

UNIVERSITY OF TARTU  
Faculty of Science and Technology  
Institute of Technology

Georgs Narbutis

# **Holonomic Motion Drive System of a Social Humanoid Robot SemuBot**

**Bachelor's Thesis (12 ECTS)**

Curriculum Science & Technology

Supervisors:

MSc, Renno Raudmäe

MSc, Farnaz Baksh

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# **Holonomic Motion Drive System of a Social Humanoid Robot SemuBot**

## **Abstract**

The perception of a humanoid robot largely depends on its ability to mimic human-like movement, including changing its position in space. This thesis conducts a comprehensive literature review of existing humanoid robot wheelbases, holonomic motion drive systems and manufacturing methods, identifying the most appropriate solution of a wheelbase for use in the social humanoid robot SemuBot.

The proposed open-source wheelbase grants holonomic motion, for which omnidirectional omni-ball wheels were designed and manufactured. It can locomote in environments made for humans and traverse obstacles. An electrical system was put in place to test the capabilities of the prototype. The wheelbase is designed to be integrated with other components made for the humanoid robot SemuBot.

## **Keywords**

Humanoid robots, Social robots, Holonomic motion, Omnidirectional motion, Open-source, Additive manufacturing, 3D printing

**CERCS:** T125 Automation, robotics, control engineering

## **Sotsiaalse humanoidroboti SemuBoti holonoomne liikuv ajamisüsteem**

### **Lühikokkuvõte**

Humanoidroboti tajumine sõltub suuresti selle võimest matkida inimesesarnast liikumist, sealhulgas muuta ruumis oma asukohta. Käesolevas lõputöös on tehtud põhjalik kirjanduse ülevaade olemasolevatest humanoidrobotite alusvankritest, holonoomilistest liikumissüsteemidest ja tootmismeetoditest, selgitades välja sobivaima lahenduse kasutamiseks sotsiaalses humanoidrobotis SemuBot.

Kavandatud avatud lähtekoodiga alusvanker tagab holonoomilise liikumise, selle jaoks projekteeriti ja valmistati omni-pall tüüpi rattad ning alusvanker. Antud süsteem oskab liikuda inimeste jaoks loodud keskkondades ja ületada takistusi. Prototüübi võimekuse testimiseks võeti kasutusele ajutine elektrisüsteem. Projekteeritud ja valmistatud alusvanker on mõeldud integreerimiseks teiste humanoidrobot SemuBoti jaoks valmistatud komponentidega.

### **Võtmesõnad:**

Humanoidrobotid, sotsiaalsed robotid, holonoomne liikumine, mitmesuunaline liikumine, avatud lähtekoodiga, lisaainete tootmine, 3D-printimine

**CERCS:** T125 Automatiseerimine, robotika, juhtimistehnika

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## **List of Abbreviations**

**AM** Additive Manufacturing

**FDM** Fused Deposition Modeling

**PLA** Polylactic acid

**ABS** Acrylonitrile butadiene styrene

**PETG** Polyethylene terephthalate glycol

**PET** Polyethylene terephthalate

**ASA** Acrylonitrile styrene acrylate

**PC** Polycarbonate

**TPU** Thermoplastic polyurethane

**BLDC** Brushless Direct Current

**RPM** Revolutions per Minute

**PWM** Pulse-width Modulation

**OS** Operating System

**SSH** Secure Shell

# INTRODUCTION

The field of robotics continues to expand with the technological advancements of the 20th and 21st centuries. From niche use cases, robots have ventured into fields such as entertainment, education, assisting [1] and specific industries where the working environments can threaten humans, like the nuclear industry [2]. One of the ultimate goals of robotics is the development of a robot that can think and behave like humans [3]. This leads to the emergence of Humanoid robots, varying in their shape and form, which largely depends on the developed robot's use case, working environments and desired functionalities [1].

Social humanoid robots are a subfield of humanoid robots that focus on interaction with humans. They also tend to be designed with a specific task in mind and can range from, but are not limited to, working in healthcare to help treat and improve a person's medical condition [4]. Educational social humanoid robots help students with learning and increase the quality of education [4]. The emergence of artificial intelligence and its integration into robots has added a new meaning to the word “social” in social humanoid robots, leading to more autonomous robots where the decision-making can be offloaded from humans, making the robot more independent [5].

Since social humanoid robots are meant to resemble humans [1], their physical appearance and movement are paramount. A humanoid robot's legs or wheels play a big role in how it is perceived in a social communication setting, including how natural the movements are and how fast and loud they are. The ability of a robot to locomote in an environment it is designed for, all while being able to keep the physical characteristics associated with its use case, can make or break a product.

The goal of this thesis is to develop a fully functioning motion drive system for a social humanoid robot, SemuBot. A collaborative project between students with the goal of developing an open-source humanoid robot platform with one of its use cases being working with children with speech impairments. The set drive system is planned to have holonomic motion capabilities while having the ability to traverse challenging human environments.

## **RESEARCH AIM**

To develop a holonomic motion drive system for the Semubot open-source humanoid robot project.

## **RESEARCH OBJECTIVES**

**RO1.** To review existing literature on existing humanoid robot mobile platforms and holonomic motion robot drive systems, additive manufacturing methods, and highlight their design principles, advantages and limitations.

**RO2.** To identify and select a drive system that is compliant with open-source humanoid robot SemuBot's project requirements.

**RO3.** To design and fabricate a working wheelbase prototype with the chosen drive system for the humanoid robot SemuBot while focusing on the reproducibility of the prototype.

# 1 LITERATURE REVIEW

## 1.1 Wheelbases of existing humanoid robots

The aim of humanoid robots is to be as human-like as possible, including bipedal locomotion [1], but developing such a system for the robot's movement is a tremendous task, both from the mechanical and software aspects of it. Moreover, controlling such a robot comes with its uncertainties, like external forces, control torques and user control inputs [6]. For this reason, many humanoid robots tend to implement wheeled or wheeled-like bases.

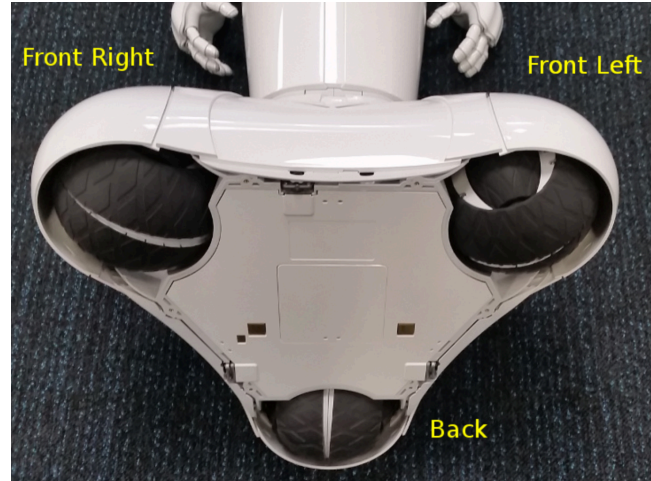


*Figure 1: Humanoid robots with different wheelbases: 1 - Tiago with omnidirectional base; 2 - Tiago with differential drive base [7]; 3 - Pepper Humanoid [8]; 4 - EVE humanoid [9]; 5 - Cruzr robot [10]*

Tiago (*Figure 1 (1,2)*) by PAL Robotics is a humanoid robot developed for research and applications in healthcare, assistance and light industry [11]. The modular design of it allows it to be customised to the specific needs of the user or the task of the robot. Tiago robot can be equipped with a four mecanum wheel wheelbase (*Figure 1 (1)*), which grants the robot holonomic motion. For non-holonomic motion, Tiago can be equipped with a differential drive base (*Figure 1 (2)*), which consists of 2 powered wheels along with four passive wheels for stability [7].

Pepper (*Figure 1 (3)*) is a social humanoid robot developed by SoftBank Robotics that is tailored to social interactions with humans. It can recognise speech and conduct dialogue in 16 languages [8]. Pepper has three omnidirectional wheels, which allow for holonomic movement, climbing over steps with a height of 1.5 centimetres and a slope of five degrees

[12]. However, from the limited number of pictures, it can be seen that instead of regular omninwheels being used to achieve holonomic motion, sphere-like wheels (*Figure 2*) are used [13], [14].



*Figure 2: Pepper robot wheelbase assembly.*

EVE humanoid (*Figure 1 (4)*) by 1X is a wheeled robot meant to work in industries like logistics and retail [9]. Its wheelbase employs a differential drive system consisting of 2 large powered wheels and one non-powered castor wheel for balance. On the contrary, Cruzr (*Figure 1 (5)*), a customer service robot, uses omniwheels to achieve holonomic motion [11].

Since people tend to move in a holonomic fashion, meaning they can take steps in any direction without having to rotate their whole bodies, social humanoid robots also choose to implement holonomic motion. Moreover, humans often operate in small and narrow environments, where robots not specialised for these environments can have trouble locomoting in.

## **1.2 Holonomic motion**

Robot drive systems can be divided into holonomic and non-holonomic motion systems. In a holonomic motion system, the controllable degrees of freedom at any instant are equal to the total number of coordinates needed to define the system configuration in space [16], [17]. A robot's mobile platform in space can be defined with three motion degrees of freedom - x, y position and orientation [16].

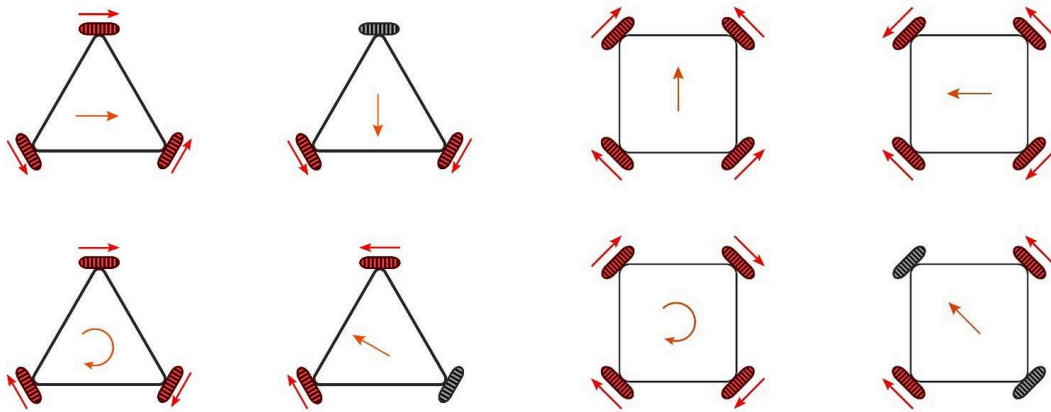
### 1.2.1 Omnidirectional wheels

A popular solution to achieve holonomic motion in mobile robots is the use of omnidirectional wheels. Most omnidirectional wheels consist of a traditional wheel with smaller, passive wheels located around the main wheel's circumference. The rotating axes of the passive wheels are perpendicular, called omniwheels, or inclined with respect to the rotating axis of the main wheel [18], called mecanum wheels.



*Figure 3: Omnidirectional [19] and Mecanum wheel [20]*

The smaller passive wheels allow movements in a direction perpendicular to that of the axial rotation of the main wheel. Combining the rotation of several active wheels with the rotation of passive wheels leads to possible locomotion in any direction along a two-dimensional plane [21].



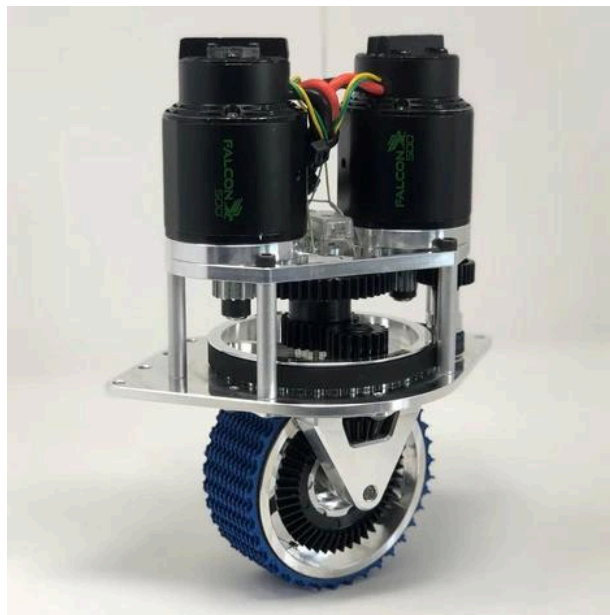
*Figure 4: Three and four-wheeled omnidirectional mobile bases [22]*

The use of omnidirectional wheels leads to the robot's inability to traverse over or climb up even relatively small obstacles such as door sills and elevator clearance gaps. This limitation is caused by the passive wheel diameter tending to be much smaller than the diameter of the

main wheel. This effect is even more pronounced when one or more of the wheels in an omniwheel motion system are moving in a direction perpendicular to the passive wheel rotational axis [23]. This effect could be mitigated by increasing the overall diameter of the wheel, thus allowing for an increase in the diameter of the passive wheels. Still, this solution comes at the cost of taking up more space.

