Design of an omnidirectional universal mobile platform

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DCT 2005.117

DCT traineeship report

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Eindhoven, September 2005

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Chapter 1

Introduction

Industrial and technical applications of mobile robots are continuously gaining in importance. Mobile robots are already widely used for surveillance, inspection and transportation tasks. A further emerging market is that of mobile entertainment robots.

The basic requirement for autonomous mobile robots is the ability to move through its operational area, avoiding hazards and obstacles, finding its way to the next location to perform its task. These capabilities are known as localization and navigation. In order to know where to go, the robot must have accurate knowledge of its current location. From here the robot can navigate to the next position, using a great variety of sensors, external references and algorithms.

The performance of a mobile robot is determined to a large extend by the tracking and localization algorithms, as well as its sensing capabilities. Research is continuously going on in this field, to improve the autonomous navigation capability of mobile robotic systems.

In order to test newly developed sensing, navigation and localization strategies, a universal mobile robotic base featuring omnidirectional motion capability is designed, providing a flexible motion platform to test and improve developed algorithms and sensing systems.

First a brief explanation of omnidirectional mobility and the specifications of the mobile base will be given. Different concepts of omnidirectional drive will be discussed and the best concept for the mobile base is selected. Next, the mobile base will be designed on system level. A kinematic and dynamic model will be derived, enabling the design and selection of all system components.

This report is the result of an internship of 18 weeks conducted at the Mechatronics and control laboratory of the Mechanical Engineering department of the National University of Singapore. This internship is a compulsory part of the study Mechanical Engineering at the Eindhoven University of Technology. This report has been established under the supervision of dr. M. Ang jr. from the National University of Singapore and prof. dr. ir. M. Steinbuch from the TU/e.

Chapter 2

Omnidirectional mobility

Robotic vehicles are often designed for planar motion, they operate on a warehouse floor, road, lake, table etc. In such a two dimensional (2D) space, a body has three degrees of freedom (3DOF). It is capable of translating in both directions $(\dot{x}, \dot{y})$ and rotate $(\dot{\theta})$ about its center of gravity (fig 2.1). Most conventional vehicles however do not have the capability to control every degree of of freedom independently. Conventional wheels are not capabele of moving in a direction parallel to their axis. This so called non-holonomic constraint of the wheel prevents vehicles using skid-steering, like a car, from moving perpendicular to its drive direction. While it can generally reach every location and orientation in a 2D space, it can require complicated maneuvers and complex path planning to do so (fig 2.2). This is the case for both human operated and robotic vehicles.

When a vehicle has no non-holonomic constraints, it can travel in every direction under any orientation. This capability is widely known as omnidirectional mobility. A variety of omnidirectional designs have been developed. They provide excellent mobility, especially in areas congested with static or dynamic obstacles, such as offices, workshops, warehouses and hospitals.

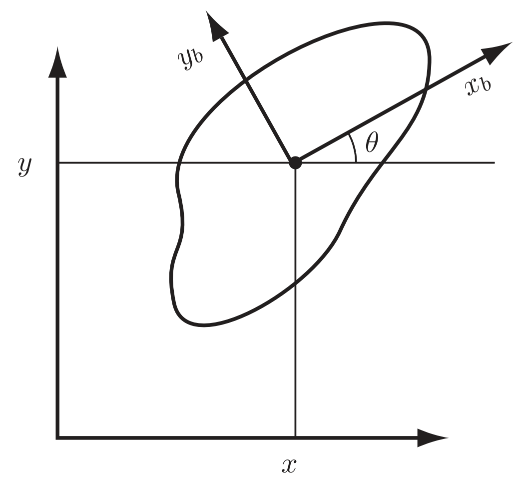

Figure 2.1: planar motion; 3 degrees of freedom

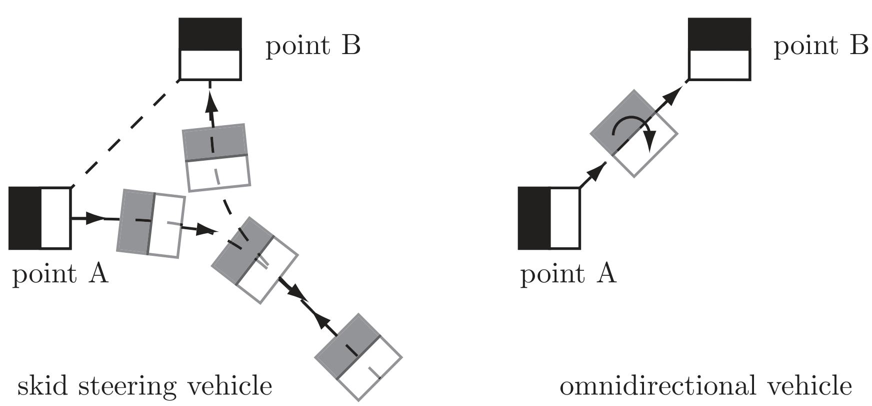

Figure 2.2: non-holonomic mobility versus omnidirectional mobility

Chapter 3

Specifications

3.1 Dimensions

The specifications of the base can be derived from the research tasks and operating environment. The mobile base will be used to conduct research in the fields of trajectory planning, localization, robotic control and navigation for robots operating in office-like environments. Those environments are constructed on a human scale with its distinct dimensions, such as doorways, passages and furniture. In order for the base to operate in such an environment, it's footprint should not exceed 350 $\times$ 350 mm for good maneuverability. Maximum weight of the base is set at 5 kg, keeping the base low weight and maneuverable. On top of the base weight another 5 kg of research payload has to be carried. The height of the base should not exceed 350 mm in order to move freely under and near common furniture, such as chairs, workbenches and tables.

3.2 Dynamics

Omnidirectional motion must be achieved with a maximum lateral speed of 1 m/s in every direction. By using the average walking speed for humans [WIK] as reference (1 m/s), the base will display good mobility in a human environment. Top speed must be reached within 1 s, hence an acceleration of 1 m/s^2. Rotational velocity is set at 1 rad/s , rotational acceleration at 1 rad/s^2.

3.3 Control

The omnidirectional base must be capable of at least 30 minutes of autonomous operations. Low level control algorithms for feedback control, as well as high level localization and navigation algorithms must be implemented on an onboard computer. Programming must be flexible, providing a universal mobile base for a broad scope of research activities. Onboard electronics have to be designed and selected to be used with multiple additional sensors and actuators, to be added in a later stadium of this project. Furthermore, the base has to be robust, simple to fabricate and assemble at low costs. All quantifiable specifications are summarized in tab. 3.1.

Specification	value
Dimensions	350 × 350 × 350 mm
Weight	< 5 kg
Payload	5 kg
Lateral speed	1 m/s
Lateral acceleration	1 m/s^2
Rotational speed	1 rad/s
Rotational acceleration	1 rad/s^2
Operating time	30 minutes

Table 3.1: mobile base specifications

Chapter 4

Concepts

A variety of designs of omnidirectional or near omnidirectional platforms have been developed. These designs can be broken into two approaches: special wheel designs and conventional wheel designs. An omnidirectional platform is usually formed using three or more of such wheels. Each design has different properties concerning mechanical design, dynamic behavior, etc. In order to select the method of motion for the omnidirectional mobile base, all designs will be reviewed.

4.1 Special wheel designs

Most special wheel designs are based on a concept that achieves traction in one direction and allow passive motion in another.

