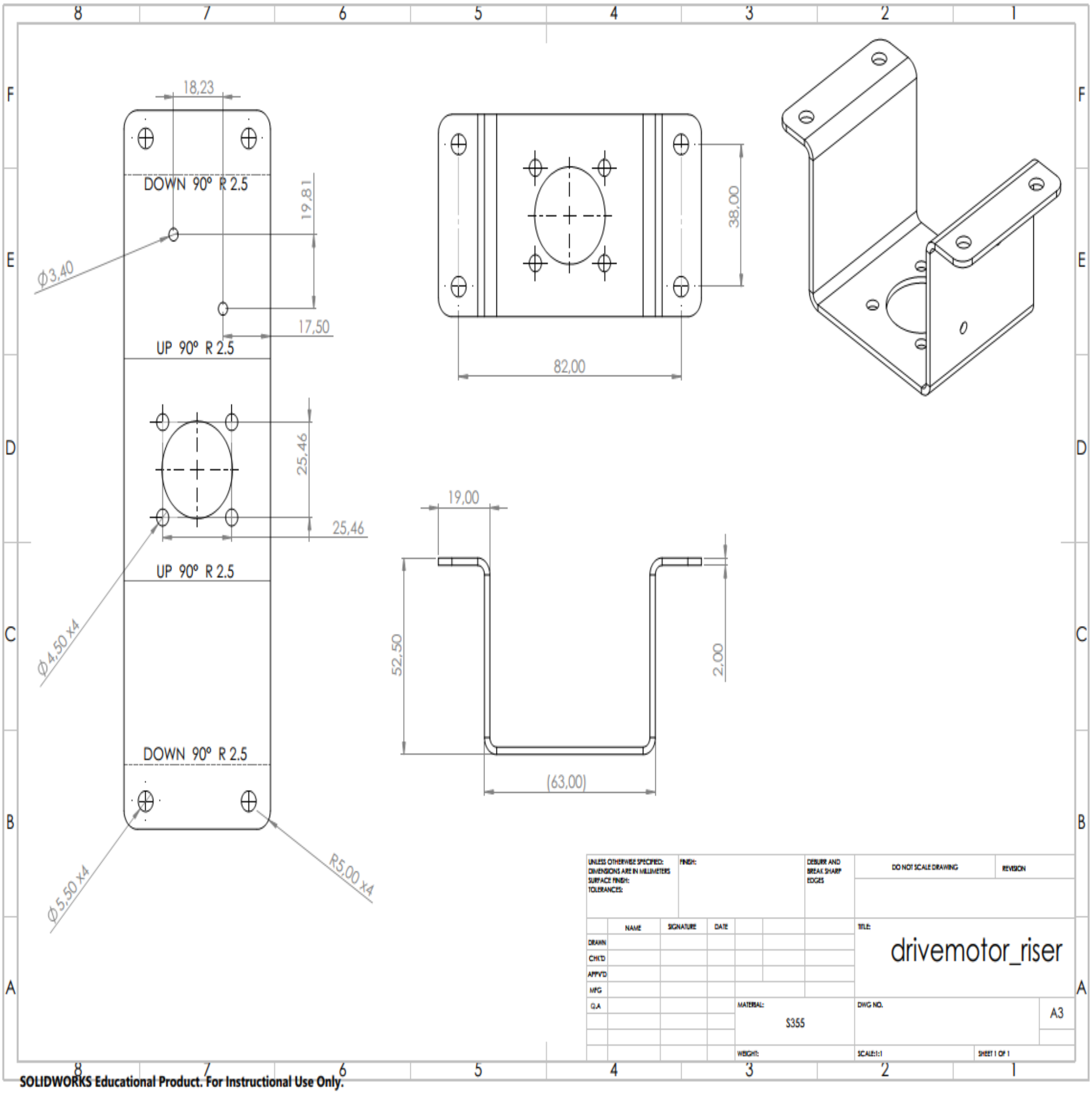
## **APPENDIX VII** Manufacturing Drawings – Wheel spacer



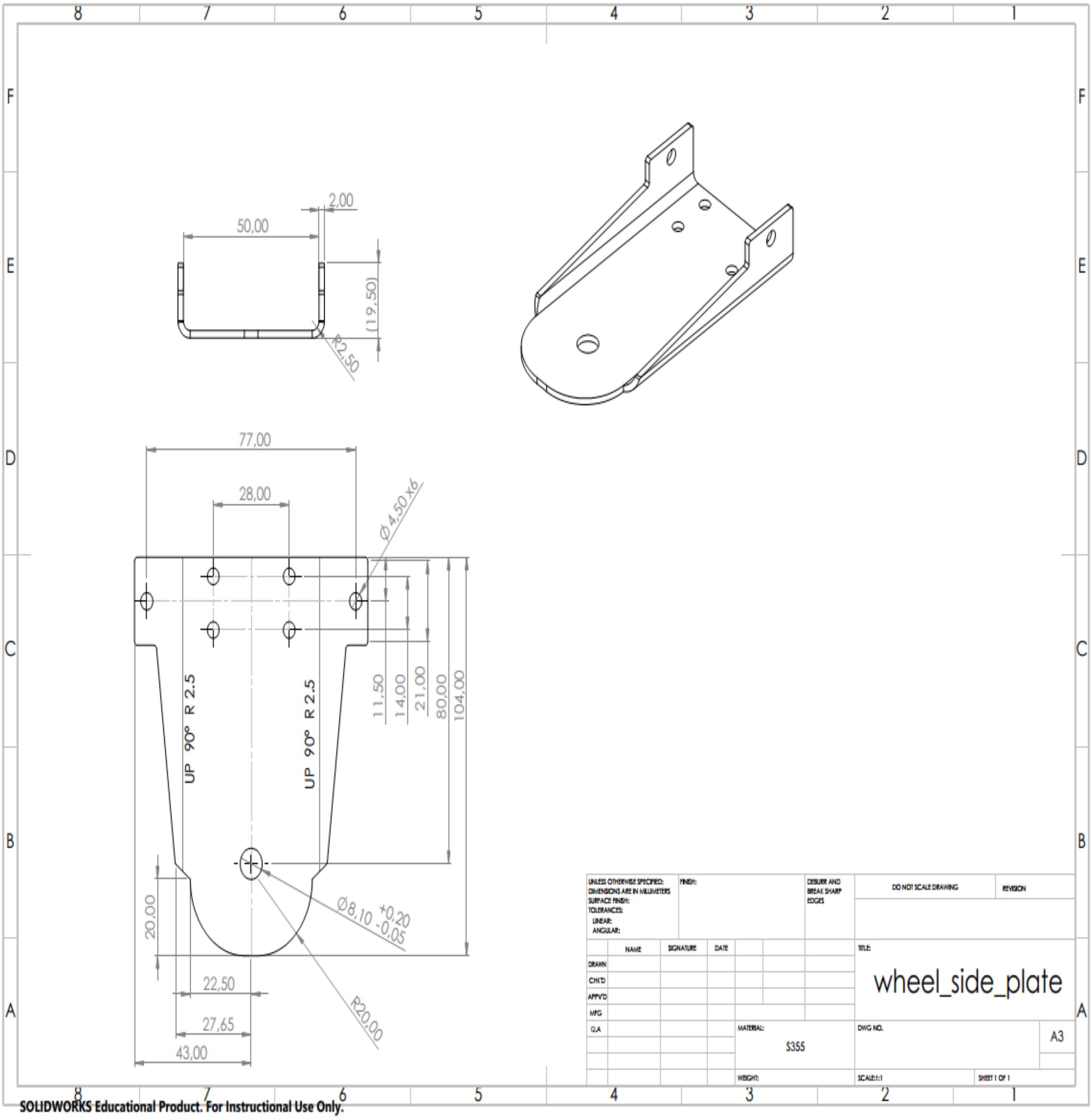
# **APPENDIX VIII** Manufacturing drawings – Module plate