### 1.2.2 Swerve drive

Swerve drive is another type of drive system which grants holonomic motion. Each swerve drive module consists of a propulsion motor that provides power to the wheel and a motor that steers the wheel. Considering that wheels with a swerve drive mechanism can rotate a full 360 degrees, there is more freedom in the placement of the wheels compared to omnidirectional wheels, which have to be placed radially and spaced equally from each other.

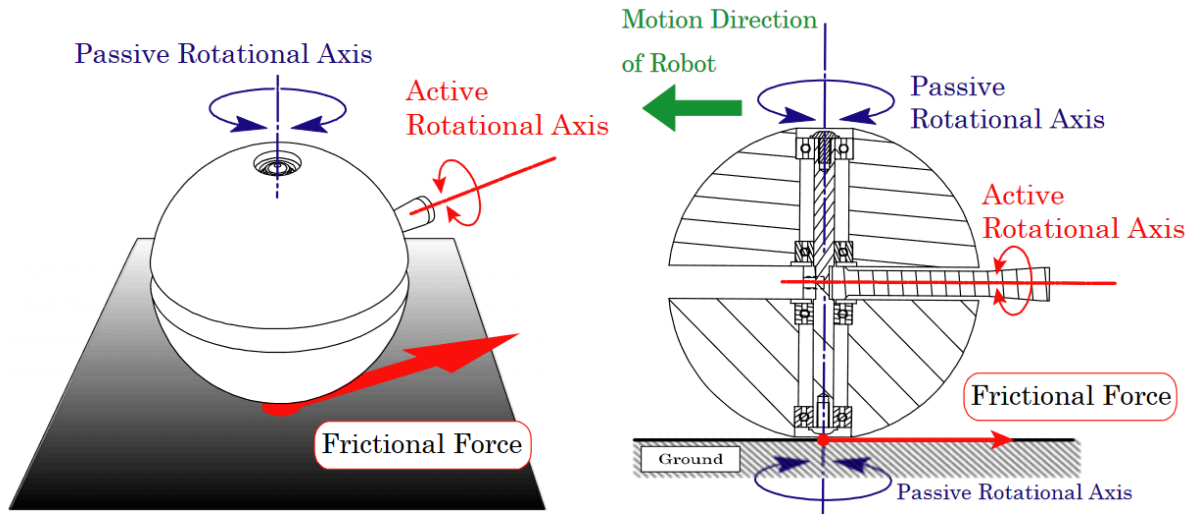


*Figure 5: Commercial swerve drive module [24]*

Due to its larger wheel size and lack of smaller passive wheels, the swerve drive system is better suited for uneven terrain. On the other hand, it is mechanically more complex compared to omnidirectional wheels. The kinematics of controlling a swerve drive system is challenging, but inaccuracies can be mitigated by using forms of PID control [25].

### 1.2.3 Omni-ball drive

Omni-balls, first mentioned in a research paper by Kenjiro Tadakuma Et al. [26], are spherical wheels capable of holonomic motion. An omni-ball consists of two passive, independently rotating hemispheres. An active rotation axis is located between the two hemispheres. Kenjiro Tadakuma Et al. have also proposed a solution to the largest drawback in the Omni-ball design: when both hemisphere rotational axes of the wheel become perpendicular to the surface and the movement is parallel to the active rotational axis. In this state, none of the passive rotational axes can spin, which, in turn, induces a large frictional force between the wheel and the surface (*Figure 6*) [26].



*Figure 6: Omni-ball rotational axes characterisation [26]*

For this reason, a smaller passive roller is located at both ends of the passive rotational axis. As a result, the wheel can move along a surface parallel to the active rotational axis without increased friction, even when in the position mentioned above (*Figure 7*) [23].



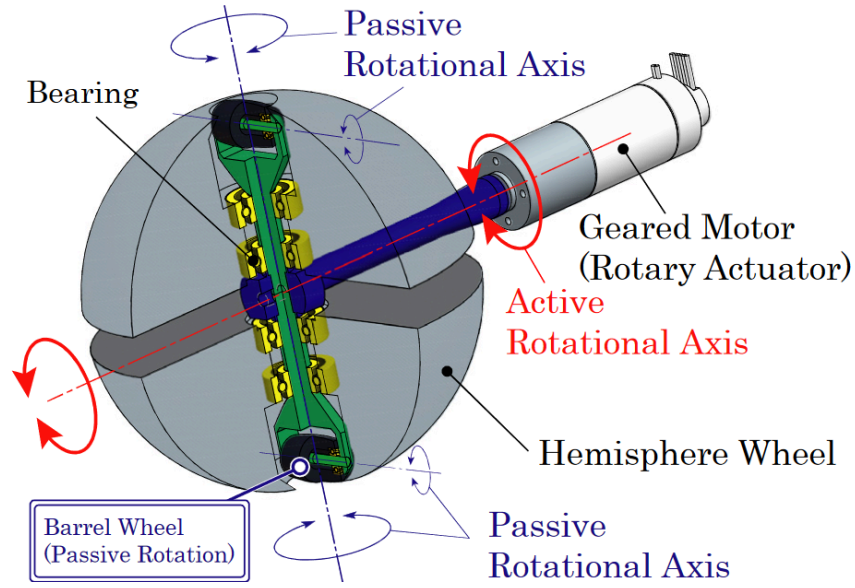


Figure 7: Section view of an Omni-ball [26]

Compared to classical omniwheels and mecanum wheels, the Omni-ball wheel design benefits from its ability to overcome larger surface obstacles, including climbing steps and traversing gaps. The two small passive rollers can interfere with the obstacle traversing ability of a robot system using omni-balls. However, the probability of the surface being perpendicular to the passive rotational axes whilst moving parallel to the active rotational axis is low. To compare omni-ball and omniwheel step-climbing and gap traversing abilities, Kenjiro Tadakuma Et al. have tested these abilities for both types of wheels (Figure 8). An omni-ball with an 80mm diameter and an omniwheel with an unknown diameter [26].

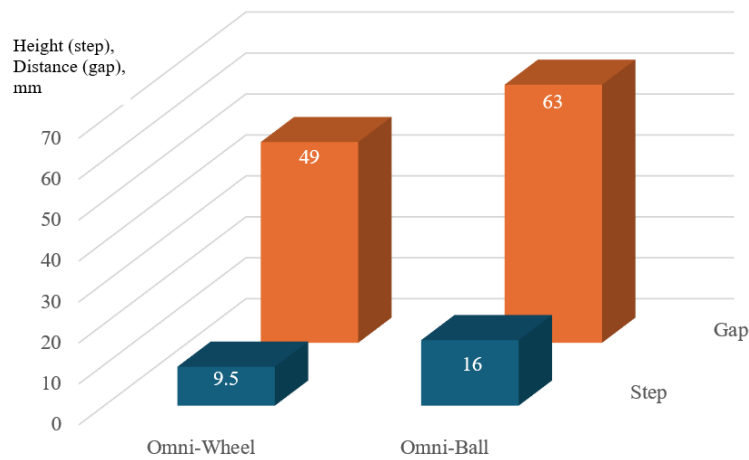


Figure 8: Step climbing and gap traversing ability comparison between Omni-wheels and Omni-Balls [26]

Considering omni-balls share the same rotational axes and kinematic constraints as omniwheels, the same inverse kinematic model can be reused to reach the desired state of the robot, given linear and angular velocity inputs. J. Javier Moreno et al. [27] provide a method to estimate the velocity of each wheel to change the pose of a mobile platform in a predictable manner [27]. The following two kinematic diagram figures and the equation describe the inverse kinematic model for the control of a robot's mobile platform using omni-ball wheels. Suppose a robot mobile platform with three omni-balls placed radially around the body, each 120 degrees apart from the other one.

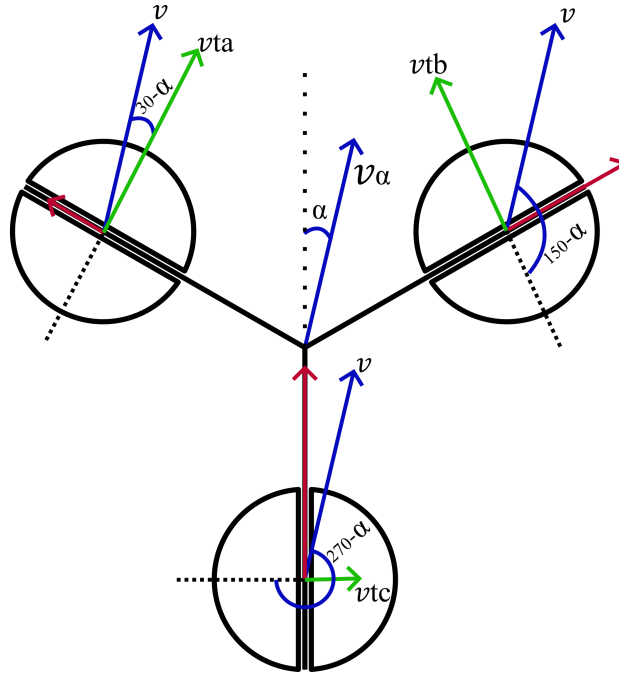


Figure 9: Translation of a mobile robot base with three omni-balls:  $v_\alpha$  denotes the input velocity vector in a polar form. This vector is translated into two vectors for each wheel, where one of the vectors is projected parallel to the active rotational axis, but the other one is perpendicular to it. Projected vectors  $v_{ta}$ ,  $v_{tb}$ ,  $v_{tc}$  in green are translation velocity vectors, which describe the rotation of the wheels to achieve the desired movement in a two-dimensional plane [27].

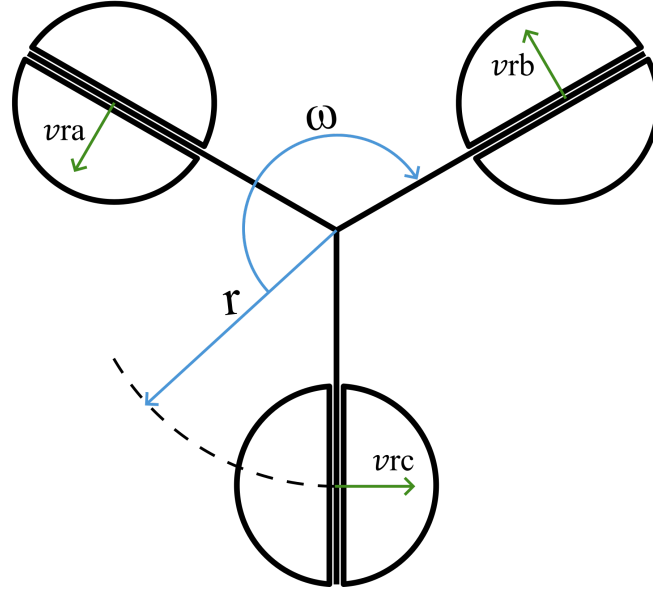


Figure 10: Rotation of a mobile robot base with three omni-balls: the rotation of the base is described in degrees and denoted as  $\omega$ . Whereas  $v_{ra}$ ,  $v_{rb}$ ,  $v_{rc}$  are wheel velocity vectors.

Translational and rotational movements are described in an equation, leading to a velocity value for each of the omni-balls.

$$v_a, v_b, v_c = v * \begin{pmatrix} \cos(30 - \alpha) \\ \cos(150 - \alpha) \\ \cos(270 - \alpha) \end{pmatrix} + \omega$$

where  $v_a$ ,  $v_b$ ,  $v_c$  stands for the velocity of each of the omni-balls,  $v$  is a velocity constant,  $\alpha$  is the orientation of the drive vector,  $\omega$  denotes the angular rotation value added equally to all three wheels [14]. This equation can be used to estimate the velocity of each wheel to translate and rotate the mobile robot platform [27].