4.1.1 Omniwheel

The omniwheel is an example of the special wheel design that has a number of small passive rollers mounted on the periphery of a normal wheel. The shafts of the rollers are perpendicular to that of the wheel. The wheel is driven in a normal fashion, while the rollers allow for a free motion in the perpendicular direction (fig.4.1). Three powered omniwheels will provide omnidirectional motion, while the base is statically determined. More wheels (passive or active) can be used, to support heavier loads or to provide better stability. This will however introduce the need for a suspension system and cause an increase of the overall

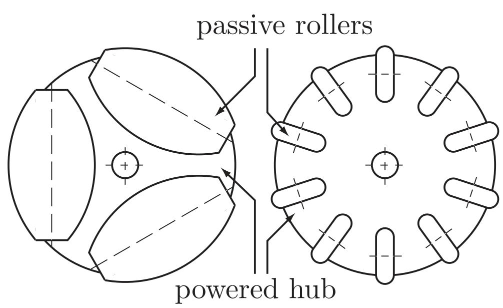

Figure 4.1: two omniwheel designs

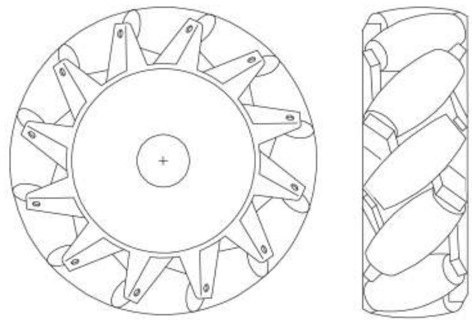

Figure 4.2: the mecanum wheel design

weight. Omniwheels are compact, commercially available, easy to install and demonstrate good omnidirectional behavior. Due to the small passive rollers on its perimeter, universal wheels are sensitive to irregularities in the floor surface, can generally only support loads op to 100 kg and show discontinuous wheel contact, introducing vibrations in the robot [OMN]. The problem of the discontinuous wheel contact can be solved by placing two rows of rollers interlocked on the periphery of the wheel. This however adds a complication for control and odometry in that the point of contact point of the wheel moves shifts between the inner and outer rows of rollers. If the distance between both rows of rollers is small in comparison with the radius of the transport system, this problem remains manageable.

4.1.2 Mecanum wheel

The Mecanum wheel consists of a hub carrying a number of free moving rollers, much like the omniwheel, but angled at 45° about the hub's circumference. The rollers are shaped in such a way that the overall side profile of the wheel is circular (fig.4.2). By installing four mecanum wheels on the corners of a rectangular base, omnidirectional motion can be achieved [COO]. The mechanical design is much more complex due to the angled rollers, but higher loads can be supported due to the smoother transfer of contact surfaces.

4.1.3 Orthogonal wheels

A pair of wide, almost spherical, wheels are placed with their shafts in orthogonal directions form the basis of the orthogonal wheel design. The wheels are able to rotate freely about their axles. A bracket holds the wheel shaft. This bracket is rotated , rolling the wheel on a portion of spherical surface, while free-wheeling in the orthogonal direction. This gives the same effect as the omniwheel. An orthogonal wheel pair can provide traction in one direction and move freely in the orthogonal direction. Again, by combining three or more such wheel pairs at different angles it is possible to achieve omnidirectional motion [ASH]. Orthogonal wheels consist of fewer parts than omniwheels and are less sensitive to floor irregularities, due to their larger roller diameter. They do however require more space and power, caused by the large inertia of all rotating components.

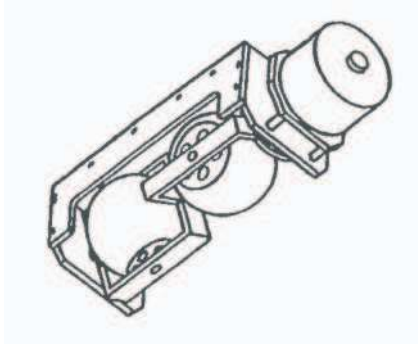

Figure 4.3: orthogonal wheel

4.2 Conventional wheel design

In order to prevent the use of small passive rollers, several designs using conventional wheels have been developed.

4.2.1 Powered castor wheel

The Powered Castor Vehicle (PCV) concept provides holonomic mobility while using normal, nonholonomic wheels [MUI]. A PCV module consist of a castor wheel, powered by two motors. One motor powers the wheel (drive), the second motor sets the rotation of the offset arm (direction) (fig.4.4). A vehicle capable of omniderictional motion is constructed by combining at least 2 PCV modules and, if necessary, one or more passive castors providing vehicle stability. The PCV design is sometimes described as the powered office chair for simpler conceptual description. Each wheel mechanism contains a single wheel which is large enough for good ground clearance. This wheel is fitted with commonly available pneumatic tires, making the PCV design robust and capable of carrying high payloads, combined with continuous contact properties. In order to power the wheels however, energy has to be transferred trough rotational joints, complicating the design. Due to the 360° orientation capability of the castor wheels, the PCV design is voluminous, often resulting in a high center of gravity. Another major drawback of the PVC design is the high friction and scrubbing during the steering when the wheel is actively twisted around a vertical axis. This reduces positioning accuracy and increases power consumption and tire wear, especially for heavy vehicles.

4.2.2 Powered offset castor wheel

The powered offset castor (POC) reduces the scrubbing problem using a dual wheel design. The dual wheel design is commonly found in the aircraft front landing gear. Wheels in the dual wheel design are always rolling even during steering, due to their offset distance relative to the rotational joint. By installing two sets of powered offset castor wheels, omnidirectional mobility can be achieved [YU]. The orientation of the wheels is controlled by driving both wheels of one assembly at different velocities. This reduces scrubbing, but introduces some other problems. Using the POC design, signals and power of two motors must be transferred

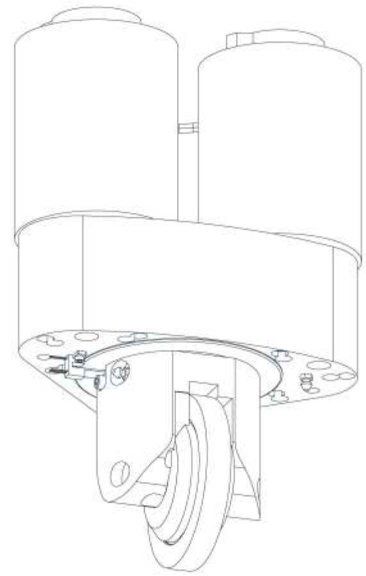

Figure 4.4: the powered castor wheel design

along the same rotational joint, again complicating the design. With four contact points between wheels and the drive surface, suspension is also required to keep all powered wheels on the ground at any time on irregular surfaces.

4.3 Other designs

Some exotic designs have been developed, to overcome some of the shortcomings of the concepts mentioned above. This often results in large and complex systems.

4.3.1 Omnitracks

The omnitrack design consists of a free roller track. The cylindrical rollers are free to rotate perpendicular to the drive direction of the belt, while providing line contacts to drive the platform. Again, by combining three or more omnitracks, omnidirectional motion can be achieved, such as the Vuton platform. [HIR2]. A platform powered by omnitracks features a large payload capacity because of the large contact area of the multiple driving rollers. It however consists of many moving parts that make it a voluminous design and cause some internal friction.

4.3.2 Legs

Legged platforms can also have omnidirectional capabilities. They are not suitable for high speeds and accelerations, due to the discontinuous movement of the legs. Legged designs are less sensitive to floor conditions, provide good traction but are also mechanically complex.