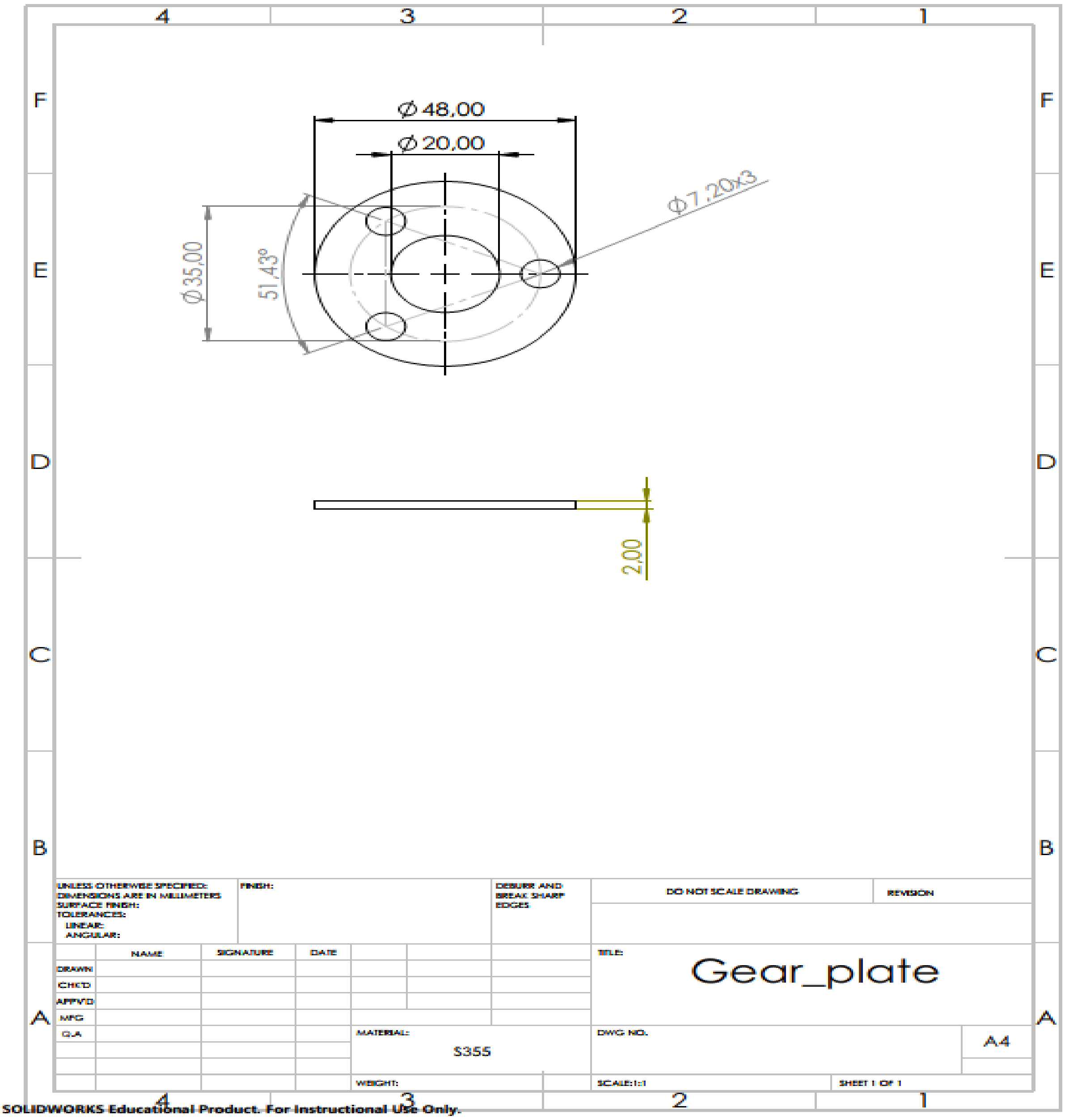
## **APPENDIX IX** Manufacturing drawings – Motor riser



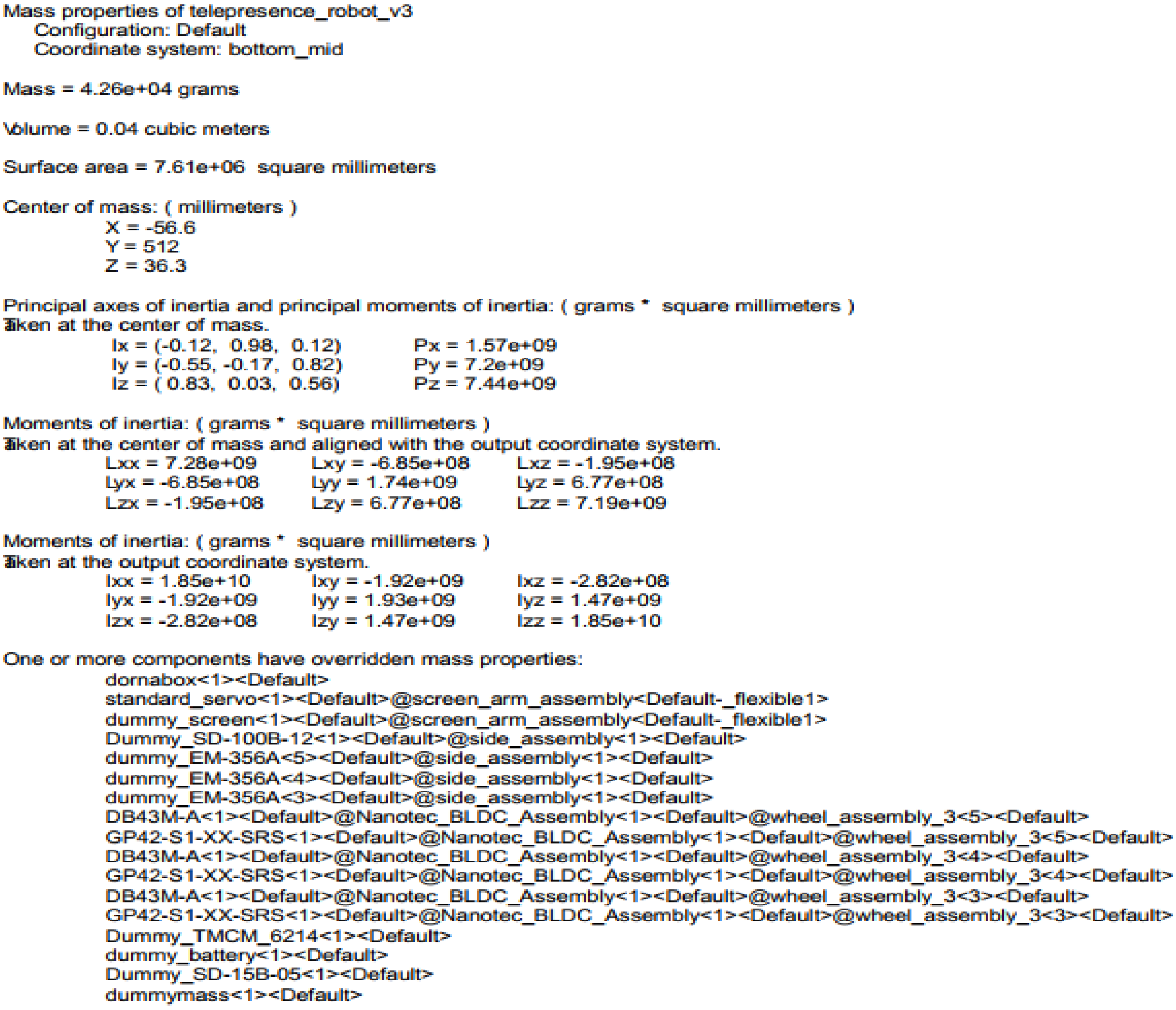
**APPENDIX X** Manufacturing drawings – Wheel side plate