#### 1.2.4 Comparison of holonomic drive systems

A comparison has been made of the three holonomic drive systems: Omniwheels / Mecanum Wheels, Swerve Drive and Omni-balls. Systems have been evaluated in three categories: mechanical complexity, obstacle traversing abilities, and control. As seen in Table 1, omniwheels and mecanum wheels gain from their low mechanical complexity and control but have poor obstacle traversing abilities. Conversely, swerve drive system suffers from high mechanical complexity and control algorithms [25] but has very good obstacle traversing abilities due to the larger wheel size. The omni-ball system stands out as a good middle

ground, with a semi-simplistic design, better than omniwheel obstacle traversing capabilities and simple control.

|                                   | <b>Mechanical complexity</b> | <b>Obstacle traversing</b> | <b>Control</b> |
|-----------------------------------|------------------------------|----------------------------|----------------|
| <b>Omniwheels, mecanum wheels</b> | Low                          | Poor                       | Simple         |
| <b>Swerve drive</b>               | High                         | Good                       | Complex        |
| <b>Omni-balls</b>                 | Medium                       | Medium                     | Simple         |

Table 1: Comparison of omniwheel, swerve drive and omni-ball drive systems

### 1.3 Additive Manufacturing

Additive manufacturing (AM), a type of rapid prototyping, allows for the creation of complex structure three dimensional objects with relatively low entry costs. Additive manufacturing stands out with a simple workflow, where a model can be fabricated directly from a computer-aided design file, bypassing setup procedures like making part-specific tools and dies [28]. Additive manufacturing works by depositing material layer by layer on top of each other, leading to the creation of a three dimensional model [29]. AM processes can be classified based on the raw material used in the manufacturing process (*Figure 11*). [30]

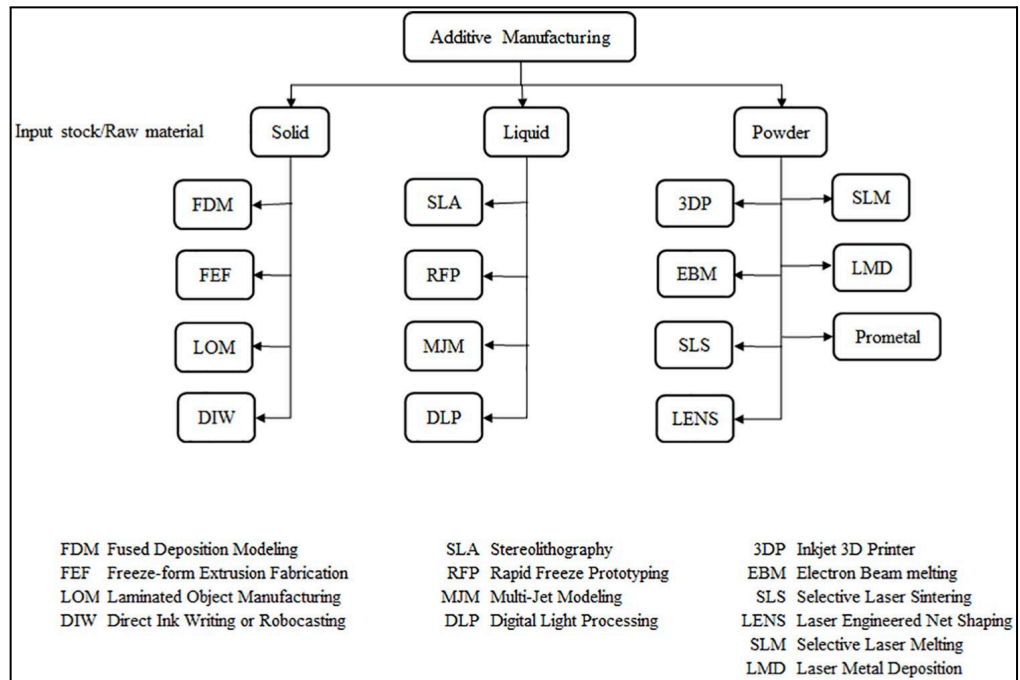
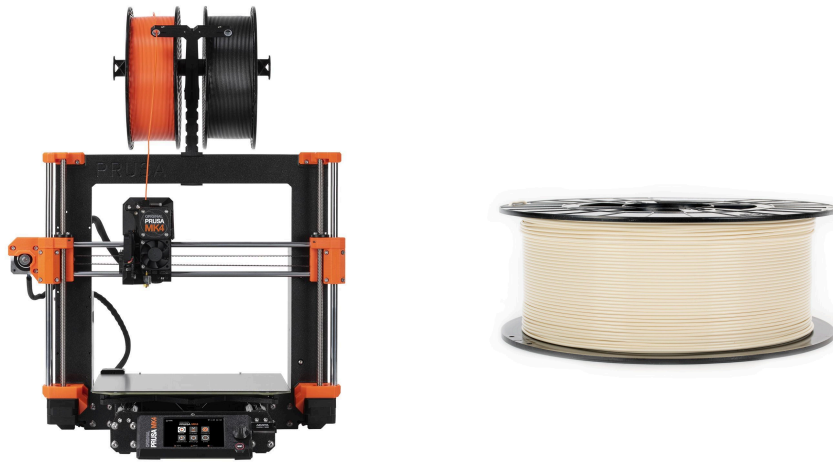


Figure 11: Classification of AM methods [30]

Focus will be placed on Fused Deposition Modeling (FDM) because it is the most popular and accessible AM method for the prototyping of a robot's mobile wheelbase parts.

### 1.3.1 Fused Deposition Modeling

The FDM process consists of having a solid strand of raw starting material, often referred to as filament. Filament gets fed into a heating chamber and heated to a semi-liquid state. Then, extruded through a nozzle into thin layers on top of each other. Filament expresses thermoplastic behaviour, which leads to the layers fusing together, making a solid structure [31].



*Figure 12: Prusa MK4 FDM printer and a roll of filament [32], [33]*

The mechanical properties of the resulting part are largely dependent on two main factors: print parameters (*Figure 13*) and filament material parameters. The former includes but is not exclusive to:

- 1) Build orientation, meaning the part's orientation with respect to the build platform.
- 2) The thickness of the deposited layer. Often referred to as raster width or road width.
- 3) The number of contours on the outside walls of the part.
- 4) Infill density, which means how many percent of the inside of the part is solid. Infill can be done in several patterns, such as rectilinear, honeycomb, and hexagonal [34].
- 5) The temperature at which material is extruded.

- 6) The speed of the nozzle traversing in the XY plane of the build platform.
- 7) Extruder nozzle diameter.
- 8) The angle of the infill deposited layer with respect to the X-axis of the building plate, also known as the raster angle [35].
- 9) Road gap width between raster paths [28].

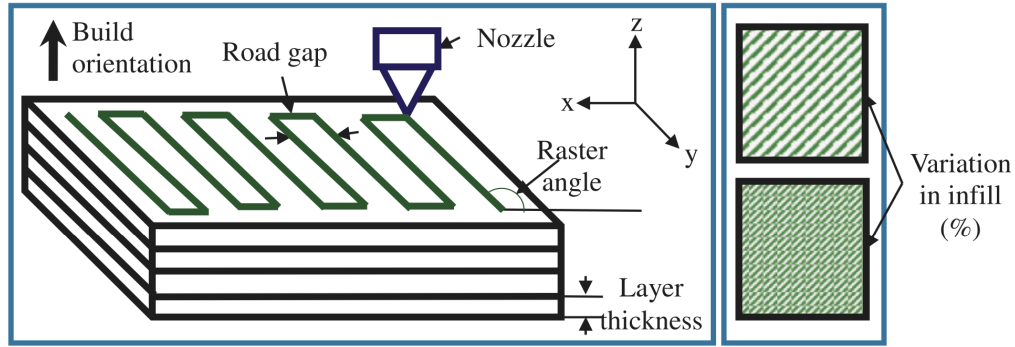


Figure 13: Different FDM 3D printing parameters [36]

### 1.3.1.1 FDM materials

In FDM additive manufacturing, thermoplastics are used as the filament material. Thermoplastics differ in their mechanical properties, ease of printing and price, thus making them suitable for a wide range of applications. Most common thermoplastics used in FDM are, but not limited to, Polylactic acid (PLA), Acrylonitrile butadiene styrene (ABS), Polyethylene terephthalate glycol (PETG), Polycarbonate (PC) and Acrylonitrile styrene acrylate (ASA).

| Material | Tensile strength (MPa) | Flexibility (Young's modulus, GPa) | Impact Strength Charpy (kJ/m <sup>2</sup> ) | Hardness (Shore D) | Density (g/cm <sup>3</sup> ) |
|----------|------------------------|------------------------------------|---------------------------------------------|--------------------|------------------------------|
| PLA      | 59 ± 3                 | 3.2 ± 0.1                          | 14 ± 1                                      | 81                 | 1.24                         |
| PETG     | 48 ± 2                 | 2.0 ± 0.2                          | 76 ± 3                                      | 81                 | 1.27                         |
| ASA      | 45 ± 2                 | 1.9 ± 0.1                          | 38 ± 11                                     | 78                 | 1.07                         |
| ABS      | 33 ± 3                 | 2.2 ± 0.19                         | 39.3 ± 3.6                                  | 76                 | 1.08                         |
| PC       | 55 ± 4                 | 2.1 ± 0.4                          | 34.8 ± 2.1                                  | 79                 | 1.2                          |

Table 2: Mechanical properties of FDM 3D printing materials. The properties are not definitive and may vary between manufacturers [37], [38], [39], [40], [41], [42], [43]

PLA is the most popular material in FDM printing due to its strength coupled with ease of printing. Nonetheless, it suffers from bad impact resistance. It is a biodegradable thermoplastic with low shrinkage and low price [44]. Often used for prototyping. The recommended nozzle temperature for printing with PLA is 200 - 220 °C and a heatbed temperature of 40 - 60 °C [37].

PETG stands out with its high impact strength thus it is a great choice for mechanical solutions. It has good thermal resistance. PETG is made of Polyethylene terephthalate (PET) with glycol added as an additive, which makes the material less brittle and more transparent than regular PET [30]. The recommended nozzle temperature for printing with PETG is 240 - 260 °C and a heatbed temperature of 70 - 90 °C [38].

ASA and ABS share similar impact resistance properties, while ASA has higher tensile strength. ABS is a tough, non-degradable material with medium toxicity and good impact resistance, but it often suffers from bad layer bonding and warping [46], [47]. Conversely, ASA, compared to ABS, is more resistant to environmental stress cracking, including better resistance to alcohol and cleaning agents. Moreover, ASA exhibits good UV resistance, which makes it a great material for outdoor use [47], [48]. The recommended nozzle temperature for printing with ABS is 240 - 270 °C and a heatbed temperature of 80 - 100 °C [49]. For ASA, a nozzle temperature of 250 - 270 °C and a heatbed temperature of 105 - 115 °C [39].

PC has both relatively high impact resistance and tensile strength, making it suitable for parts that undergo increased mechanical stress. 3D printing with PC should be done in an enclosed chamber to prevent warping [50]. The recommended nozzle temperature for printing with PC is 260 - 280 °C and a heatbed temperature of 90 - 110 °C [41].

## 2 REQUIREMENTS

By analysing the intended use case of the SemuBot humanoid robot as a robot therapist for children with speech impairments, which is set to operate in environments designed for humans, the following requirements were set for the development of its wheelbase:

| Requirement                                                                 | Justification                                                                                                                                                                                                                                                                                                                                                       |
|-----------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| 1. Holonomic motion capabilities.                                           | The environments humans operate in tend to be limited in space, meaning there might not be enough area to perform complex turns. Holonomic motion capabilities allow a robot to manoeuvre in limited space and perform complex trajectory paths [27], meaning it can move in any direction, no matter the position and orientation of the robot [16].               |
| 2. Move on solid indoor surfaces, such as carpets, wood or laminate floors. | One of SemuBot's use cases is set to be in a hospital environment. The ability to locomote on different terrains not only supports the idea that the developed robot is truly humanoid-like but also grants the robot the ability to operate in diverse domains.                                                                                                    |
| 3. Traverse over ledges and gaps.                                           | Environments such as households, offices and hospitals, where humanoid robots often operate, are abundant with small obstacles like door sills, small ledges and elevator floor gaps [26]. The success in completion of the tasks a humanoid robot is set to do depends on the ability to overcome these obstacles.                                                 |
| 4. Motion controller.                                                       | To test the holonomic motion and obstacle traversing capabilities of the manufactured wheelbase, a motion controller should be developed to control the translation and rotation of the wheelbase manually.                                                                                                                                                         |
| 5. Open-source.                                                             | Open-source hardware decreases the development costs for third parties, leading to more time saved, which rapidly increases the rate of innovation [51]. Having the hardware and software of the SemuBot humanoid robot readily available to everyone makes it possible to adjust the design for a specific use case and collaboratively contribute to the project. |

*Table 3: SemuBot wheelbase requirements*



### **3 DESIGN AND DEVELOPMENT**

The holonomic motion drive base was designed and fabricated iteratively, improving upon the previous iterations and analysing the improvements comparatively.

Considering the advantages mentioned before, it was decided to develop the drive base by employing the omni-ball motion system first mentioned in a research paper by Kenjiro Tadakuma Et al. [23], [26]. While focusing on making the mechanical solution easily reproducible with simple and available manufacturing methods to keep in line with the open-source nature of the SemuBot humanoid robot project.