An overview of the properties of all concepts is given in tab.4.1.

Omniwheel	+ low weight, compact design + simple mechanic design + commercially available	- discontinuous wheel contact or variable drive-radius (2 rows) - sensitive to floor irregularities
Mecanum wheel	+ compact + high load capacity	- discontinuous wheel contact - high sensitivity to floor irregularities - complex wheel design
Orthogonal wheel	+ robust to floor conditions	- heavy and bulky design - high inertia - complex mechanical design
Powered castor wheel	+ continuous wheel contact + high load capacity + robust to floor conditions	- heavy and bulky design - high friction and scrubbing while steering - complex mechanical design
Powered offset castor wheel	+ continuous wheel contact + high load capacity + low scrubbing force during steering + robust to floor conditions	- voluminous design - transmit power and signals across rotational joints - complex mechanics
Omnitrack	+ high load capacity + flat design + robust to floor conditions + low slippage	- complex mechanical design - low top speed
Legs	+ robust to floor conditions + low slippage	- complicated motion control - complex mechanical design - low top speed

Table 4.1: concepts of omnidirectional drive

Chapter 5

choice of concepts

All concepts are introduced and reviewed on their specific properties in chapter 4. In order to select the most suitable design for a low weight and small mobile platform, the concept designs will be evaluated according to the specifications of the mobile base (tab. 3.1).

5.1 Selection

The special wheel designs are smaller, lighter and less complex than the conventional wheeled, which generally feature better wheel contact, a higher payload capability, higher top speed and less sensitivity to floor irregularities.

For the small, lightweight omnidirectional universal mobile base the special wheel design appears to be the preferred choice. Especially the omniwheel design, featuring a simple overall design, low weight and good omnidirectional capabilities.

All other concepts will be compared to the omniwheel powered base to verify if this the best design for achieving omni-direction motion, using tab 4.1 and the key specifications of the mobile base as benchmarks. In table 5.1 the ability of each design type to satisfy these specifications, relative to the omniwheel design, is denoted, using "+" for better performance and "-" for worse. "0" will be awarded when no significant difference can be found. Please note that table 5.1 only displays the general properties of the designs, while the performance of the base can only be determined after all design choices have been made. To select the most suitable way of constructing the omnidirectional mobile base however, insight in the properties of the different concepts can be obtained using this method.

As can be seen from tab. 5.1, all other concepts score less than the omniwheel concept, so the omnidirectional universal mobile robotic base will be based on this concept.

Design	dimensions	mass	speed	simplicity	contact	clearance	total
Omniwheel	0	0	0	0	0	0	0
Mecanum	0	-	0	0	0	0	-
Orthogonal	-	-	0	-	0	+	- -
PCV	-	-	0	-	+	+	-
POC	-	-	0	-	+	+	-
Omnitracks	-	-	0	-	0	+	- -
Legs	-	-	-	-	+	+	- -

Table 5.1: concept evaluation

Chapter 6

System design

All robotic systems consist of of multiple subsystems, in order to control, sense and realize motion. Those systems include mechanical, electrical and software components. In this chapter the mobile base is designed on system level.

6.1 Mechanical system

The mechanical subsystems will consist of two parts, the active drive train and the passive framework. The active mechanical components will provide the actual propulsion of the base.

The omniwheel design is selected as design concept. In order to build a lightweight platform, only three omniwheels will be used. Not only does this cut down the number of actuators, sensors, bearings etc, but due to the statically determined nature of a three wheeled vehicle, there is no need for a suspension system. Al three wheels will always be in contact with the floor, independent of its roughness. If three wheels are positioned in a symmetrical way relative to the center of gravity of the base, the best omnidirectional abilities will be achieved [CAR], in the case of three wheels this will be 120°. The larger the distance between the wheels and the center of gravity, the more stable the platform will become. Each wheel has to be powered by a motor, in order to achieve omnidirectional mobility and motion control. The motor must be connected to the wheel using a shaft, coupling and/or gearbox.

The framework must provide a stiff base which transfers the force, implied by the mass of the different components, to the supports: the wheels. It accommodates all components, provide space for the research payload and protect the vulnerable systems, like electronics and motors, from getting damaged by impact or light crashes.

6.2 Electrical system

The electrical system will provide the means to control the motors, enable the use of sensors and provide to power to all subsystems. First of all, the electrical system must supply the motors with a current or voltage to operate them, this can be accomplished by using amplifiers. Second, the motors must be controlled using feedback information, so the position of the motor shafts or wheels must be measured. Furthermore, all signals from the sensors have to be processed using a data-acquisition system and calculated using a signal processor. After calculating the new control signals, they have to be sent to the motor controller. Finally, a power supply has to power al electrical systems, enabling stand-alone operation of the base. The electrical system must be flexible and easily expandable, so new sensors or actuators can be added relatively easy.

6.3 Software

The mobile base will perform as an experimental platform for different control strategies and algorithms to be implemented and tested. The software will be programmed after the mechanical and electrical systems have been realized and goes beyond the scope of this report. It is however important to realize that the software controlling the robot should be easy to implemented in any on board computing device.

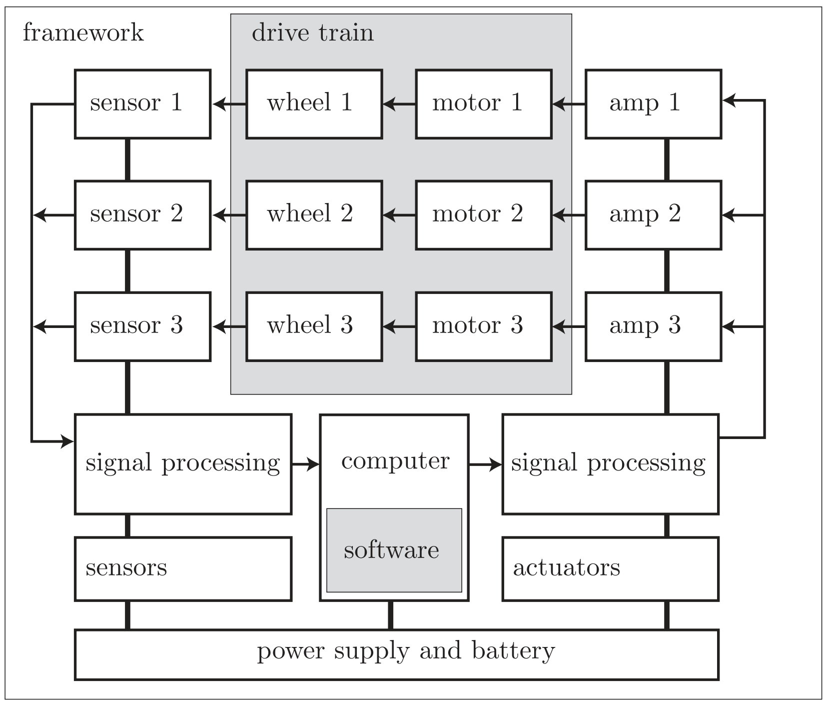

Figure 6.1: system diagram of the mobile base

Chapter 7

Modelling

The acceleration and velocity of the mobile base are known on system level, and need to be translated to component level in order to design the drivetrain. In order to calculate the specifications on drivetrain level from the global system specifications a kinematic and dynamic model will be derived. Both models will expres the desired global acceleration and velocity in terms of required torque and angular velocities of the wheels.