## APPENDIX XI Manufacturing drawings – Gear attachment plate



## APPENDIX XII Example Solidworks mass properties output



```
Mass properties of telepresence_robot_v3
     Configuration: Default
     Coordinate system: bottom_mid

Mass = 4.26e+04 grams

Volume = 0.04 cubic meters

Surface area = 7.61e+06  square millimeters

Center of mass: ( millimeters )
                X = -56.6
                Y = 512
                Z = 36.3

Principal axes of inertia and principal moments of inertia: ( grams *  square millimeters )
Taken at the center of mass.
                 Ix = (-0.12,  0.98,  0.12)          Px = 1.57e+09
                 Iy = (-0.55, -0.17,  0.82)          Py = 7.2e+09
                 Iz = ( 0.83,  0.03,  0.56)          Pz = 7.44e+09

Moments of inertia: ( grams *  square millimeters )
Taken at the center of mass and aligned with the output coordinate system.
                Lxx = 7.28e+09        Lxy = -6.85e+08       Lxz = -1.95e+08
                Lyx = -6.85e+08       Lyy = 1.74e+09        Lyz = 6.77e+08
                Lzx = -1.95e+08       Lzy = 6.77e+08        Lzz = 7.19e+09

Moments of inertia: ( grams *  square millimeters )
Taken at the output coordinate system.
                Ixx = 1.85e+10        Ixy = -1.92e+09       Ixz = -2.82e+08
                Iyx = -1.92e+09       Iyy = 1.93e+09        Iyz = 1.47e+09
                Izx = -2.82e+08       Izy = 1.47e+09        Izz = 1.85e+10

One or more components have overridden mass properties:
                dornabox<1><Default>
                standard_servo<1><Default>@screen_arm_assembly<Default-_flexible1>
                dummy_screen<1><Default>@screen_arm_assembly<Default-_flexible1>
                Dummy_SD-100B-12<1><Default>@side_assembly<1><Default>
                dummy_EM-356A<5><Default>@side_assembly<1><Default>
                dummy_EM-356A<4><Default>@side_assembly<1><Default>
                dummy_EM-356A<3><Default>@side_assembly<1><Default>
                DB43M-A<1><Default>@Nanotec_BLDC_Assembly<1><Default>@wheel_assembly_3<5><Default>
                GP42-S1-XX-SRS<1><Default>@Nanotec_BLDC_Assembly<1><Default>@wheel_assembly_3<5><Default>
                DB43M-A<1><Default>@Nanotec_BLDC_Assembly<1><Default>@wheel_assembly_3<4><Default>
                GP42-S1-XX-SRS<1><Default>@Nanotec_BLDC_Assembly<1><Default>@wheel_assembly_3<4><Default>
                DB43M-A<1><Default>@Nanotec_BLDC_Assembly<1><Default>@wheel_assembly_3<3><Default>
                GP42-S1-XX-SRS<1><Default>@Nanotec_BLDC_Assembly<1><Default>@wheel_assembly_3<3><Default>
                Dummy_TMCM_6214<1><Default>
                dummy_battery<1><Default>
                Dummy_SD-15B-05<1><Default>
                dummymass<1><Default>
```

## APPENDIX XIII Bill of Materials – Standard components (1/3)

| Manufacturer | Item | Amount | Bought? (when) | Price/pc | Price (0% VAT) | Notes |
|---|---|---|---|---|---|---|
| **Bearings** | | | | | | |
| Generic | 608 -Z/2RS | 9 | Yes (previous project) | 0,97 | 8,73 | |
| Generic | 5303/3203-2RS/ZZ | 3 | 5.11. | 9,26 | 27,78 | |
| Generic | MR128-ZZ | 6 | 5.11. | 1,16 | 6,96 | Build note: These are easily damaged, replacements are recommended! |
| Generic | LV201-ZZ/2RS | 4 | 5,11 | 10,46 | 41,84 | Other track rollers could be adapted |
| **Electronics** | | | | | | |
| Intel | NUC BXNUC10FNH | 1 | Yes (previous project) | 600 | 600,00 | Alternative NUC - style computers can be used |
| TDK-LAMBDA | i6A 24014A033V-001 | 1 | Yes (previous project) | 26,94 | 26,94 | Convert from Battery to 19V for NUC |
| Mean Well | RSD-30G-05 | 1 | 29.01.00 | 31,8 | 31,80 | 5V for Arduino, servo etc. |
| Mean Well | SD-100B-12 | 1 | 12.11. | 44,5 | 44,50 | Power for screen/other 12V appliances/sensors. Replace with RSD-100B-12 in future (better efficiency) |
| Arduino | Mega2560 | 1 | 5.11. | 35 | 35,00 | General IO (sensors, communication)<br>Possibility to change to DUE for more capability (3,3V logic!) |
| Electromen | EM-356A | 3 | 5.11. | 88 | 264,00 | BLDC controllers |
| Electromen | EM-328A | 1 | 5.11. | 14,9 | 14,90 | Programming unit/cable for BLDC controllers |
| Generic | 120-ohm resistor | | | | | RS-485 termination resistor |
| Trinamic | TMCM-6214-TMCL | 1 | 5.11. | 283,17 | 283,17 | Stepper controller for 6 steppers, three encoder inputs |
| Multicomp | MCPIP-T12L-001 | 3 | 5.11. | 17,21 | 51,63 | Wheel steering zero position<br>Similar inductive sensors can be used (PNP) |
| TELEMECANIQUE SENSORS | XEP3S1W2B524 | 4 | 5.11. | 3,98 | 15,92 | Movement limit switches<br>Similar microswitches can be used |
| Niceview | 10.1" TFT Full-HD touch screen | 1 | 5.11. | 265,32 | 265,32 | |
| FTDI | USB-COM485-PLUS2 | 1 | 5.11. | 37,84 | 37,84 | For enabling NUC RS485 communication |
| Maxbotix | MB1010 | 4 | 5.11. | 27,21 | 108,84 | Ultrasonic sensors for collision detection (Cheaper Alternative eg. HC-SR04 below) For cost reasons only four in current prototype. Amount can be increased if deemed necessary. Alternative models with different beam patterns available if deemed better. |
| Adafruit | HC-SR04 | 3 | 5.11. | 3,34 | 10,02 | Ultrasonic sensors for table/tower obstacle detection. If deemed good could be used for other applications also. |