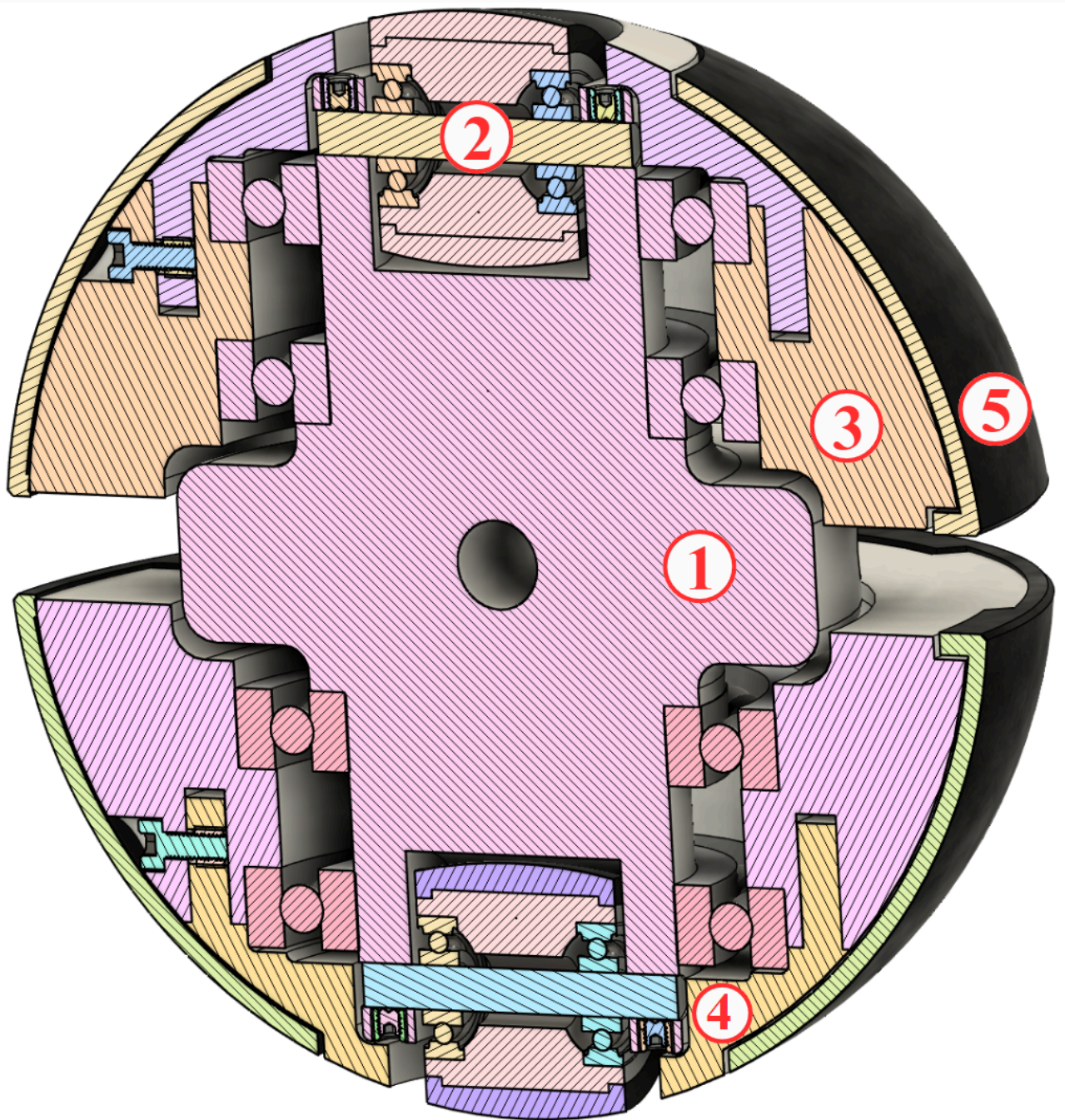
#### **3.1 Methods**

For mechanical design, the Fusion360 [52] computer-aided design (CAD) program was chosen mainly due to its stability and cloud collaboration capabilities. Considering that the SemuBot robot is being developed collaboratively with many participants, Fusion360 offers a good way for participants to work on the same design and construct assemblies with components designed by multiple people. Furthermore, it is possible to access the design history of a part, which allows to revert unwanted changes.

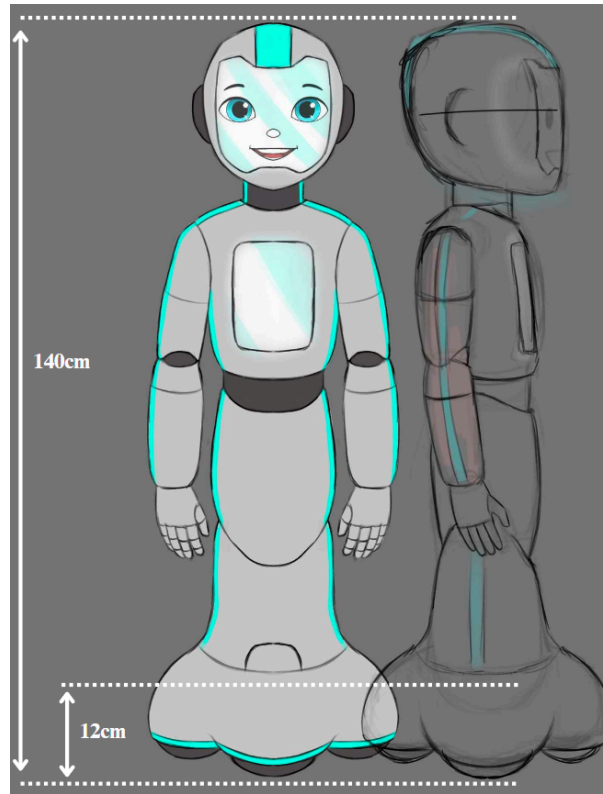
FDM 3D printing was used to manufacture many mechanical components. It allows for rapid prototyping and a fast turnover rate for iterations. Two types of FDM 3D printers were used; “Original Prusa i3 MK3S+” (Figure 12) [53] and “Bambu Lab X1-Carbon” [54] with an “Automatic Material System.” A band saw was used to lengthen the aluminium extrusions. Cordless drills, drill press, lathe for drilling and boring holes. Along with other miscellaneous tools.

#### **3.2 Omni-ball design and assembly**

By taking into account that the finished humanoid robot SemuBot will be about 140 centimeters in height, it was decided for the omni-ball wheels to be about 120 millimetres in diameter. (*Figure 15*) Around 8.6% of the whole robot's height. This wheel size proved to be optimal for traversing over obstacles with a height of at least 30 millimetres while not being oversized and disproportional to the rest of the robot's body.



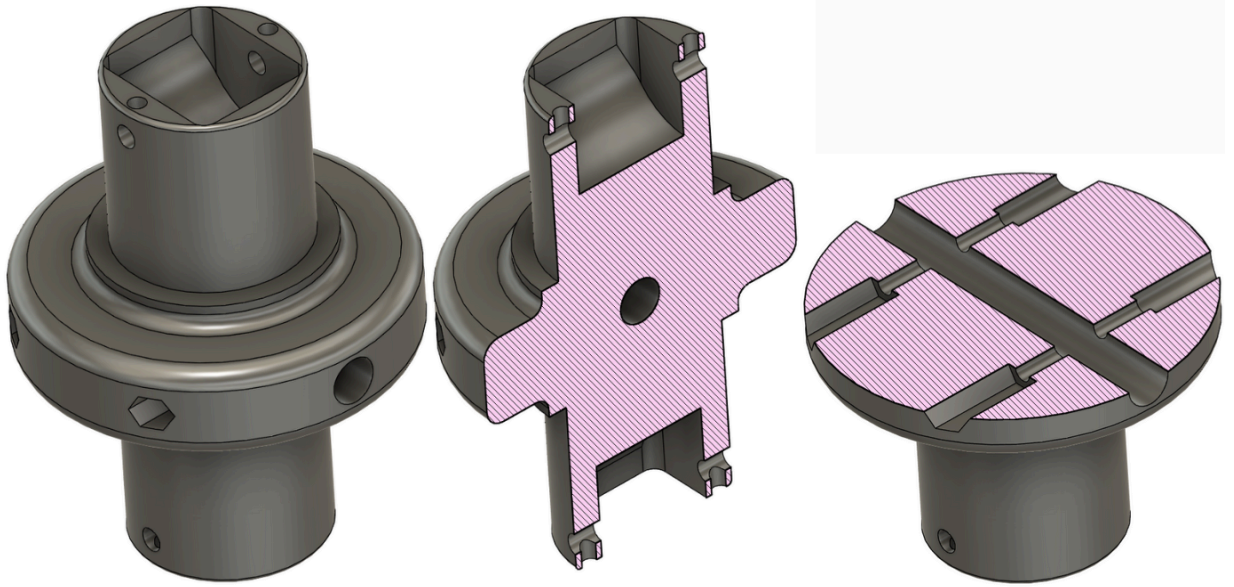
*Figure 14: Section view of an omni-ball: 1 - wheel core; 2 - roller assembly; 3 - lower hemisphere; 4 - upper hemisphere; 5 - soft shell*



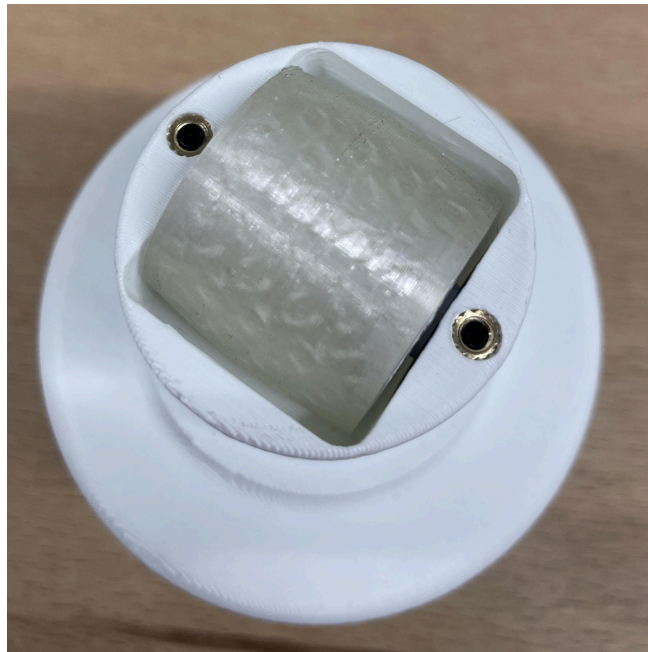
*Figure 15: Semubot sketch with its expected dimensions*

The proposed design of an omni-ball consists of a middle core fixed to the active rotational axis. (Figure 14 (1), 16) It also acts as an anchor piece for all of the other moving components to connect to. Considering all of the forces acted upon the omni-ball are transferred through the core, it is manufactured out of PLA, a material with high tensile strength, which is easy to 3D print [55]. PLA does not have the highest impact resistance capabilities, but most impacts are planned to be absorbed by the soft outer shell of the omni-ball wheel. The core was printed on a Prusa i3 MK3+ 3D printer with a 0.4mm nozzle, sliced with Prusa Slicer, 0.3mm layer height, six perimeters and grid supports. Printed at 45 degrees to decrease the probability of splitting layers. A hole for a 10mm shaft is placed through the middle of the core, and two holes for its attachment. This grants the omni-ball to rotate along its active rotational axis. The cavities on the opposite ends of the parts are meant to house the passive roller assembly, as well as to secure it in place with the use of M2 heat-set inserts and setscrews (Figure 17).





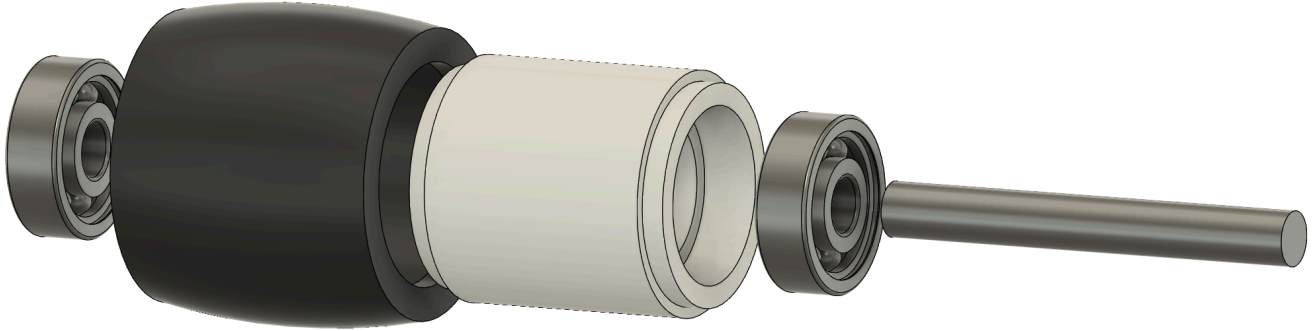
*Figure 16: Omni-ball's core and its section views*