7.1 Kinematics

The omniwheel powered base consists of three omniwheels, positioned at an angle α_i, relative to the local frame $[x_l, y_l]$. The center of this frame coincides with the center of gravity of the base and wheel 1 is located on the local axis (x_l), in other words: $\alpha_1 = 0$ (fig. 7.1. The orientation of the base with respect to the global frame (x_g, y_g) is given by the global coordinates $[x, y, \theta]$ The relation between the global velocity of the platform $(\dot{x}, \dot{y}, \dot{\theta})$ and translational velocity v_i of wheel hub i can be obtained using the inverse kinematic equation of each wheel hub. The component of v_i in x_g direction, denoted as $v_1 x$ in fig. 7.1, must be equal to $\dot{x}$, due to the fixed position of the hub relative to the center of mass. For $v_i y$ a similar relation can be derived. When the base rotates, the hub speed v_i needs to satisfy the condition $v_i = \theta \cdot R$, hence eq.7.9. Please note that r refers to the wheel radius, while R represents the distance from the center of mass of the platform to the wheels, along a radial path.

$$v_i = -\sin(\theta + \alpha_i)\dot{x} + \cos(\theta + \alpha_i)\dot{y} + R\dot{\theta} \tag{7.1}$$

The translational velocity of the hub can be rewritten as a angular velocity $\dot{\phi}_i$ of the wheels using eq.7.2, resulting in eq.7.3.

$$v_i = r\dot{\phi}_i \tag{7.2}$$

$$r\dot{\phi}_i = -\sin(\theta + \alpha_i)\dot{x} + \cos(\theta + \alpha_i)\dot{y} + R\dot{\theta} \tag{7.3}$$

This can be transformed to matrix representation (eq.7.4):

$$\underline{\dot{\phi}} = J_{inv}\underline{\dot{u}} \tag{7.4}$$

From eq.7.3 and eq.7.4 the inverse jacobian J_{inv} for the omniwheel powered base can be obtained, providing a direct relation between global velocities and angular velocities of the

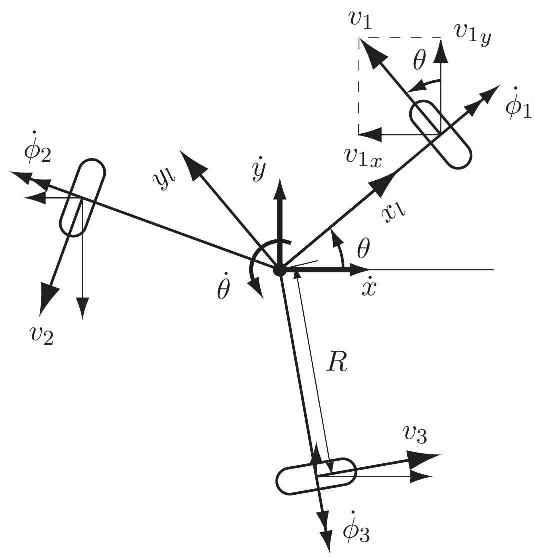

Figure 7.1: kinematic diagram of the three wheel base

wheels (eq.7.15).

$$\begin{bmatrix} \dot{\phi}_1 \\ \dot{\phi}_2 \\ \dot{\phi}_3 \end{bmatrix} = \frac{1}{r} \begin{bmatrix} -\sin(\theta) & \cos(\theta) & R \\ -\sin(\theta+\alpha_2) & \cos(\theta+\alpha_2) & R \\ -\sin(\theta+\alpha_3) & \cos(\theta+\alpha_3) & R \end{bmatrix} \begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{\theta} \end{bmatrix} \tag{7.5}$$

Using the inverse jacobian matrix, the wheel shaft rotational velocity can be derived using the specified maximum velocities in tab.3.1, when both wheel radius and platform dimensions (r, R) are known.

Using a Matlab-file, angular velocities of the wheels are calculated, for all directions of travel. Velocity vector $\underline{\dot{u}}$ is set as $[1, 0, 1]'$, representing maximum lateral and rotational velocity as stated in tab.3.1. By changing θ incrementally from 0 to 2π radians, the maximum shaft output velocities are obtained as a function of the wheel radius r. The resulting angular velocities of the wheels can be found in fig.7.3.

7.2 Dynamics

In order to determine the specifications for the motors, a dynamic model will be derived. The shaft output torque is determined by calculating all forces acting on each wheel. The main force acting on the wheels is the force to overcome the inertia of the base, while accelerating. This force consists of two components, on one hand a force is required to accelerate the base laterally while on the other hand all the components of the drivetrain need to be accelerated angularly. Other forces acting on the base include friction forces and the force to overcome small obstacles on the drive surface. All forces will be reviewed in this chapter and a model will be derived. Based on this model all required components can be selected and designed.

7.2.1 Base inertia

Due to the inertia of the base, force need to be applied to accelerate and decelerate the base. This force is exerted by the wheels, which transfer the motor torque to the drive surface. Torque is linear related to the driving force of the hub, by the radius of the wheel (eq.7.6). The required force can be calculated using Newton's second law (eq.7.7):

$$T = Fr \tag{7.6}$$

$$\underline{F} = \underline{M\ddot{u}} \tag{7.7}$$

For a body in a 2D space, The magnitude of the global forces can be written using the mass M, moment of inertia J_z and moment M_t as:

$$\begin{bmatrix} F_x \\ F_y \\ M_t \end{bmatrix} = \begin{bmatrix} M & 0 & 0 \\ 0 & M & 0 \\ 0 & 0 & J_z \end{bmatrix} \cdot \begin{bmatrix} \ddot{x} \\ \ddot{y} \\ \ddot{\theta} \end{bmatrix} \tag{7.8}$$

The global forces F_x and F_y can be substituted by the sum of x respectively y components of the lateral shaft forces, while global moment M_t is given by the product of the combined local force vectors and the radius on which they act (fig.7.2):

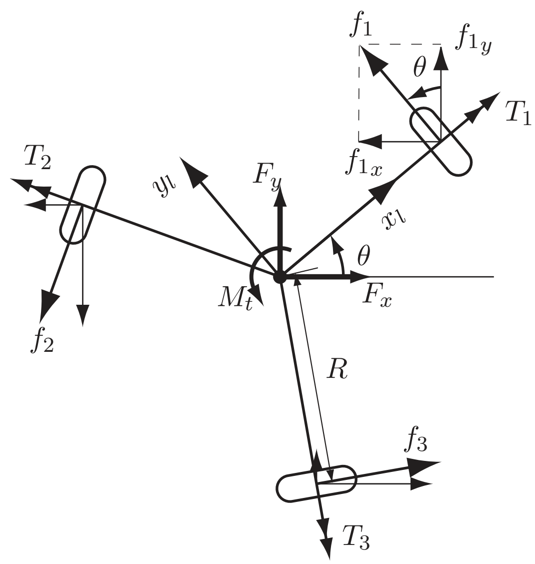

Figure 7.2: dynamic diagram of the three wheel base

$$F_x = f_{1x} + f_{2x} + f_{3x} = -f_1 \cdot sin(\theta) - f_2 \cdot sin(\theta + \alpha 2) - f_3 \cdot sin(\theta + \alpha 3) \tag{7.9}$$

$$F_y = f_{1y} + f_{2y} + f_{3y} = f_1 \cdot cos(\theta) + f_2 \cdot cos(\theta + \alpha 2) + f_3 \cdot cos(\theta + \alpha 3) \tag{7.10}$$

$$M_t = (f_1 + f_2 + f_3) \cdot R \tag{7.11}$$

In a more general notation:

$$\underline{F} = \underline{A}\underline{f} \tag{7.12}$$

with:

$$\underline{A} = \begin{bmatrix} -\sin(\theta) & -\sin(\theta+\alpha_2) & -\sin(\theta+\alpha_3) \\ \cos(\theta) & \cos(\theta+\alpha_2) & \cos(\theta+\alpha_3) \\ R & R & R \end{bmatrix} \tag{7.13}$$