# Bill of Materials – Standard components

(2/3)

| | | | | | | |
|---|---|---|---|---|---|---|
| **Motors** | | | | | | |
| Savöx | SC-0251MG | 1 | 16.11. | 32,99 | 32,99 | Servo for screen up-down motion, see alternative link |
| Nanotec | DB43M024030-A/GP42-S1-4-SR | 3 | 12.11. | 185,04 | 555,13 | BLDC+ 1:4 Gear drive motor |
| Nanotec | ST4118M1206-A | 1 | Yes (previous project)/12.11 | 21,43 | 21,43 | Second one has been ordered! |
| Nanotec | ST4118S1006-A | 1 | Yes (previous project)/12.11 | 19,16 | 19,16 | Second one has been ordered! |
| Oriental motor | PKP244D15A2-R2FL + cable + encoder cable | 3 | 10.11. | 90,9 | 272,70 | Steppers with encoders for steering<br>PKP245U12A2-R2FL Ordered by accident (Can be modified relatively easily) |
| **Power transmission** | | | | | | |
| Mekanex/Norelem/RSPro | M2 Z10 bevel gear (PA/POM) 4:1 | 3 | 5.11. | 2,43 | 7,29 | Plastic gears for self-lubricating properties. |
| Mekanex/Norelem/RSPro | M2 Z40 bevel gear (PA/POM) 4:1 | 3 | 5.11. | 9,74 | 29,22 | Machined flat + 3 screw holes (see drawings) |
| Generic | HTD-3M-9 12T | 5 | 5.11. | 1,66 | 8,30 | 5x 5mm axle + M4 set screws |
| Generic | HTD-3M-9 24T | 2 | 5.11. | 2,00 | 4,00 | 1x Machined (see drawings)<br>1x 6mm axle + M4 set screws |
| Generic | HTD-3M-9 72T | 3 | 5.11. | 5,64 | 16,92 | 3x machined (see drawings) |
| Generic | HTD285-3M | 3 | 5.11. | 2,85 | 8,55 | Plans can be adapted for near sizes if better available |
| Generic | HTD225-3M | 1 | 5.11. | 5,64 | 5,64 | For head movement |
| Generic | HTD201-3M | 1 | 5.11. | 5,38 | 5,38 | For lead screw |
| Generic | TR12x3-500 | 1 | 10.11. | 44 | 44,00 | Trapezoidal screw for linear movement<br>One end machined to fit FK08! (included in price) |
| SYK | FK08 C7 | 1 | 10.11. | 44 | 44,00 | |
| | TR12x3 | 1 | 10.11. | 4 | 4,00 | Trapezoidal nut, steel |
| Traxxas | Connection Link TRX3941R (72mm) | 1 | 28.1. | 0 | 0,00 | See also Alternative link<br>Alternative 3D printed |
| GMT | FAME30-B-8-10 | 3 | 10.11. | 13,62 | 40,86 | Alternatives RAC-S-25-8-10 or FAMS24-8-10 or similar |
| Fastrax | FAST328B | 1 | 16.11. | 11,20 | 11,20 | Servo arm, see also alternative link |

# Bill of Materials – Standard components

(3/3)

| | | | | | | |
|---|---|---|---|---|---|---|
| **Other** | | | | | | |
| Powerslide | Spinner 110mm 85A | 3 | 5.11. | 8,9 | 26,70 | Alternative 100/110mm wheels available<br>latter link for future purchases, includes spacers and bearings and has better sprocket spacing. |
| Dorna | Arm 2 | 1 | 10.12. | 3500 | 3500,00 | Doran 2 ordered, has different mount pattern compared to first |
| Intel | D435i | 1 | 5.11. | 189 | 189,00 | Also available from local supplier |
| Tsubaki | MONO-0130.20-20-FA-MA-1-560 | 1 | 10.11. | 18 | 18,00 | Alternatives available (Size 10x20 R20) |
| PEI | Bellow cover 15/140-50/400 | 1 | 10.11. | 19 | 19,00 | See links for cheaper alternatives |
| Sunon | 120x120x25 24V | 2 | 5.11. | 22,08 | 44,16 | |
| Enerpower | Battery 24V, XT-60 + 3A charger | 1 | 16.11. | 298 | 298,00 | >=20Ah >700W power output, BMS integrated |
| Visaton | DX-10 | 1 | Yes (previous project) | 49,5 | 49,50 | Speaker 90mm |
| Soberton | XPCB-12BT | 1 | 5.11. | 16,85 | 16,85 | Audio amplifier |
| Tripp Lite | U360-004-2f | 1 | 24.11. | 35,82 | 35,82 | Powered USB HUB for external equipment |
| Seeed | 114991925 | 1 | 24.11. | 4,2 | 4,20 | USB hub for internal equipment |
| Multicomp | MCC2E-BVE11R | 1 | 24.11. | 10,73 | 10,73 | Emergency stop NC + NO |
| Panasonic | AHES3192 | 1 | 24.11. | 11,7 | 11,70 | Power relay *one damaged in shipping |
| C&K | DF62J12S215PQA | 1 | 24.11. | 5,04 | 5,04 | Power switch |
| Generic | 1/4" male to 1/4" male camera adapter | 2 | 12.12. | 2,2 | 4,40 | For attaching the RGB-D camera/other components to the screen |
| Generic | Power resistor >=25W 10 ohm | 3 | 24.11. | 2,6 | 7,80 | For braking EM-546A (if battery full) peak rating for 5s load >100W<br>Possibly not needed, to be evaluated with prototype<br>One burned out, configuration error |
| Generic | Fuse holder for 6 or more blade fuses | 1 | 02.02. | 6,99 | 6,99 | Alternative holders/fuse types available |
| | | | | | **Total** | |
| | | | | | 7253,85 | |