*Figure 17: Roller assembly in the core.*

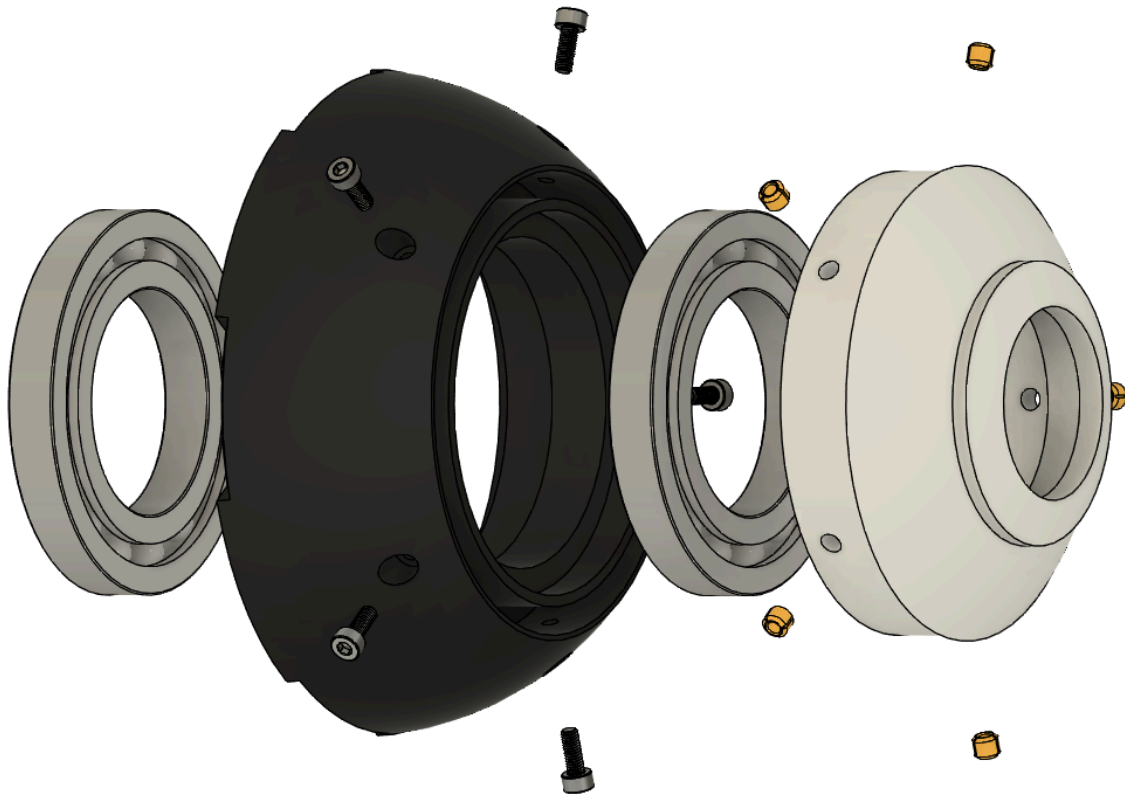
The passive roller assembly (*Figure 18*) consist of a PLA core and a softer Thermoplastic polyurethane (TPU) shell to ensure proper traction with the surface it contacts with. The TPU material used is “NinjaFlex 85A” [56], which offers more flexibility than other TPU filaments. The flexible shell is press-fit onto the core and kept on with overhangs on both sides. To ensure the turning of the roller, a 625-2RS deep groove ball bearing is press-fit into each side of the roller. A 5mm shaft going through the roller is secured in the omni-ball core

with M2 setscrews. Both roller core and shell were sliced with Prusa Slicer. Core settings being 0.2mm layer height, 50% infill and eight perimeters. Shell settings - 0.2 mm layer height, 20% infill and two perimeters.



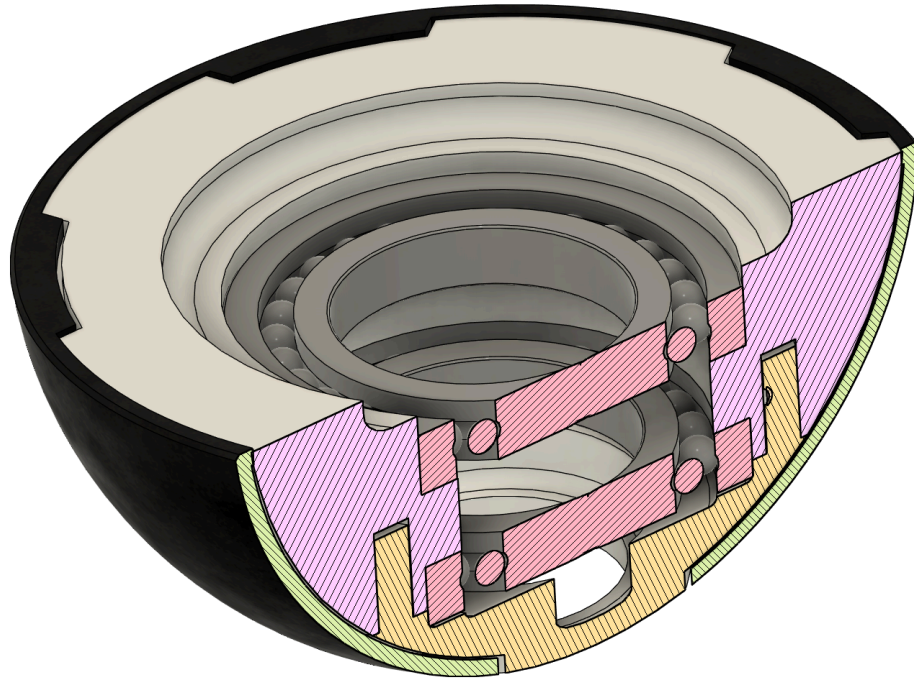
*Figure 18: Exploded view of the passive roller.*

Each independently rotating hemisphere consists of two sub-parts. The hemispheres had to be divided into a lower hemisphere (*Figure 14 (3)*) and an upper hemisphere (*Figure 14 (4)*) in order to house a 16008 deep groove ball bearing inside, which is responsible for granting the hemisphere rotational movement perpendicular to the active rotational axis of the omni-ball. The two parts are conjoined by five M3x8mm bolts and M3 heat-set inserts located radially around the hemisphere. Another 16008 bearing is press-fit into the bottom cavity of the lower hemisphere. The lower hemisphere is manufactured out of PLA material, but the upper hemisphere is made of Polyethylene terephthalate glycol (PETG) material. This choice was made because PETG has higher impact resistance compared to PLA, and a part of the upper hemisphere comes in direct contact with the driving surface; thus, it is more prone to sudden force exerted upon it [55]. Both hemisphere parts were sliced in Prusa Slicer and printed on a Prusa I3 mk3s+ with a layer height of 0.2mm, 20% of infill and six perimeters. After securing the passive roller assembly into the omni-ball core, the hemisphere assembly is attached to the core using an interference fit between the inner bores of the 16008 bearings and the shaft of the core.



*Figure 19: Exploded view of the hemisphere assembly.*

Each hemisphere is covered with a soft, flexible shell (*Figure 14 (5)*), which is manufactured out of “NinjaFlex 85A” material [56]. The flexible nature of this material helps with absorbing impact forces which act upon the omni-ball while driving, and it also provides better traction with the driving surface. The shell is slightly stretched over the hemisphere and secured in place with five overhangs located radially around the bottom of the flexible shell, which fit into five equally sized indentations on the bottom of the lower hemisphere (*Figure 20*). The shell was sliced with Prusa Slicer with print settings - 0.2 mm layer height, 5% infill and two perimeters.



*Figure 20: Section view of the hemisphere and shell assembly.*

A fully assembled omni-ball is 124 mm in diameter and weighs 1060 grams. (Figure 21)

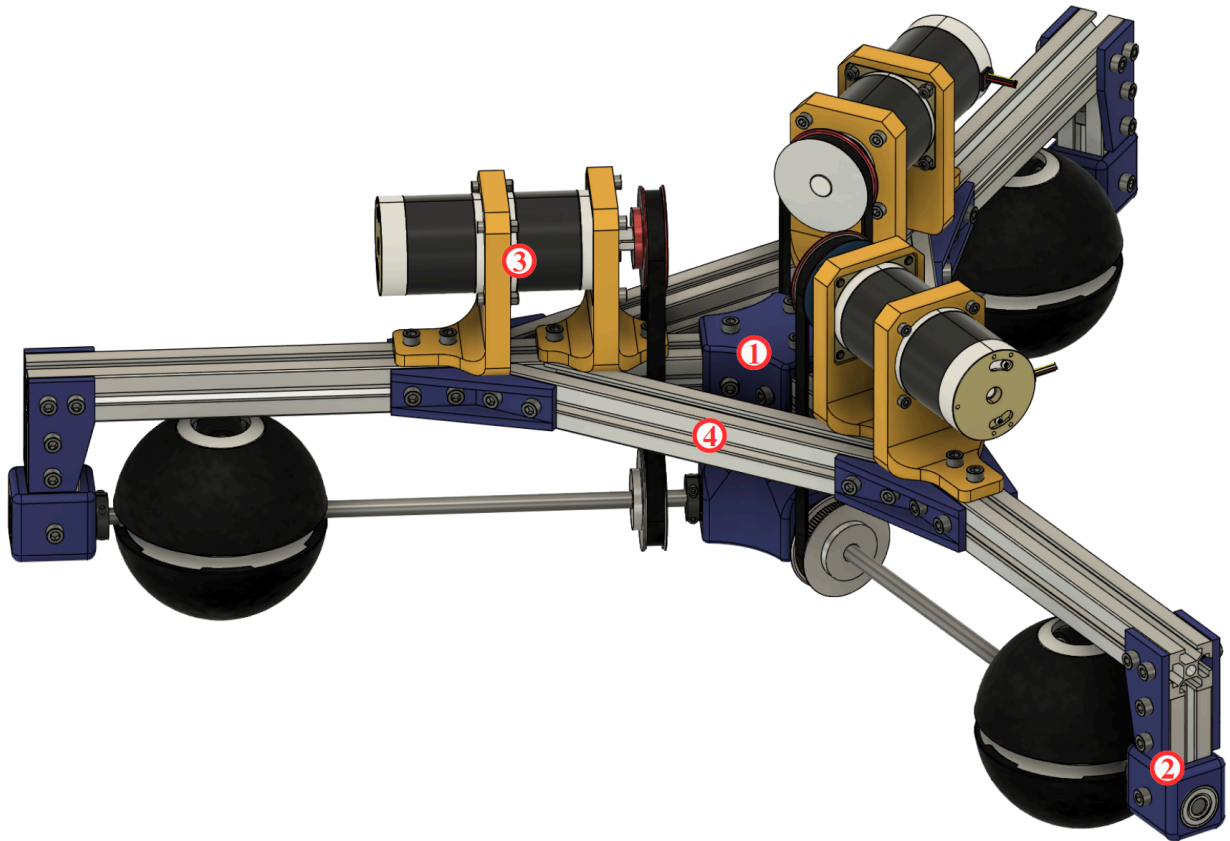


*Figure 21: Assembled omni-ball*



### 3.3 Wheelbase design and assembly

For SemuBot's wheelbase (*Figure 22*), it was decided to develop it with three wheels. In three-dimensional space, three points can be used to define a plane, making the robot more stable in situations when the driving surface is not completely flat.