The general relation between shaft output force and desired global accelerations can now be obtained from eq.7.8 and 7.12, resulting in eq.7.14

$$\underline{f} = \underline{A}^{-1}\underline{M\ddot{u}} \tag{7.14}$$

When eq.7.6 is substituted in eq.7.14, with $\alpha_2 = \frac{2\pi}{3}$ and $\alpha_3 = \frac{4\pi}{3}$, the direct equation between shaft output torque $\underline{T}$ and global accelerations ($\underline{\ddot{u}}$) is given in matrix notation by:

$$\begin{bmatrix} T_1 \\ T_2 \\ T_3 \end{bmatrix} = r \begin{bmatrix} -\sin(\theta) & -\sin(\theta+\frac{2\pi}{3}) & -\sin(\theta+\frac{4\pi}{3}) \\ \cos(\theta) & \cos(\theta+\frac{2\pi}{3}) & \cos(\theta+\frac{4\pi}{3}) \\ R & R & R \end{bmatrix}^{-1} \begin{bmatrix} M & 0 & 0 \\ 0 & M & 0 \\ 0 & 0 & J_z \end{bmatrix} \begin{bmatrix} \ddot{x} \\ \ddot{y} \\ \ddot{\theta} \end{bmatrix} \tag{7.15}$$

A simulation is carried out, again by using the specifications of the base as input parameters. The moment of inertia is calculated by modeling the base as a simple cylinder, according to eq7.16. Again, with a platform radius R of 0.15 m and a total mass M of 10 kg. The torque applied by each shaft can be found in fig.7.3. The maximum torque required under these assumptions equals 0.28 Nm. Jz is calculated by modeling the base a homogeneous disc.

$$J_z = \frac{1}{2}MR^2 \tag{7.16}$$

7.2.2 Drive train inertia

Torque needs to be applied to overcome the inertia of the platform, but also to accelerate all components of the drive train (e.g. wheels, rotors, gears). The torque required to give components a angular acceleration, can be calculated for every component using eq.7.18. The manufacturers do not supply information on the inertia of the wheel, but by modeling the wheel as a homogenous disc, using eq.7.16, an estimation of the moment of inertia can be given. The required torque is calculated using the different radius of each wheel. Other components will include the rotor of the motor and a wheel shaft. General values [FAU] for inertia and angular acceleration are used.

$$\ddot{\phi} = \frac{\ddot{x}}{r} \tag{7.17}$$

$$T = J_z\ddot{\phi} = \frac{1}{2}Mr^2\frac{\ddot{x}}{r} \tag{7.18}$$

From tab.7.1 can be concluded that the torque required for accelerating the drive train components, is one or two orders of magnitude less than the torque required for accelerating the platform. The drive train inertia will be neglected in this phase of the design proces, and will compensated for using a general safety margin when selecting the motors.

part	radius r	mass m	I_z $[Nm^2]$	rad/sec^2	torque $[Nm]$
base					0.28
wheel	0.020 m	0.056 kg	$1{\cdot}10^{-6}$	50	$5{\cdot}10^{-5}$
	0.030 m	0.112 kg	$5.0{\cdot}10^{-5}$	33	0.0017
	0.040 m	0.280 kg	$2.3{\cdot}10^{-4}$	25	0.0055
	0.060 m	0.520 kg	$9.4{\cdot}10^{-4}$	17	0.0156
shaft	0.005 m	0.060 kg	$7.7{\cdot}10^{-7}$	50	$4{\cdot}10^{-5}$
rotor			$1{\cdot}10^{-6}$	500	$5{\cdot}10^{-4}$

Table 7.1: Specifications available omniwheels

7.2.3 Friction

The rolling friction is the force needed to overcome elastic deformation of both the wheels and the drive surface during rolling of the wheel. This force can be estimated using eq. 7.19. The dynamic rolling friction coefficient for polyurethane on concrete $\mu_r \approx 0.002$ [ENG].

$$F_{rolling} = \frac{M}{3} g \frac{\mu_r}{r} = \frac{0.07}{r} \tag{7.19}$$

7.3 Results

A Matlab .m file is written to calculate power, torque and angular velocity for the different wheel sizes available: radius between 0.02 and 0.06 m. This will provide insight in the effect of the wheelradius on the motor specifications. The results for the 0.05 [m] omniwheels are given in fig.7.3.

The acceleration and velocity vectors used in this simulation represent both maximum velocity and acceleration: $\ddot{u} = [1, 0, 1]^t$ and $\dot{u} = [1, 0, 1]^t$, resulting in the maximum required shaft output power, torque and velocity. The required power is calculated from the product of torque and angular velocity (eq.7.20).

$$P = T\dot{\phi} \tag{7.20}$$

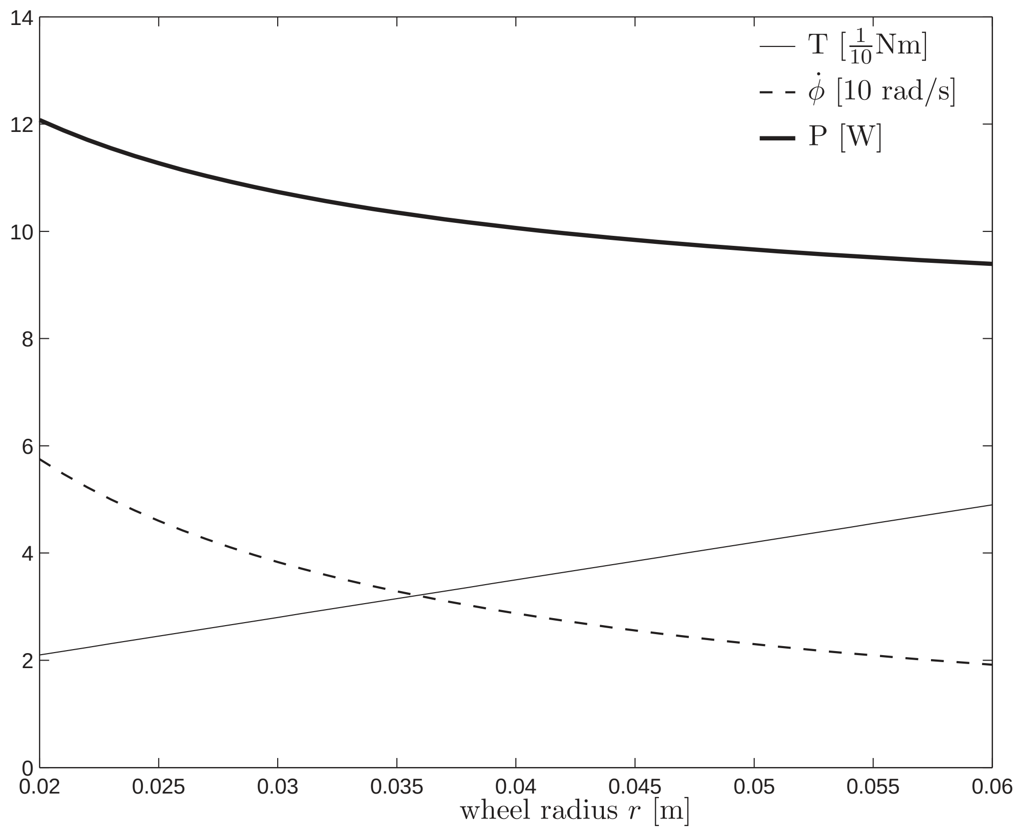

Figure 7.3: shaft output parameters

Chapter 8

Drivetrain

In this chapter, the mobile base will be designed, based on the specifications, economy of costs and ease of production.