# APPENDIX XIV Bill of materials – Cables and connectors

| Manufacturer | Item | (Min.) Length [m] | Amount | Bought? (when) | Price/pc (/m) | Price (0% VAT) | Notes |
|---|---|---|---|---|---|---|---|
| **Cables** | | | | | | | |
| Trinamic | TMCM-6214-CABLE | | 1 | 5.11. | 20,26 | 20,26 | Cable set for stepper driver |
| Roline | USB-C-B | 0,5 | 1 | 24.11. | 11,35 | 11,35 | USB cable for USB HUB |
| Tripp lite | HDMI flat | 2 | 1 | 24.11. | 10,87 | 10,87 | Flat cable for routing through energy chain |
| Assmann | USB-A male to A male | 2 | 1 | 24.11. | 2,7 | 2,7 | For screen touch panel |
| Assmann | USB-A male to mini B male | 0,5 | 1 | 29.01 | 1,29 | 1,29 | RS485-adapter cable |
| Orientalmotor | LC2U06E | 0,6 | 3 | 5.11. | 5 | 15 | Motor cable for Orientalmotor |
| Orientalmotor/Molex | LCE08A-006/Molex picoblade 1,25 mm 8 pin/JST 1.25 8 pin | 0,6 | 3 | 27.12. | 4,81 | 14,43 | Orientalmotor encoder cable, see alternatives |
| CNC tech | 3,5mm male to male | 1 | 1 | 24.11. | 2,05 | 2,05 | Audio from screen to amplifier |
| 3M | Flat ribbon 24AWG | 1,20 | 1 | JHC has alternative | 27,3 | 27,3 | Ribbon cable for energy chain/general use |
| Tripp lite | USB C-USB C (USB3.1) | 2 | 1 | 24.11. | 18,14 | 18,14 | Cable for D435i, routed through energy chain |
| Assmann | CAT 5e cable | 0,5 | 1 | 24.11. | 2,06 | 2,06 | Dorna communication cable |
| Tensility International | Barrel plug 5.5 OD 2.5 ID, male >90W | 0,50 | 1 | 24.11. | 3,41 | 3,41 | NUC DC input plug |
| Generic | Power cable (min 2,5 mm^2) | 2,00 | 1 | JHC has alternative | 2 | 4 | Cable for battery, power relay, power resistors etc. High power applications |
| Belden | 24AWG, 3 core, shielded | 3,5 | 10 | 24.11. | 1,48 | 5,18 | General use shielded cable (sensors, motor control, etc) 10m roll is enough for two bots |

## Bill of materials – Cables and connectors (2/2)

| | | | | | | |
|---|---|---|---|---|---|---|
| **Connectors/Adapters** | | | | | | |
| Generic | XT-60, male | 1 | 16.11. | | 0 | Battery connector, one came with the battery so unnecessary |
| Neutrik | XLR 3-pin female | 1 | 24.11. | 2,45 | 2,45 | Connectors for docking station and battery connection in bot (see alternative) |
| Neutrik | XLR 3-pin male | 1 | 24.11. | 2,45 | 2,45 | Connectors for docking station and battery connection in bot (see alternative) |
| IO-Audio technologies | XLR 3-pin female, panel | 1 | 27.12. | 2,92 | 2,92 | Charging port to mount to the frame (alternative to docking).<br>(Wrong product link, fixed 29.11.) |
| Mill-Max | Spring loaded contacts | 2 | 24.11. | 6,26 | 12,52 | Docking male connector, need for bigger connectors for less critical positioning to be evaluated<br>Tapped to M3 |
| Mill-Max | Spring loaded connectors female | 2 | 24.11. | 4,69 | 9,38 | Docking female connector<br>Tapped to M3 |
| Generic | Barrel plug 5.5 OD 2.1 ID, male | 2 | 24.11. | 1,17 | 2,34 | Audio board DC/Screen DC input |
| Molex | 3,81mm terminal block 3 pin | 3 | 24.11. | 0,88 | 2,64 | RS-485 plug for electromen |
| Generic | 2,54 mm screw terminal 3 pin | 3 | 13.01. | 0,85 | 2,55 | Soldered to MB-10xx, alternatively female dupont |
| Generic | 2,54 mm screw terminal 4 pin | 3 | 13.01. | 1,14 | 3,42 | Soldered to MB-10xx, alternatively female dupont |
| Generic | 2,54 mm header crimp 1 pin - female | 20 | JHC | 0,13 | 2,6 | Connecting sensors, servo, etc. to arduino |
| Generic | 2,54 mm header 1 pin crimp - male | 10 | JHC | 0,22 | 2,2 | Connecting sensors, servo, etc. to arduino |
| Generic | 2,54 mm header 1 pin housing - female | 12 | JHC | 0,49 | 5,88 | Connecting sensors, servo, etc. to arduino |
| Generic | 2,54 mm header 3 pin housing - male | 1 | JHC | 0,39 | 0,39 | Servo connection |
| Generic | 2,54 mm header 4 pin housing - female | 3 | JHC | 0,4 | 1,2 | HC-SR04 connection |
| Generic | Crimp connector, blade red | 10 | JHC | | 0 | Appliance to fusebox |
| Generic | Crimp connector, blade blue split | 2 | JHC | | 0 | Battery to fusebox, last |
| Generic | Crimp connector, blade yellow | 7 | JHC | | 0 | Battery to fusebox, first 7 (Yellow 10-12 AWG) |
| Generic | Crimp connector, Ring blue M6 | 1 | JHC | | 0 | Battery Ground to ground rail |
| Generic | Crimp connector, Ring red M4 | 7 | JHC | | 0 | Appliance grouds ground rail |
| Amphenol ICC | DE09S064TLF | 2 | 24.11. | 0,46 | 0,92 | DB-9 plugs for RS-485 bus USB adapter |
| | | | | | **Total**<br>137,6 | |

## APPENDIX XV Bill of Materials – Manufactured components (1/3)

| Item/part | Finished size | Amount | Material Bought? (/machining ordered) (When) | Made? (when) | Used Manufacturing method(s) | Laser Manufacturing time /pc (toolpath) | CNC manufacturing time /pc (toolpath) | CNC Tool changes | Overall time | Alternative manufacturing method(s) |
|---|---|---|---|---|---|---|---|---|---|---|
| **Thermoformable plywood** | | | | | | | | 0:02:00 | | |
| Outline Right | 6,5x260x301 | 1 | JHC provided | 15.12. | Laser cutting + CNC (+ Manual Drilling) | 0.12.53 | 0:09:06 | 1 | 0:11:06 | Water jet cutting/+ Heat bending |
| Outline left | 6,5x260x301 | 1 | JHC provided | 7.1. | Laser cutting + CNC (+ Manual Drilling) | 0.11.56 | 0:08:16 | 1 | 0:10:16 | Water jet cutting/+Heat bending |
| Tower hatch | 6,5x900x120 | 1 | JHC provided | 9.12. | Laser cutting | | 0:02:32 | 0 | 0:02:32 | Water jet cutting |
| Tower top | 6,5x304x200 | 1 | JHC provided | 13.12. | Laser cutting | 0.03.20 | 0:01:50 | 0 | 0:01:50 | Bending/Water jet cutting |
| Tower back | 6,5x1100x200 | 1 | JHC provided | 9.12. | Laser cutting | 0.14.27 | 0:05:34 | 0 | 0:05:34 | Water jet cutting |
| Tower Front | 6,5x1076x200 | 1 | JHC provided | 9.12. | Laser cutting | 0.13.30 | 0:05:14 | 0 | 0:05:14 | Water jet cutting |
| Vesa plate | 6,5x90x90 | 1 | JHC provided | 29.11. | CNC | 0.02.39 | 0:00:53 | 0 | 0:00:53 | Water jet -/Laser cutting |
| Hatch support | 6,5x15x30 | 9 | JHC provided | 9.12. | CNC/Laser cutting | 0.00.36 | 0:00:26 | 0 | 0:03:54 | Water jet cutting |
| **Birch plywood** | | | | | | | | | | |
| Baseplate | 24x510x510 | 1 | 24.11. | 10.12. | CNC + Drilling | | 0:07:14 | 1 | 0:09:14 | Water jet cutting/Manual cuttingting+Drilling |
| linear movement plate | 24x545x124 | 1 | 24.11. | 7.12. | CNC + Drilling | | 0:05:31 | 1 | 0:07:31 | Water jet cutting + Drilling |
| Dorna plate | 24x280x90 | 1 | 24.11. | 6.12. | CNC | | 0:10:26 | 1 | 0:12:26 | Water jet cutting + Drilling |
| Lead motor plate | 24x170x70 | 1 | 24.11. | 6.12. | CNC + Drilling | | 0:02:24 | 1 | 0:04:24 | Water jet cutting/Saw + Drilling |
| lead nut housing | 24x76x60 | 1 | 24.11. | 3.12. | CNC + Drilling | | 0:02:52 | 1 | 0:04:52 | Water jet cutting + Drilling |
| Wheel bearing housing | 24x90x80 | 1 | 24.11. | 25.11. | CNC + Drilling | | 0:03:13 | 1 | 0:05:13 | |
| Top plate | 15x510x510 | 1 | 24.11. | 10.12. | CNC | | 0:03:36 | 1 | 0:05:36 | Water jet cutting/Manual cutting |