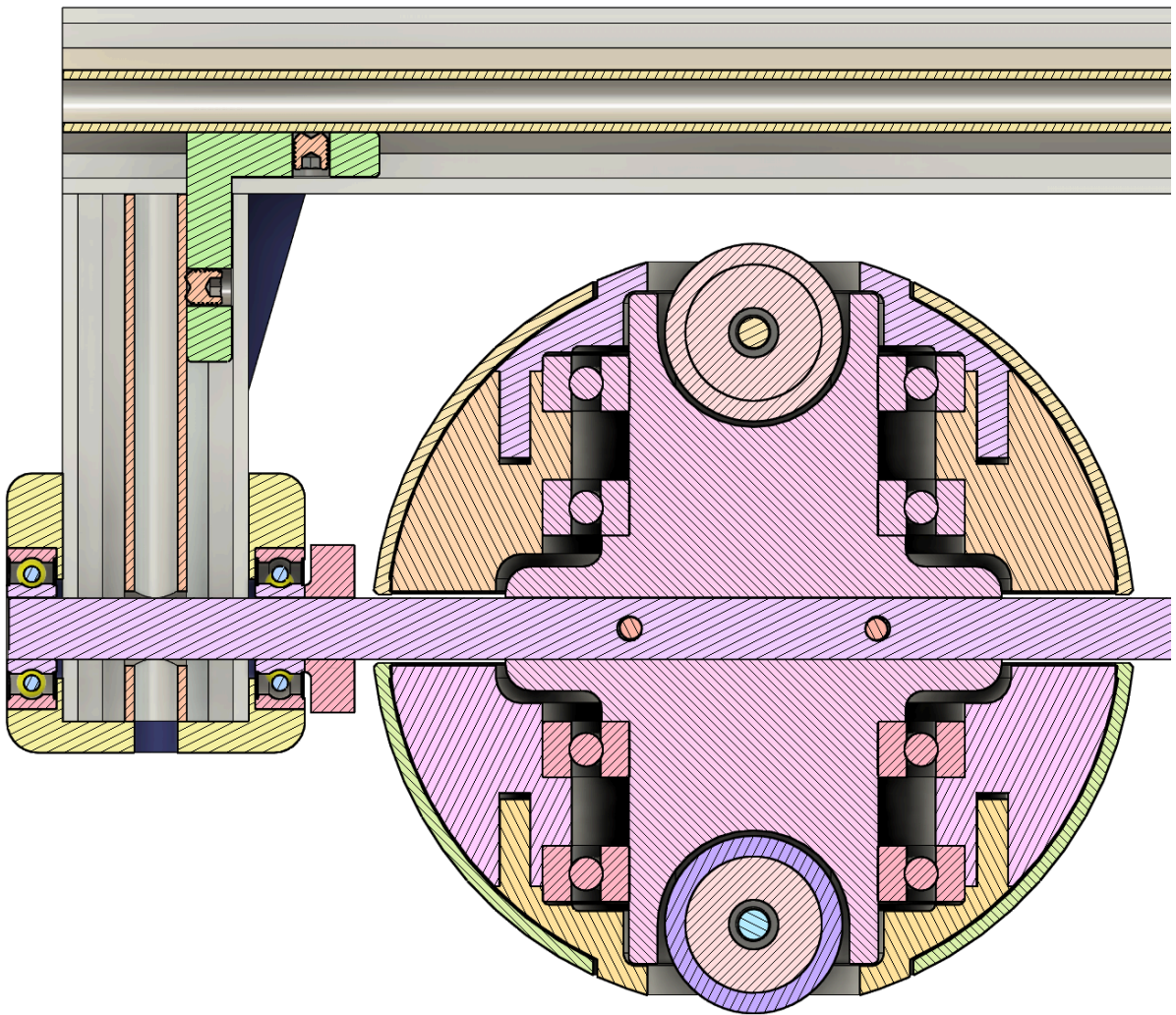
*Figure 22: Wheelbase assembly*

The middle three-way connector of the base (*Figure 22 (1)*) is responsible for connecting three identical sub-assemblies, each responsible for fixing and granting rotational movement of an omni-ball wheel. The three-way connector consists of three identical square holes in the top, 120 degrees from each other, where 30x30 mm aluminium extrusion profiles are fixed with the help of M6 bolts and T-slot nuts, which fit into the rail of an aluminium extrusion profile (*Figure 24 (1)*). On the bottom, three 6000-2RS deep groove ball bearings are interference fit pressed into the connector. The bearings provide non-frictional rotational movement for the 10mm diameter shafts on which the omni-ball wheels are fixed with M4 bolts going through the shaft and omni-ball wheel core. The three-way connector was 3D



printed with PETG material on “Bambu Labs X1 Carbon” [54] 3D printer and sliced with “Bambu Studio” software [57] with the following print settings: 0.28mm layer height, five wall loops (perimeters) and an infill of 25%.

On the other side of the shaft, it is suspended by a connector, which houses two 6000-2RS bearings (*Figure 22 (2)*). Sliced with “Bambu Studio” software with the same print settings as the three-way connector. This connector is fixed to a vertical 30x30mm aluminium extrusion profile with M6 bolts and T-nuts. The vertical profile has a 12mm through-hole, so there is no interference between the profile and the shaft going through it. The vertical aluminium profile is attached to the horizontal aluminium profile with an L-joint bracket and two flat 3D printed brackets secured with M6 bolts and T-nuts. (*Figure 23*)

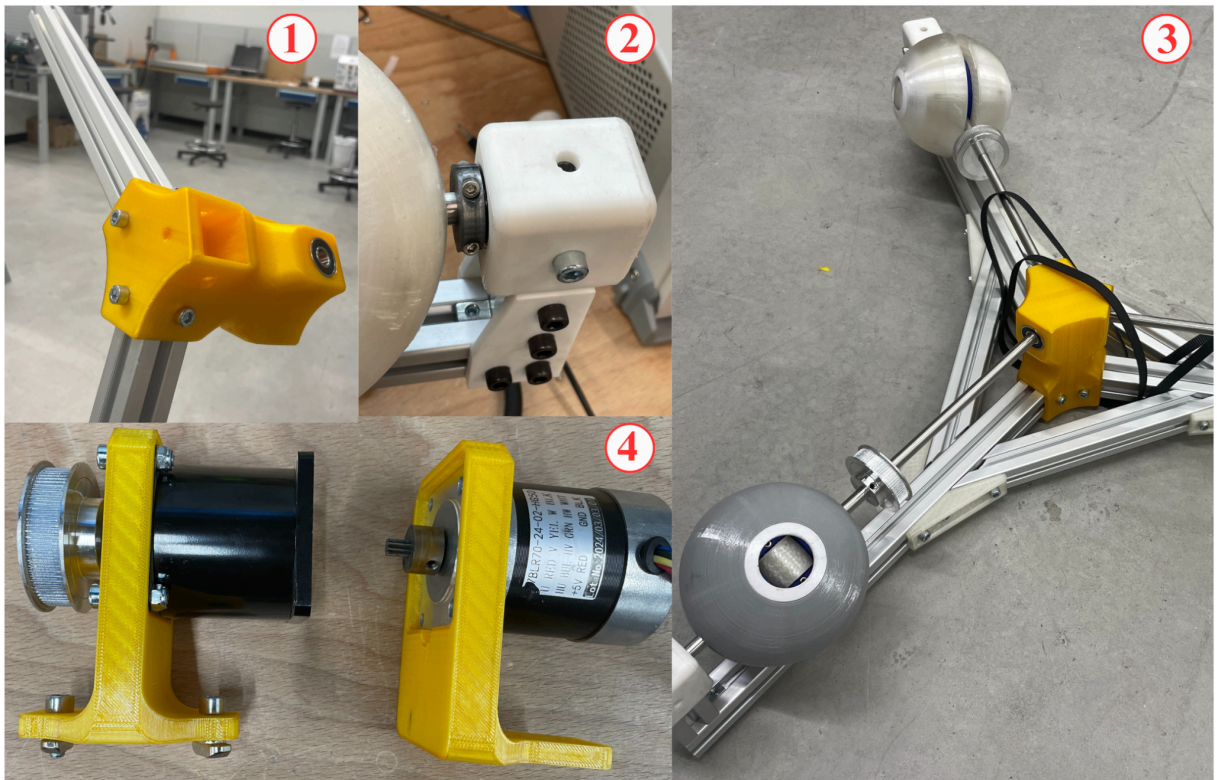


*Figure 23: Section view of the wheelbase assembly*

To keep the shaft from sliding through the ball bearings, each shaft is fixed with two shaft collars 3D printed out of polycarbonate (*Figure 24 (2)*). The shaft collar is tensioned around and fixed on the shaft using M3 screws and heat-set threaded inserts. Also, an 80-tooth 10mm wide GT2 pulley is fixed on the shaft, which is used to transfer torque from the BLDC (brushless direct current) motor to the omni-ball wheels.

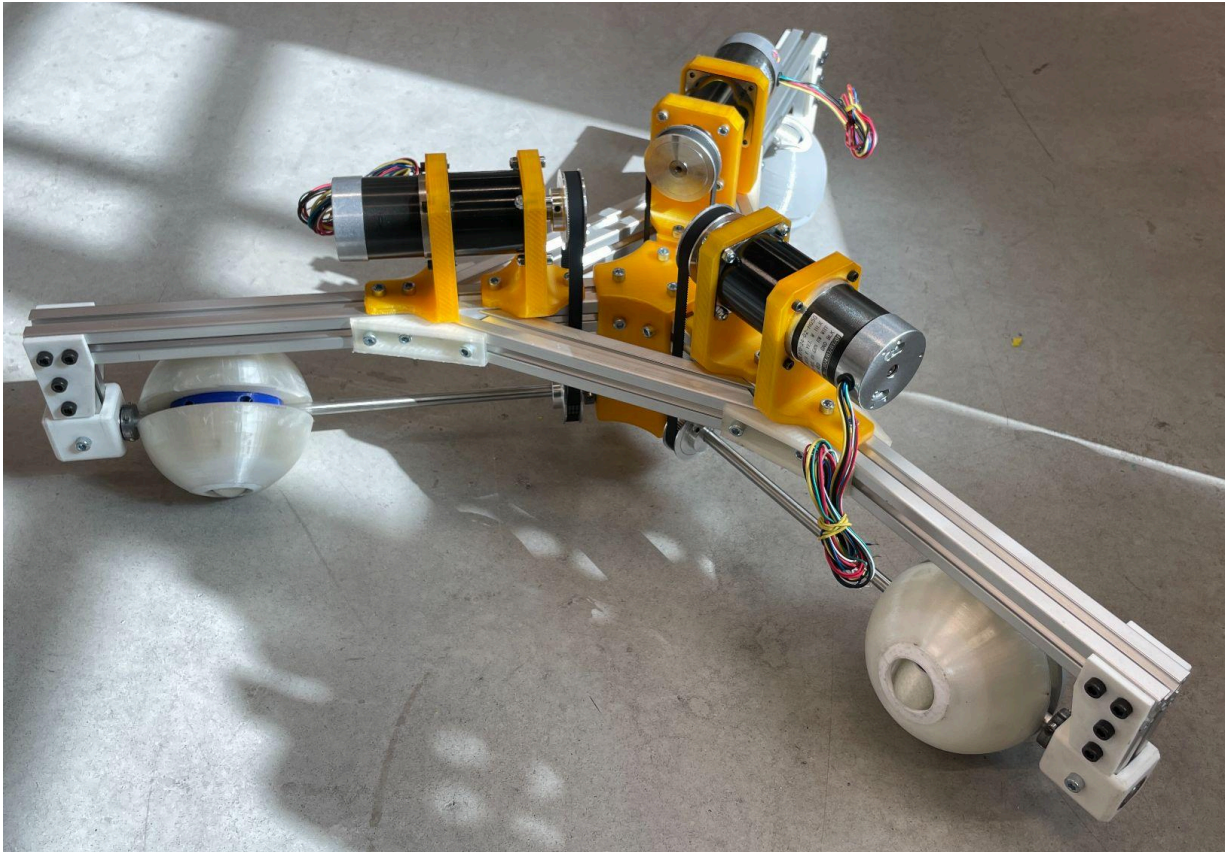
To keep the three omni-ball wheel subassemblies from flexing sideways, they are secured to each other with 30x30 mm aluminium extrusion profile crossbeams, cut at 30 degrees from both sides and secured with 3D printed 150-degree brackets (*Figure 24 (3)*).

The BLDC motor + gearbox assembly (*Figure 24 (4)*) is equipped with the same 80-tooth GT2 pulley as the omni-ball wheel shaft. Each motor assembly is fixed to the base with two 3D printed mounts out of PETG, M6 bolts and T-nuts. The height of the brackets is chosen accordingly to have the 500 mm GT2 belt tensioned between the two pulleys. The mounts are printed using the same procedure and parameters as the three-way connector.



*Figure 24: 1 - Base three-way connector; 2 - Shaft collar and base subassembly; 3 - Base assembly with crossbeams; 4 - BLDC motor and gearbox mounts*





*Figure 25: Assembled SemuBOT wheelbase*

### **3.4 Electronics and Software**

To test the wheelbase's holonomic motion and abilities to locomote in challenging environments, an electrical system had to be implemented along with a temporary software solution to be able to control the three BLDC drive motors. Most of the used electrical components are readily available for purchase to ensure simple reproducibility.

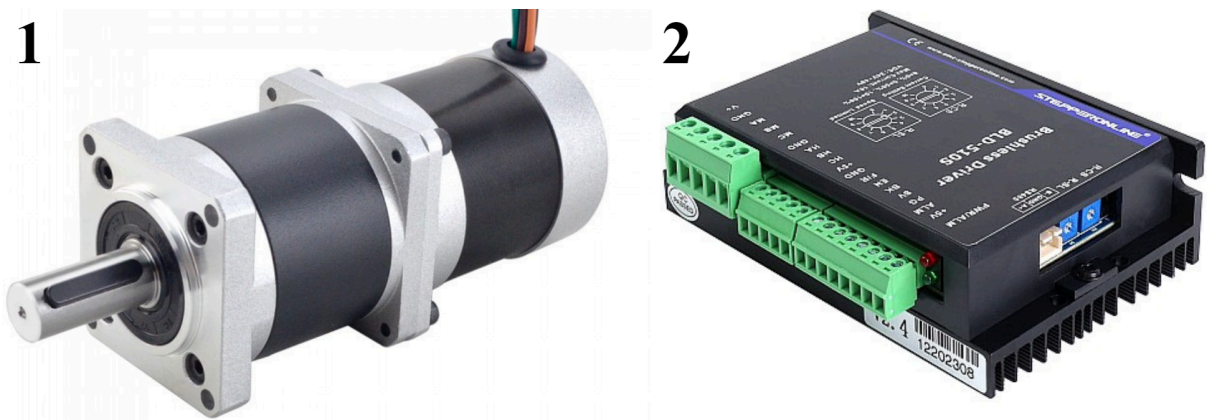
#### **3.4.1 Electrical components**

- **Motors**

A “57BLR70-24-02-HG50” BLDC motor (*Figure 26 (1)*) [58] is used to turn each omni-ball wheel. It is rated for 24 Volts, 172 Watts and with a rated torque of 0.47 Newton meters. The motor is attached to a 50:1 planetary gearbox to increase the torque output to the wheels. The three-phase BLDC motors require an external driver for power and control.