8.1 Wheels

In figure 7.3, the torque and shaft output speed required to operate the base according the specifications are given as a function of the wheel radius. In general it can be concluded that a larger wheel requires less power due to its smaller amount of rolling friction and requires less torque to overcome a small obstacle. Drawbacks of a large wheel is its lager inertia (however neglected in the model), the larger axial distance between the two rows of rollers and their increasing price, as can be seen form fig 8.1. The performance of the largest available wheel (60 mm radius) is not increasing proportionally to its price, and is relatively expensive, making The 40 mm radius wheel the best choice for this application. The motor output requirements for this wheel is given in tab.8.1. The 40 mm radius wheels of Acroname are selected, due to their softer poly-urethane rollers, offering better traction and economy of costs. The load capacity of these wheels is 500 N (fig.8.2).

8.2 Motors and gears

Each wheels must be powered by a motor in order to achieve omnidirectional mobility. In close loop motion control (servo) applications, three common types of motors can be distinguished: The alternating current (AC), direct current (DC) and the brushless DC motor. For most robotic applications the DC motor is the preferred choice, because it is easier to control than an AC motor and is more economical compared to the expensive but highly reliable brushless motors.

The output shaft requirements for the selected 40 mm radius omniwheels are given in tab. 8.1. In order to compensate for drivetrain inertia and internal friction losses, a safetyfactor of 2 is applied on the required power.

No small electrical motor matches the required range of torque and rotational velocity. DC motors operate on a higher (typically 5.000 rpm) speed and lower torque. A gearbox can be

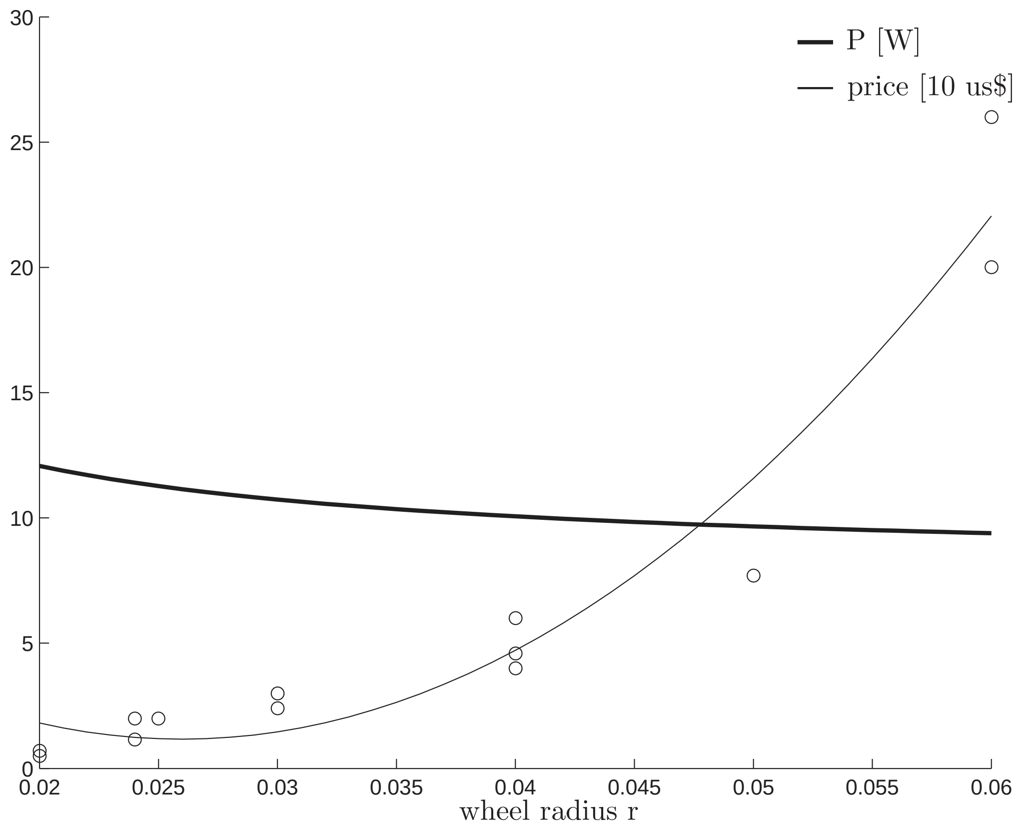

Figure 8.1: omniwheel pricing

Figure 8.2: the 40 mm radius omniwheel

Specification	wheel shaft	2642 DC motor	gearbox output
Power	9.8 watt	23 watt	18.4 watt
Torque (nominal)	0.34 Nm	0.028 Nm	0.32 Nm
Torque (stall)		0.132 Nm	1.5 Nm
Maximum rotational velocity	275 rpm	6000 rpm	428rpm

Table 8.1: Motor output specifications

used to match the motor shaft specifications to the wheel shaft specifications. For DC Micromotors, often planetary gearheads are used, providing high efficiency and relatively small size. The mechatronics and control laboratory has a long standing relationship with a local supplier for electric motors and gearboxes, offering the full range of Faulhaber motors and planetary gearheads. [FAU].

The 2642 012 CR DC micromotor is selected to power the wheels, providing the required output power of . The properties of this motor can be found in [**?**]. To mach the shaft output to the wheel parameters, the 26/1 14:1 gearbox is selected, which offers 0.78% efficiency.