# Bill of Materials – Manufactured components

(2/3)

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Birch plywood** | | | | | | | | | | |
| Tower side plate | 15x1176x160 | 2 | 24.11. | 8.12. | Laser marking + Ripping-/Band saw + Belt sander | 0.00.38 | 0:08:23 | 1 | 0:18:46 | Water jet cutting (+ Drilling)/CNC |
| Linear rail | 15x900x30 | 2 | 24.11. | 8.12. | Ripping saw + Drilling | | | | 0:00:00 | Water jet cutting/CNC + Milling cuttingter |
| Rail end | 15x60x30 | 4 | 24.11. | 23.11. | Ripping-/band saw + Drilling | | 0:00:39 | 0 | 0:02:36 | Water jet cutting/CNC |
| Cable carrier plate | 15x80x25 | 1 | 24.11. | 23.11. | Ripping-/band saw + Drilling | | 0:01:06 | 1 | 0:03:06 | Water jet cutting/CNC |
| Support block | 15x15x60 | 5 | 24.11. | 10.12 | Ripping-/band saw + Drilling | | 0:00:46 | 0 | 0:03:50 | Water jet cutting/CNC |
| Neck plate | 15x150x120 | 1 | 24.11. | 22.11. | CNC + Drilling | | 0:02:10 | 0 | 0:02:10 | Water jet cutting |
| Neck bearing "lollipop" | 15x68x30 | 2 | 24.11. | 15.11. | CNC | | 0:02:20 | 0 | 0:04:40 | Water jet cutting + Drilling |
| Screen flange | 15x60x60 | 1 | 24.11. | 16.11. | CNC | | 0:01:44 | 0 | 0:01:44 | Water jet cutting + Drilling |
| Dorna support plate | 15x120x30 (triangular) | 2 | 24.11. | 22.12. | CNC + Drilling | | 0:00:58 | 0 | 0:01:56 | Water jet cutting |
| Table main plate | 9x250x160 | 2 | JHC provided | | CNC + Drilling | | 0:01:48 | 0 | 0:03:36 | Water jet cutting |
| Table frame vertical | 9x150x15 | 1 | JHC provided | | CNC + Drilling | | 0:00:50 | 0 | 0:00:50 | Water jet cutting |
| Table frame horizontal | 9x160x32 | 1 | JHC provided | | CNC + Drilling | | 0:01:12 | 0 | 0:01:12 | Water jet cutting |
| Table support | 9x145x145 (triangular) | 2 | JHC provided | | CNC + Drilling | | 0:02:06 | 0 | 0:04:12 | Water jet cutting |
| **S355/alternative - Sheet** | | | | | | | ***Bending** | | | |
| Wheel module plate | 2x160x120 | 3 | LUT Voima provided | 5.12. | Laser cutting | 0:00:24 | | | 0:01:12 | Manual cutting + Drilling |
| Motor riser | 2x186x64 | 3 | LUT Voima provided | 5.12. | Laser cutting + Bench press | 0:00:12 | 0:00:40 | | 0:00:36 | Manual cutting + Drilling |
| Wheel side plate | 2x104x76,1 | 3 | LUT Voima provided | 5.12. | Laser cutting + Bench press | 0:00:19 | 0:00:28 | | 0:00:57 | Manual cutting + Drilling |
| Wheel attachment plate | 2xd48 | 3 | LUT Voima provided | 5.12. | Laser cutting + Rivet nut tool | 0:00:06 | 0:02:30 | | 0:00:18 | Sheet metal work centre with tapping ability |
| Nema 17 bracket | 2x100x42 | 2 | LUT Voima provided | 5.12. | Laser cutting + Bench press | 0:00:20 | | | 0:00:40 | |

## Bill of Materials – Manufactured components (3/3)

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **S355/alternative - Round** | | | | | | | | | |
| Steering Axle | D17x3,5x60 | 3 | LUT Voima provided | 7.12. | Turning | 0:20:00 | | 1:00:00 | |
| Drive axle | D10x107 | 3 | LUT Voima provided | 7.12. | Turning | 0:10:00 | | 0:30:00 | |
| Wheel axle | D8x41 | 3 | LUT Voima provided | 7.12. | Turning + Drilling + Tapping | 0:15:00 | | 0:45:00 | |
| Spacers 8mm ID | 10x1x10 OR 12x2x10 | 6 | LUT Voima provided | 7.12. | Turning | 0:02:00 | | 0:12:00 | |
| **Aluminium** | | | | | | | | | |
| U-profile | 10x20x10x1,5/2x1000 | 2 | 18.01. | 20.01. | Drilling | 0:00:25 | 0 | 0:00:50 | |
| HTD-3M-9 12T | Standad component | 5 | 11.12. | 22.12. | Drilling + Tapping | 0:08:00 | 1 | 0:42:00 | |
| HTD-3M-9 24T | Standard component | 1 | 11.12. | 22.12. | Drilling + Tapping | 0:08:00 | 1 | 0:10:00 | |
| HTD-3M-9 24T neck | Standard component | 1 | 11.12. | 21.12. | Turning + Drilling + Tapping | 0:15:00 | 2 | 0:19:00 | Milled |
| HTD-3M-9 72T | Standard component | 3 | 11.12. | 21.12. | Turning + Drilling | 0:15:00 | 2 | 0:49:00 | Milled |
| **Plastic** | | | | | | | | | |
| M2 Z40 bevel gear (PA/POM) 4:1 | Standard component | 3 | 5.11. | 24.11. | Turning + Drilling | 0:10:00 | 0 | 0:30:00 | |
| M2 Z10 bevel gear (PA/POM) 4:1 | Standard component | 3 | 5.11. | 29.12. | Drilling + tapping | 0:02:00 | 0 | 0:06:00 | |
| 72mm servo link | | 1 | JHC provided | 28.1. | 3D printing (FDM) | 0:26:00 | 0 | 0:26:00 | |
| Maxbotix spacer | | 4 | JHC provided | 19.11. | 3D printing (FDM) | 0:05:15 | 0 | 0:21:00 | |
| HC-SR04 main enclosure | | 3 | JHC provided | 3.12. | 3D printing (FDM) | 0:30:00 | 0 | 1:30:00 | |
| HC-SR04 top enclosure | | 3 | JHC provided | 3.12. | 3D printing (FDM) | 0:12:00 | 0 | 0:36:00 | |
| Zero detect part | | 3 | JHC provided | 22.12. | 3D printing (FDM) | 0:00:58 | 0 | 0:02:54 | |
| AHES3191 holder | | 1 | JHC provided | 02.02. | 3D printing (FDM) | 0:01:05 | 0 | 0:01:05 | |
| PCB spacer | | 30 | JHC provided | 21.12. | 3D printing (FDM) | 0:00:38 | 0 | 0:19:00 | |
| | | | | | | | | **Combined Manufacturing time (machines)**<br>10.42.45 | |