- **Motor Drivers**

Each BLDC motor is driven by a “BLD-510S” brushless driver (*Figure 26 (2)*) [59]. It supports input voltage in the 12-48 V range and up to 200 W. It uses PWM (pulse-width modulation) to control the motors. Other features include changing the direction of motion, braking stop, an alarm and overvoltage/overcurrent protection. Includes built-in potentiometers for speed and current limiting. Furthermore, it can be controlled with a PWM signal.



*Figure 26: 1 - BLDC motor and gearbox [58]; 2 - BLD-510S brushless driver [59]*

- **Raspberry PI 4b**

A Raspberry PI 4b [60] was chosen to process user input, calculate wheel velocities, and control the brushless driver. It is a single-board computer with a Broadcom BCM2711 Quad core Cortex-A72 processor, 40 GPIO pins and runs on 5V. Furthermore, it has built-in 2.4 GHz and 5.0 GHz Wi-Fi and Bluetooth 5.0 for wireless connectivity [60]. It provides plenty of processing power to be responsible for communications between the user and the wheelbase, along with inverse kinematic calculations and the control of any downstream peripherals.

- **Power circuitry**

As of the time of writing, SemuBOT robot’s power requirements have not been fully defined; thus, a temporary power circuitry solution was used to test the wheelbase. Considering the

BLDC motors have a voltage rating of 24V, a 24V battery is used. Both the Raspberry Pi 4 and brushless motor drivers have an input voltage of 5V, so a 5V voltage rail was introduced by using a “Daygreen B10-1224-05” 50W DC-DC 5V converter [61]. The converter is rated for 10A and stays within the 5V rail current draw.

### **3.4.2 Electrical connections**

As seen in Figure 27, Power for the whole wheelbase is provided by the temporary 24V battery. Since the BLDC motors are rated for 24V, no conversion is needed. On the other hand, the Raspberry Pi 4 and BLD-510S brushless driver are powered through a 5V DC-DC converter, which takes 24V as an input and steps it down to 5V. The brushless drivers are also connected to the 24V rail to power the motors. A cut-off switch was introduced on the output of the battery, which, when activated, cuts the power off of the whole system and can be used in emergency situations.

The BLD-510S brushless drivers are controlled by the Raspberry Pi 4 with two connections each - a PWM signal for controlling the speed of the motor and a connection for changing the direction of the motor. The speed of the motors can be controlled with a PWM signal with a frequency in the range from 1kHz to 2kHz. By changing the PWM signal's duty cycle, the motors' speed can be controlled in a close to linear fashion. The motor stops if the speed control voltage drops below 0.3V. The direction of the motor is controlled by pulling a terminal on the brushless driver to common ground. If the terminal is left floating, the motor turns clockwise, but when grounded, it turns counterclockwise [59].

For sending control commands to the Raspberry Pi 4, which acts as the wheelbase's central processing unit, a wireless Xbox controller was used, which connects to the RPi 4 using Bluetooth.

### **3.4.3 Software**

Raspberry Pi OS [62] was used as the operating system for the Raspberry Pi 4. Raspberry Pi Imager was used to install the OS (operating system) more easily. To remotely access the RPi 4, an SSH (secure shell) connection was used, which allowed to change system settings and execute code on the wheelbase remotely. To test the driving capabilities of the wheelbase, a Python script was written which interprets the Xbox controller inputs using pygame [63]

Python library. The controller inputs were used to translate and rotate the wheelbase along the driving surface, the joystick values were converted to radians, and the correct wheel velocities were calculated using the method described in chapter 1.2.3. With the help of linear conversion, the velocity values were converted into duty cycle values and passed onto the brushless drivers as a PWM signal, where a duty cycle of 0% denotes the motor not turning and 100% the motor turning at full speed.

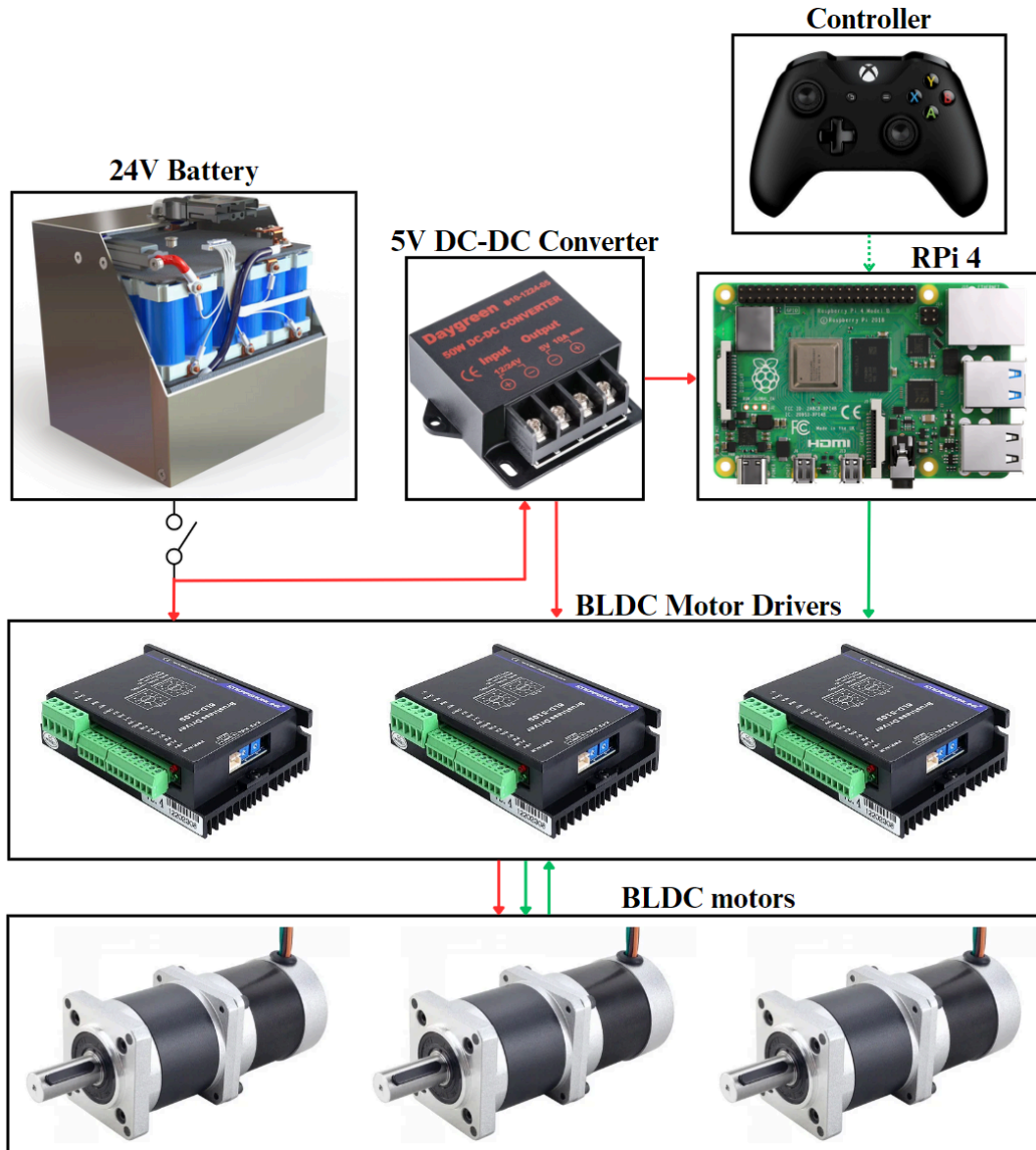
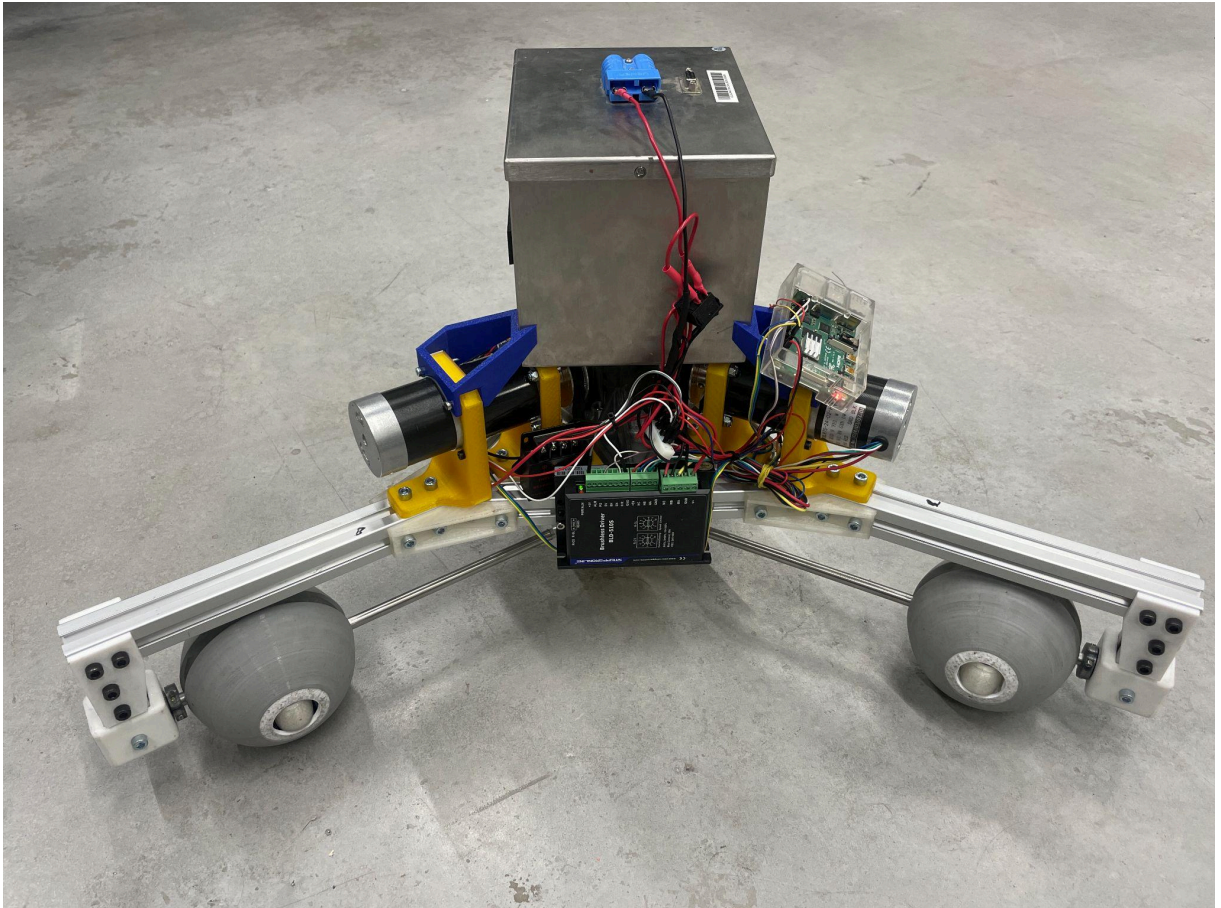


Figure 27: Wheelbase electrical connection scheme, where arrows in red denote power lines and green arrows denote signal lines.





*Figure 28: Assembled wheelbase*



## 4 RESULTS & DISCUSSION

The research aim of this thesis was successfully reached, and a holonomic motion drive system for the humanoid robot SemuBot was designed and manufactured.

All research objectives were addressed and completed. A literature review on existing humanoid robot mobile platforms, holonomic drive systems and additive manufacturing methods was conducted, and a decision on which drive system to implement for the humanoid robot SemuBot was reached. A functional wheelbase was designed and manufactured, yet during the design and development part of the thesis, limitations of the current wheelbase version were found, and improvements to fix these limitations were identified.

### 4.1 Requirement results

The humanoid robot SemuBOT wheelbase was developed in accordance with the established requirements and was an overall success.