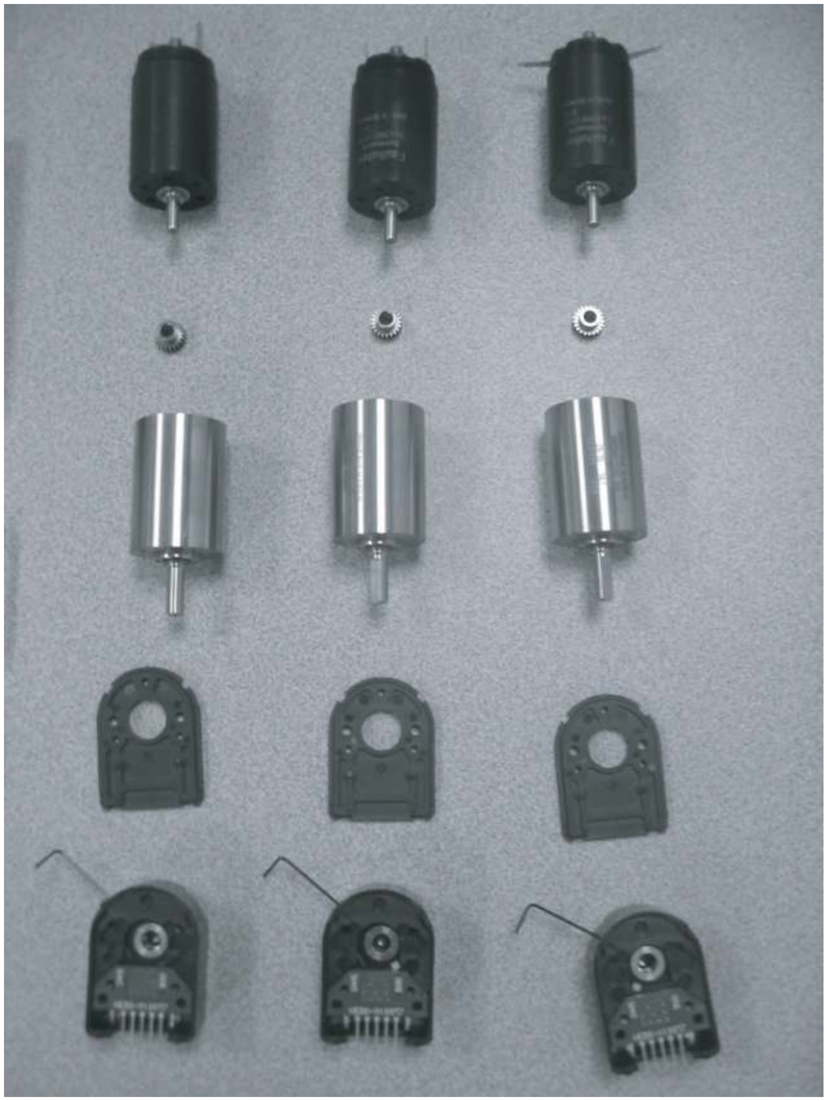

Figure 8.3: motor, gearbox and encoders

Chapter 9

Electrical design

The electrical systems consists of three main parts, all involved in the feedback control of the motors.

9.1 Amplifier

The control signal will be sent to the motor from a computing device. This device however will not be able to sent out high voltages and currents to deliver electrical power to the motor. A wide variety of motor drivers and amplifiers is available. Most of them however do not only consist of a motor driver, bud also include encoder inputs and a motion control processor. Designing a flexibele and universal mobile base, the motion control feedback loop should be closed in a central computing device, enabling the use of encoder data combined with other sensors for the use of path planning and localization. Those integrated motion control solutions are often expensive and bulky. There are however some low level circuits available for driving DC motors, such as the H-bridge.

The H-bridge consists of four electronic switches enabling forward and backward drive of he motor as well as braking, using an independent power source. A H-bridge isolates the high currents and voltage form other ic's, while it can control high currents and voltages by high frequent switching. The output of the H-bridge is controlled by a PWM-signal, that has to be generated by the computing device.

The selected motor operates at 12v DC, drawing a peak current of 2,4 A. A suitable H-bridge for this range of operation is the LM18200 3A H-bridge. the LM18200 features three inputs, determining the bridge output. When controlling the bridge using sign/magnitude pulse width modulation (PWM) control, DIR input controls direction, PWM controls duty-cycle and BRAKE controls braking. These signals need to be supplied by any I/O-device that can provide PWM signals, 3 channels per device. Generally good results are achieved using PWM frequencies between 1Khz and 10Khz, but responses are heavily dependent on motor characteristics and the load, and should thus be determined experimentally.

Due to the large currents drawn by the motors, the bridges can overheat. To prevent this, a thermal flag output is present on each bridge. The thermal flag (TF) output (pin 9) is an open collector transistor, permitting a wired OR connection of thermal warning flag outputs

Specification	value
supply voltage	12-60 V
Continous output current	3 A
Peak output current (200μs)	6 A
power dissipation	3 W

Table 9.1: H-bridge specifications

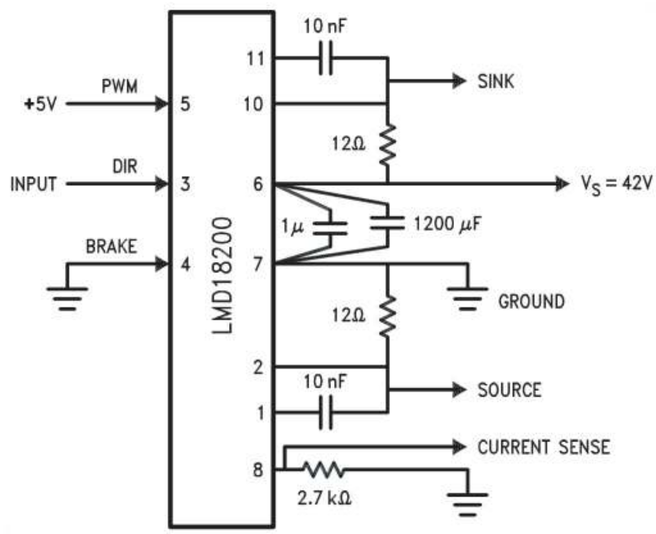

Figure 9.1: H-bridge configuration

from multiple LMD18200s. This is achieved by connecting all thermal flag outputs to a pull up resistor which is connected to the +5V power supply. If the TF-output of one or more of the three bridges drops to low, all outputs are connected to ground and the I/O card reads a low voltage. If all TF-outupts are stay high, all outputs get charged to +5 V level. The H-bridge configured as in fig. 9.1, can operate at switching frequencies up to 500 kHz and is available in a TO-220 power package, for simple mounting on a testboard. .

9.2 Sensing

The performance of a drive or servo system depends on the accuracy and reliability of all components, but especially the sensors. Encoders are the most common type of rotary position sensors. They provide information on the actual position of the shafts, allowing for compensation using a PID- control feedback algorithm. The Faulhaber company manufactures encoders that match the selected motors. The encoders are mounted directly on to the shaft, reducing the influence of resonance frequencies induced by backlash and reduced stiffness of the drivetrain. For the 2642 CR series motor the HEDS5500A, with 500 lines/rev is selected. This optical encoder offers good resolution combined with a small housing and power consumption. This encoder can operate up to 100 Khz, or a rotational speed of 12.000 rpm. The two output channels per encoder shifted phase by 90°, so direction of motion can be detected (fig.9.3).

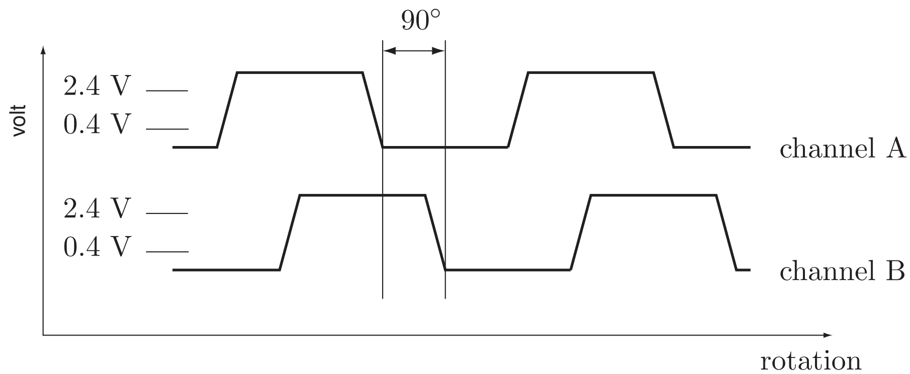

Figure 9.2: phase shift of both encoder channels

9.2.1 Signal processing

In order to read the signal from the encoders properly, a high sampling frequency is required. The Nyquist-shannon theorem states that the sampling frequency must be greater than twice the bandwidth of the input signal in order to be able to reconstruct the signal. The frequency of the encoder signal will be between 0 and 50 KHz (6000(rpm)/60(sec/min)×500(pulses)). If B is the bandwidth and F_s is the sampling rate, then the theorem can be stated mathematically as:

$$2B < F_s \tag{9.1}$$

Eq. 9.1 shows that the six encoder channels have to be sampled at at least 100 Khz each. This is will require a reasonable amount af calculating power and slow down other processes in central signal processor.