# APPENDIX XVI Bill of Materials – Fasteners and other fixing elements

(1/2)

| ISO/DIN standard | Item | Amount | Bought (when) | Amount (pack) | Price (pack) | Price (bot) | Notes |
|---|---|---|---|---|---|---|---|
| **Wood screws, countersunk** | | | | | | | |
| | 4x40/4x45 | 6 | JHC | 200 | 11,4 | 0,34 | Trapezoidal screw plate, dorna support |
| | 4x30 | 100 | JHC | 200 | 8,6 | 4,30 | General use wood screws |
| | 4x16 | 12 | JHC | 200 | 6 | 0,36 | |
| **Wood screws, Pan head** | | | | | | | |
| | 3,5x9,5 | 30 | JHC | 250 | 3,5 | 0,42 | HC-SR04 attachment, angle irons, cable management |
| **Machine screws, hex** | | | | | | | |
| ISO 4016/ISO 4017 | M12x60 (M12x50) | 4 | 16.12. | 150 | 50 | 1,33 | For attaching LV201 track roller Length minimum 50mm for T-nut, for ordinary 60 |
| ISO 4016/ISO 4017 | M8x30 | 1 | JHC | 100 | 12,35 | 0,12 | Attaching the screen flange |
| ISO 4016/ISO 4017 | M8x50 | 4 | 16.12. | 200 | 33,5 | 0,67 | Dorna attachment, doesn't need to be fully threaded |
| **Machine screws, cap head** | | | | | | | |
| ISO 4762/DIN912 | M6x30 | 18 | 16.12. | 100 | 6,36 | 1,14 | Wheel modules, doesn't need to be fully threaded |
| ISO 4762/DIN912 | M5x35 | 9 | 16.12. | 100 | 5,75 | 0,52 | Bevel gears |
| ISO 4762/DIN912 | M5x12 | 19 | 16.12. | 100 | 4,8 | 0,91 | Wheel module assembly |
| ISO 4762/DIN912 | M4x12 | 4 | JHC | 100 | 4,3 | 0,17 | Screen vesa mount |
| ISO 4762/DIN912 | M4x10 | 20 | JHC | 100 | 4,2 | 0,84 | Drive motor attachment, ground rail |
| ISO 4762/DIN912 | M3x30 | 8 | JHC | 100 | 7,52 | 0,60 | Fan attachment |
| ISO 4762/DIN912 | M3x12 | 12 | 16.12. | 100 | 4,49 | 0,54 | Microswitches, lead screw bearing FK08 |
| ISO 4762/DIN912 | M3x8 | 54 | 16.12. | 100 | 3,5 | 1,89 | Nema 17 motors, board mounting, power resistors |
| **Machine screws, countersunk** | | | | | | | |
| ISO 10642/DIN7991 (or ISO 14581/ISO 7046) | M3x10 | 26 | 16.12. | 100 | 4 | 1,04 | DC-DC converters, charging ports, steering sense |
| **Set Screws** | | | | | | | |
| ISO4029/DIN916 | M4x5 | 12 | 16.12. | 20 | | 0,00 | Pulleys 5x12, 1x24 |
| ISO4029/DIN916 | M3x10 | 2 | 16.12. | 20 | | 0,00 | Head horizontal movement pulley attachment |
| ISO4029/DIN916 | M3x4 | 6 | 16.12. | 20 | | 0,00 | Bevel gear shaft attachment |
| **Washers** | | | | | | | |
| DIN125 | 17 | 14 | JHC | 100 | 8,9 | 1,25 | |
| DIN125 | 8,4 | 12 | JHC | 20 | 3,6 | 2,16 | |
| DIN125 | 6,4 | 22 | JHC | 20 | 3,6 | 3,96 | Wheel modules + dorna |
| DIN125 | 5,3 | 12 | JHC | 30 | 3,6 | 1,44 | Wheel gears, wheel, |
| DIN125 | 4,3 | 12 | JHC | 30 | 3,6 | 1,44 | Motor mounting |
| DIN125 | 3,2 | 80 | 16.12. | 50 | 1,8 | 2,88 | Electronics, motors, etc. |

## Bill of Materials – Fasteners and other fixing elements (2/2)

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| **Nuts** | | | | | | | |
| ISO 8675/DIN439/DIN 936 | M16x1,5 Thin | 6 | 17.12. | 1 | 0,75 | 4,50 | Steering axle attachment |
| ISO4032/DIN934 | M12 | 4 | JHC | 10 | 3,3 | 1,32 | If T-nuts not available! |
| ISO4032/DIN934 | M8 | 4 | JHC | 100 | 6,5 | 0,26 | Head vertical movement, wheels |
| ISO4032/DIN934 | M6 | 1 | JHC | 100 | 4,9 | 0,05 | Ground rail, battery |
| ISO4032/DIN934 | M4 | 8 | JHC | 25 | 2,3 | 0,74 | Ground rail, appliaces |
| **T-nuts** | | | | | | | |
| | T-nut M8 | 6 | JHC | 20 | 3,2 | 0,96 | |
| | T-nut M6 | 16 | 16.12. | 20 | 2,9 | 2,32 | wheel modules |
| **Rivet Nuts** | | | | | | | |
| | Rivet nut M5, small flange | 21 | 16.12. | 40 | 6,9 | 3,62 | Wheel module assembly, bevel attachment plate (these can be replaced with threads/inserts made with punching machine |
| **Misc** | | | | | | | |
| | M8x90 rod | 1 | JHC | 1000 | 2,8 | **0,27** | Head vertical axle |
| Din7865/Ensat309/other | M3 thread inserts for wood | 100 | 17.12. | | 20,06 | | Threaded or expansion inserts work<br>Attaching points for electronics or other components. |
| | Angle iron 40x40x20 | 4 | JHC | | | | Attachment of tower to baseplate |
| | T-plate 70x50x16 | 1 | JHC | | | | Attachment of dorna plate to the linear plate |
| | Piano hinge 20mm | 1m | 17.12. | | 4 | 3,00 | Foldable table hinges |
| | Cable clips, sticker | 30 | 20.01. | | 3,99 | 2,50 | Cable management and routing |
| | M3 3mm spacer nylon | 34 | Alternative | | 11,82 | | Spacer for PCB attachment (can be printed) |
| | | | | | | **Total** | |
| | | | | | | 47,87 | |