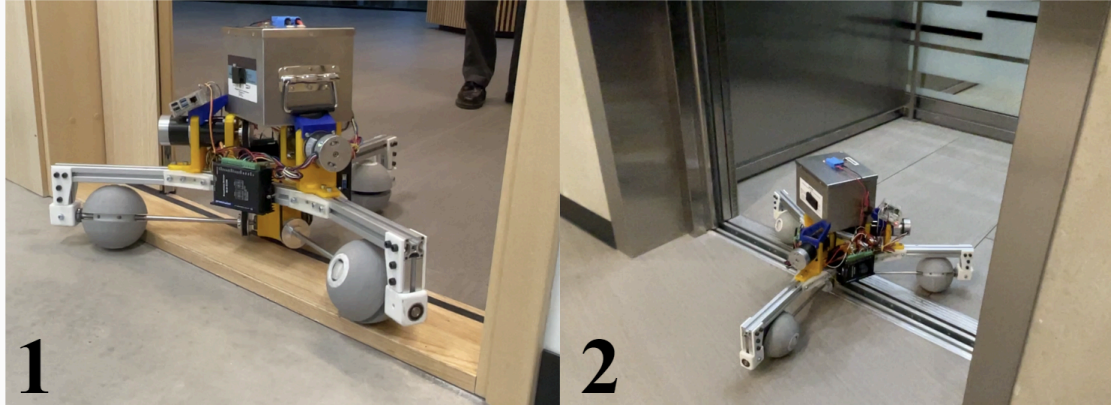
In compliance with the first requirement, holonomic motion was achieved, and the developed wheelbase can conduct translational movement in a holonomic fashion along with rotational movement. The wheelbase driving capabilities were tested on solid concrete, tile and carpet surfaces (*Figure 29*), on which the designed omni-ball wheels had no problem driving on. Due to the outer shell of the omni-ball wheels being manufactured out of a flexible material, no slippage between the wheels and the driving surface was observed.



*Figure 29: Tested drive surfaces: 1 - concrete floor; 2 - tile floor; 3 - carpet*

In accordance with the third requirement, obstacle traversing capabilities were tested. The omni-ball wheel solution proved to be a good alternative to omniwheels since it successfully and repeatedly went over a 3 cm high doorsill (*Figure 30 (1)*). Some wheel slippage was observed when two of the three wheels were in contact with the door sill simultaneously, but it still traversed the obstacle successfully. This slippage could be almost completely mitigated

by moving the wheelbase over the door sill in an orientation where the climbing is done by one wheel at a time. When testing gap traversing abilities, the wheelbase experienced no problems going over a 3 cm wide elevator floor gap (*Figure 30 (2)*), proving its ability to integrate into a modern human environment where the SemuBot humanoid robot is set to operate.



*Figure 30: Obstacle traversing: 1 - door sill; 2 - elevator floor gap*

To address the fourth requirement of a control algorithm, the calculations mentioned in chapter 1.2.3 were implemented where each omni-ball wheel velocity vector can be calculated using simple trigonometrics. This method is not resource-intensive and should be possible to be implemented even on the lowest power hardware. The open-source CAD files of the prototype and software are available in the project's GitHub [64] repository [65].

## 4.2 Challenges

### 4.2.1 3D printing settings

While manufacturing the omni-ball wheels and wheelbase with FDM 3D printing, several parts underwent multiple iterations mainly because of two factors. Firstly, the lack of physical property simulation software for FDM 3D printed parts makes predicting a part's structural properties difficult before manufacturing it. The printing orientation of a part influences its strength drastically, and in some situations, it is not trivial to determine the optimal orientation at which a part should be printed. For example, the three-way connector (*Figure 24 (1)*) went through several 3D printed iterations to prevent layer separation and splitting in the region where bearings are interference press-fit.

Secondly, which also correlates with printed layers splitting, is the shrinkage factor of FDM manufactured parts while cooling down to room temperature [66]. This means that holes on a

3D printed part may turn out fractionally smaller than designed in a CAD program and previewed in a slicer software, which, in this thesis case, led to some mechanical parts not having the intended fit. This issue was fixed by marginally increasing the size of features for parts with functional dimensions.

#### **4.2.2 Raspberry Pi 3b+ connectivity issues**

At first, it was planned to use a Raspberry Pi 3b+ [67] as the central processing unit for the wheelbase, which would receive driving commands from the Xbox controller using Bluetooth, but the on-board Bluetooth of the Raspberry Pi could not be successfully set up. Lengthy troubleshooting was done to pinpoint the cause of the problem, but to no luck. It still remains unknown whether the issue lies in a defective unit or software and OS. It was decided to switch to a newer Raspberry Pi 4 [68] on which the Bluetooth functioned properly from the start.

#### **4.3 Limitations and Future Work**

Even though PLA material is easy to print and great for prototyping purposes, it does not have the most suitable mechanical properties for parts meant to last a long time under increased load. Manufacturing all the mechanical parts out of a more suitable material like polycarbonate could increase the mechanical rigidity of the wheelbase, which is of utmost importance for a humanoid robot interacting with people.

In addition, the wheelbase manufactured in the scope of this thesis does not implement encoders for the omni-ball wheels. Currently, the speed of the motors is controlled by a PWM signal with a variable duty cycle, and it is assumed that the brushless motor drivers change the speed of the motors linearly based on the duty cycle, but in practice, each controller is not precisely the same, and there are some variations between the motor speeds, meaning, that in some cases the wheelbase might move in a slightly different direction than intended. To solve this, encoders should be attached to the motor output, and a feedback loop should be implemented in the control system to make the locomotion more precise.

Lastly, for transferring the torque from the motors to the wheels, GT2 pulleys and timing belts were used. Although they are a great choice for precisely timed movement, GT2 belts are not great for high-torque applications because of their relatively low slipping torque. Once the

SemuBot robot is fully assembled, it will weigh substantially more than at the moment of writing, which may lead to belt slipping when moving over obstacles. It is proposed that the GT2 system be changed to a belt system rated for high-torque applications, like a larger pitch GT or HTD belt system [69].

Future work should also include more thorough testing of the manufactured wheelbase's obstacle traversing capabilities, testing its movement on more terrains and conducting load testing to identify the maximum weight it can support while moving.

## **5 CONCLUSION**

This thesis focused on exploring existing humanoid robot motion systems, further focusing on holonomic motion systems and the design and development of an omni-ball wheel and a holonomic motion wheelbase for the social humanoid robot SemuBot. The manufactured wheelbase prototype proved to be a viable option for granting a robot controlled and reliable movement in several different environments. All while using off-the-shelf or easily reproducible components using additive manufacturing methods.

Through the development and testing stage of the prototype, several hardware limitations were identified, which are planned to be addressed in future work. As the SemuBot humanoid robot is an open-source collaborative project between multiple parties, there are plans to integrate the wheelbase prototype with other robot components.

## **ACKNOWLEDGEMENTS**

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Grammarly [70] was used to proofread this thesis, correct grammatical errors and improve the readability of the text. ChatGPT [71] based on the GPT-3.5 large language model provided helpful suggestions on writing in active voice and suggestions for improving text clarity in the Abstract, Introduction and Acknowledgements.

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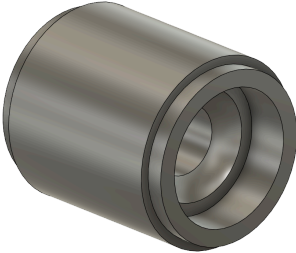
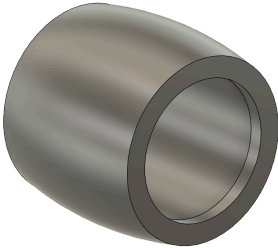
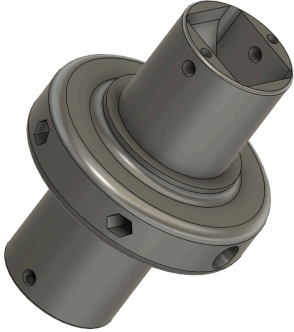
# APPENDIX

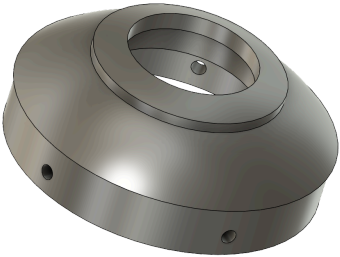
## 1. Repository with CAD files.

The CAD files for the designed SemuBot wheelbase, software, as well as images can be accessed in the repository of this thesis:

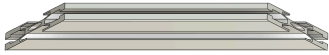
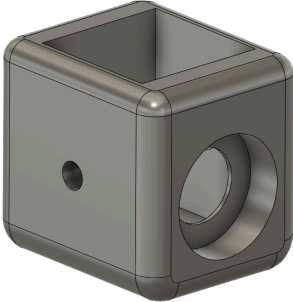
<https://github.com/SemuBot/narbut's-thesis-2024-semubot-wheelbase>

## 2. Omni-ball BOM

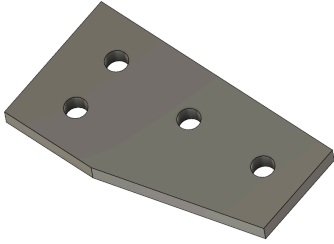
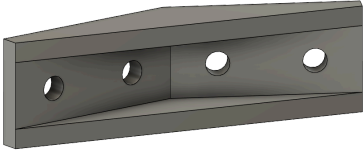
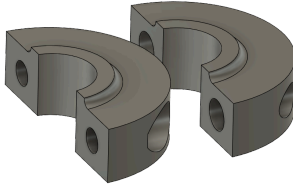
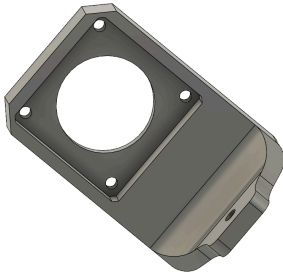
| Item                                                                                                        | Quantity | Material |
|-------------------------------------------------------------------------------------------------------------|----------|----------|
| <div>Roller Core</div>    | 2        | PLA      |
| <div>Roller Shell</div>  | 2        | TPU      |
| <div>Middle Core</div>   | 1        | PLA      |

|                                                                                                             |    |       |
|-------------------------------------------------------------------------------------------------------------|----|-------|
| <p>Lower Hemisphere</p>    | 2  | PLA   |
| <p>Upper Hemisphere</p>    | 2  | PETG  |
| <p>Hemisphere Shell</p>  | 2  | TPU   |
| <p>Roller Shaft (5mm diameter, 39.5mm length)</p>                                                           | 2  | Steel |
| <p>625-2RS Deep Groove Ball Bearing</p>                                                                     | 4  |       |
| <p>16008 Deep Groove Ball Bearing</p>                                                                       | 4  |       |
| <p>M2 Heat-set Insert</p>                                                                                   | 4  |       |
| <p>M3 Heat-set Insert</p>                                                                                   | 10 |       |
| <p>M2x3mm Set-screw</p>                                                                                     | 4  |       |
| <p>M3x8mm Hex Socket Bolt</p>                                                                               | 10 |       |

### 3. Wheelbase BOM

| Item                                                                                                                             | Quantity | Material  |
|----------------------------------------------------------------------------------------------------------------------------------|----------|-----------|
| Omni-ball                                                                                                                        | 3        |           |
| Wheel Shaft (10mm diameter, 260mm length)                                                                                        | 3        | Steel     |
| 30x30mm Aluminium Extrusion (417mm length)                                                                                       | 3        | Aluminium |
| 30x30mm Aluminium Crossbeams<br>                | 3        | Aluminium |
| 30x30mm Aluminium Extrusion (85mm length)<br> | 3        | Aluminium |
| Three-way Connector<br>                       | 1        | PETG      |
| Shaft Connector<br>                           | 3        | PETG      |



|                                                                                                               |        |      |
|---------------------------------------------------------------------------------------------------------------|--------|------|
| 90deg Connection Bracket<br> | 6      | PLA  |
| 30x30mm extrusion L-joint bracket (with its respective hardware)                                              | 3      |      |
| 150deg Bracket<br>           | 6      | PLA  |
| Shaft Collar halves<br>     | 6 each | PC   |
| Motor Mount Front<br>      | 3      | PETG |
| Motor Mount Back<br>       | 3      | PETG |
| GT2 Pulley (80tooth, 10mm wide, 10mm bore)                                                                    | 3      |      |

|                                            |    |  |
|--------------------------------------------|----|--|
| GT2 Pulley (80tooth, 10mm wide, 14mm bore) | 3  |  |
| GT2 Closed Belt (500mm, 10mm wide)         | 3  |  |
| 6000-2RS Deep Groove Bearing               | 9  |  |
| T-slot Nut (for 30x30mm extrusion)         | 75 |  |
| M3 Heat-set Insert                         | 12 |  |
| M3x14mm Hex Socket Bolt                    | 12 |  |
| M6x12mm Hex Socket Bolt                    | 60 |  |
| M6x16mm Hex Socket Bolt                    | 15 |  |
| M4 Hex Nut                                 | 6  |  |
| M4x35mm Hex Socket Bolt                    | 6  |  |
| M5x14mm Hex Socket Bolt                    | 12 |  |
| M4x20mm Hex Socket Bolt                    | 12 |  |
| M4 Nylon Insert Hex Nut                    | 12 |  |

#### 4. Electronics BOM

| Item                                            | Quantity |
|-------------------------------------------------|----------|
| 57BLR70-24-02-HG50 BLDC Motor with Gearbox      | 3        |
| BLD-510S Digital Brushless DC Motor Driver      | 3        |
| Daygreen B10-1224-05 DC-DC converter            | 1        |
| Xbox Wireless Controller (for testing purposes) | 1        |
| Raspberry Pi 4b (for testing purposes)          | 1        |
| 24V Battery (for testing purposes)              | 1        |

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