# APPENDIX XVII Material costs (1/2)

| **Thermoformable plywood** | **Amount** | **Thickness** | **Length** | **Width** | **m^2** | **m^3** | **Price/m^2** | **Material cost** |
|---|---|---|---|---|---|---|---|---|
| Outline Right | 1 | 6,5 | 301 | 260 | 0,07826 | 0,0005087 | | 1,17 |
| Outline left | 1 | 6,5 | 301 | 260 | 0,07826 | 0,0005087 | | 1,17 |
| Tower hatch | 1 | 6,5 | 900 | 120 | 0,108 | 0,0007020 | | 1,62 |
| Tower top | 1 | 6,5 | 304 | 304 | 0,092416 | 0,0006007 | | 1,39 |
| Tower back | 1 | 6,5 | 1100 | 200 | 0,22 | 0,0014300 | | 3,30 |
| Tower Front | 1 | 6,5 | 1076 | 200 | 0,2152 | 0,0013988 | | 3,23 |
| Vesa plate | 1 | 6,5 | 90 | 90 | 0,0081 | 0,0000527 | | 0,12 |
| Hatch support | 9 | 6,5 | 30 | 15 | 0,00405 | 0,0000029 | | 0,06 |
| **6,5 mm grada Combined** | | | | | **0,804286** | **0,0052045** | **15** | **12,06** |
| **Birch plywood BB/WG** | **Amount** | **Thickness** | **Length** | **Width** | **m^2** | **m^3** | **Price/m^2** | **Material cost** |
| Baseplate | 1 | 24 | 510 | 510 | 0,2601 | 0,0062424 | | 11,44 |
| linear movement plate | 1 | 24 | 545 | 124 | 0,06758 | 0,00162192 | | 2,97 |
| Dorna plate | 1 | 24 | 280 | 90 | 0,0252 | 0,0006048 | | 1,11 |
| Lead motor plate | 1 | 24 | 170 | 70 | 0,0119 | 0,0002856 | | 0,52 |
| lead nut housing | 1 | 24 | 60 | 76 | 0,00456 | 0,00010944 | | 0,20 |
| Wheel bearing housing | 3 | 24 | 90 | 80 | 0,0216 | 0,0001728 | | 0,95 |
| **24 mm Combined** | | | | | **0,39094** | **0,009037** | **44** | **17,20** |
| Top plate | 1 | 15 | 510 | 510 | 0,2601 | 0,0039015 | | 6,76 |
| Tower side plate | 2 | 15 | 1176 | 160 | 0,37632 | 0,0028224 | | 9,78 |
| Linear rail | 2 | 15 | 900 | 30 | 0,054 | 0,000405 | | 1,40 |
| Rail end | 4 | 15 | 60 | 30 | 0,0072 | 0,000027 | | 0,19 |
| Cable carrier plate | 1 | 15 | 80 | 25 | 0,002 | 0,00003 | | 0,05 |
| Support block | | 15 | 60 | 15 | 0 | 0,0000135 | | 0,00 |
| Neck plate | 1 | 15 | 150 | 120 | 0,018 | 0,00027 | | 0,47 |
| Neck bearing "lollipop" | 2 | 15 | 68 | 30 | 0,00408 | 0,0000306 | | 0,11 |
| Screen flange | 1 | 15 | 60 | 60 | 0,0036 | 0,000054 | | 0,09 |
| Dorna support plate | 2 | 15 | 120 | 30 | 0,0072 | 0,000054 | | 0,19 |
| **15mm combined** | | | | | **0,7325** | **0,007608** | **26** | **19,05** |
| Table main plate | 1 | 9 | 250 | 160 | 0,04 | 0,00036 | | 0,68 |
| Table frame vertical | 1 | 9 | 150 | 15 | 0,00225 | 0,00002025 | | 0,04 |
| Table frame horizontal | 1 | 9 | 160 | 32 | 0,00512 | 0,00004608 | | 0,09 |
| Table support | 2 | 9 | 145 | 145 | 0,04205 | 0,00018923 | | 0,71 |
| **9mm combined** | | | | | **0,08942** | **0,0006156** | **17** | **1,52** |

## Material costs (2/2)

| **S355 Sheet metal** | **Amount** | **Thickness** | **Length** | **Width** | **m^2** | **m^3** | **Price/m^3** | **Material cost** |
|---|---|---|---|---|---|---|---|---|
| Wheel module plate | 3 | 2 | 160 | 120 | 0,0576 | 0,0001152 | 7865 | 0,91 |
| Motor riser | 3 | 2 | 186 | 64 | 0,035712 | 7,1424E-05 | | 0,56 |
| Wheel side plate | 3 | 2 | 104 | 77 | 0,024024 | 4,8048E-05 | | 0,38 |
| Wheel attachment plate | 3 | 2 | 48 | 48 | 0,006912 | 1,3824E-05 | | 0,11 |
| Nema 17 bracket | 2 | 2 | 100 | 42 | 0,0084 | 0,0000168 | | 0,13 |
| **Combined** | | | | | **0,132648** | **0,0002653** | | **2,09** |

| **S355 round stock** | **Amount** | **Diameter** | **Length** | **Wall thickenss** | **m^3** | **Price/m^3** | **Material cost** |
|---|---|---|---|---|---|---|---|
| Steering Axle | 3 | 17 | 60 | 3,50 | 4,8038E-06 | 7865 | 0,04 |
| Drive axle | 3 | 10 | 107 | | 8,3995E-06 | | 0,07 |
| Wheel axle | 3 | 8 | 41 | | 2,0598E-06 | | 0,02 |
| Spacers 8mm ID | 4 | 10 | 10 | 1 | 0,00000019 | | 0,00 |
| **Combined** | | | | | **1,545E-05** | | **0,12** |

| **Aluminium profile** | **Amount** | **Width** | **Heigth** | **Length** | **Wall thickness** | **m^3** | **Price/m^3** | **Material cost** |
|---|---|---|---|---|---|---|---|---|
| Bellow support U-profile | 2 | 20 | 10,00 | 1000 | 2,00 | 0,000208 | 16260 | 3,38 |
| Ground rail U-profile | 1 | 20 | 10,00 | 80 | 2,00 | 0,00000832 | | 0,14 |
| **Combined** | | | | | | **0,0002163** | | **3,52** |

| **3D printer plastic PETG** | **Amount** | **m^3** | **Price/m^3** | **Material cost** |
|---|---|---|---|---|
| 72mm servo link | 1 | 2,908E-06 | 2760 | 0,01 |
| Maxbotix spacer | 4 | 1,356E-06 | | 0,00 |
| HC-SR04 main enclosure | 3 | 1,4184E-05 | | 0,04 |
| HC-SR04 top enclosure | 3 | 3,981E-06 | | 0,01 |
| Zero detect part | 3 | 2,076E-06 | | 0,01 |
| AHES3191 holder | 1 | 1,0747E-05 | | 0,03 |
| Microswitch plate | 2 | 1,478E-06 | | 0,00 |
| PCB spacer | 30 | 0,00000144 | | 0,00 |
| **Combined** | | **3,817E-05** | | **0,11** |

**Total**

**55,66**