9.2.2 Quadrature decoder

To solve this problem, a quadrature decoder circuit can be applied such as the HCTL2016 encoder counter [HCT]. This CMOS IC is designed to improve system performance in digital closed loop motion control systems and digital data input systems. It does this by shifting time intensive quadrature decoder functions to a cost effective hardware solution. The quadrature decoder decodes the incoming filtered signals at a clock frequency of 14 Mhz into 16-bit count information, wich can be read at any desired frequency by any digital I/O device, using 12 channels. This circuitry also multiplies the resolution of the input signals by a factor of four (4X decoding) when using an encoder for motion sensing, increasing the resolution and providing better system control [LEG]. The major drawback is that for 3 encoders 36 I/O channels need to be available. This can be insignificantly reduced to 15 by connecting the three encoder counters IC's parallel and read them subsequently.

9.2.3 Clock

the HCTL2016 counters are used together with an LM555 timer used to generate clock pulses to run the encoder counter. A 5V power supply is required for both the LM555 Timer and the HCTL2016. The OUTPUT (Pin3) of the LM555 is connected to the CLK (Pin2) of the three HCTL2016 IC's.

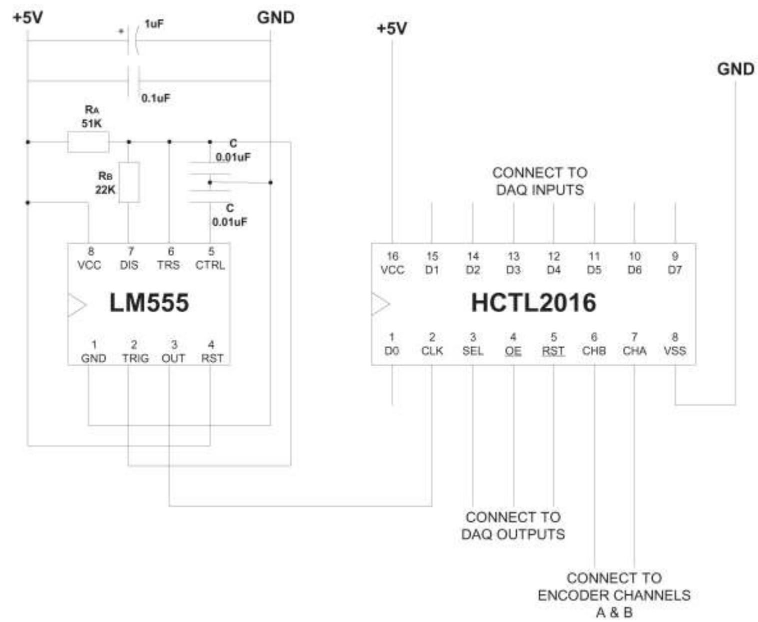

Figure 9.3: implementation of the HCTL2016 counter and the LM555 timer

9.3 Signal processor

The motion control feedback relies on sensors, actuators and a computing device. For the mobile robotic base one central computing device is selected, providing integrated motion control feedback, path-planning and localization algorithms. There are three basic computing devices available.

9.3.1 Microcontroller

A microcontroller is a type of microprocessor emphasizing self-sufficiency and cost-effectiveness, in contrast to a general-purpose microprocessor. A typical microcontroller contains all the memory and I/O interfaces needed, whereas a general purpose microprocessor requires additional chips to provide these necessary functions. Microcontrollers trade away speed and flexibility to gain ease of equipment design and low cost. For the mobile base a microcontroller will not support the flexible system architecture.

9.3.2 Digital Signal Processor(DSP)

The DSP is a microcontroller designed specifically for high speed digital signal processing, generally in real-time. DSP's use low level programming and require very specific instructions. They offers low cost, high speed digital signal processing, but it is not suitable for a research robot due to the highly specified software required to run this processor efficiently. Implementing new localization or motion control algorithms will be a time consuming task using a DPS.

9.3.3 Microprocessor

general microprocessors are the most flexible and versatile processors available. This makes them more expensive than the DSP or microcontroller. They can be programmed using higher level programming languages, such as C++, providing good accessability and ease of programming. A number of ”of the shelf” solutions is available, integrating the microprocessor, memory and I/O functionality on a single board. A common used computer for embedded applications is the PC/104 standard.

9.3.4 PC/104

The PC/104 is an industrial standard, combining personal computer performance with a compact form factor. PC/104 boards measures 3.6 by 3.8 inches and feature a unique self-stacking bus, eliminating the cost and bulk of backplanes and card cages and allowing for easy expansion of the computing system. The PC/104 standard includes low power consumption, high flexibility, easy programming and small system volume, making it an ideal solution for the universal mobile base. The PM-1041 main board features the Intel 486DX2 66MHz processor, memory a VGA video interface and two RS323 serial ports. This card is available at the mechatronics and control laboratory and will serve as the computer of the mobile base. The PM-1041 requires a +5v power supply and draws 1.4 A maximum. Additional cards such as data aquisition, video signal processing or other applications can be purchased and stacked, providing maximum system flexibility.

9.3.5 I/O

The microprocessor needs to receive information from sensors and control the motors using the H-bridges. In order to do so an I/O (Input/Output) card must be added to the system. The encoder counter IC’s require a total of 15 Input channels and 6 output channels while the H-bridges require 9 outputs and 1 input, bringing the total to 16 input and 15 output channels. To accomodate a number of additional small sensors, the PC104-DIO48 I/O card is selected. This digital 48 channel I/O card can be stacked on de main board using the PC/104 bus. The I/O channels can be programmed as input or output in 4 blocks of eight and 4 blocks of four channels. +5V and is supplied through the PC/104 bus. .

9.3.6 DC power supply

As can seen above, all electrical devices require a power supply. Besides the already selected components, it is expected that more sensors will be installed. The +5V power supply is dimensioned with a 1 A margin, reserved for ten general small sensors which typically use a +5V power supply and draw 100 mA each. Batteries need to supply all power consumed by the mobile base. The +5 Volt will be converted from a higher voltage, so only one battery can be used. Providing one light and small power source for the platform.
The +5V can be converted from higher voltages using a step-down regulator an a number of

Component	V	I	qty	total
PM1041 PC/104	+5V	1,4 A	1	1,4 A
PC104-DIO48	+5V	0,2 A	1	0,2 A
LM555 timer	+5V	leq10mA	1	0,01
HCTL2014 counter	+5V	leq10mA	3	0,03
HEDS5500A encoder	+5V	17mA	3	0,05
add-on sensors	+5V	0,1A	10	1 A
total +5 volt supply				2.7 A
2641 012 CR DC motor	+12 V	2,3 A	3	6,9 A
LMD18200 H-bridge	+12-55 V	0,3 A @ 12V	3	0,9 A
total +12 volt supply				7,8 A

Table 9.2: power consumption

standard components. The LM2576 simple 3A buck regulator will supply an output voltage of 5 volts to a maximum current of 3 A. When supplied with 12 Volts, it will draw 1,5 A due to some internal losses. As can be seen from tab. 9.2, the battery needs to supply 12 Volts, with a maximum current of 7,8+1,5=9,3 A, including the +5V circuitry.

9.4 Battery

A battery must be found that is light weight and can supply high current in a short time. 8,4 A will be the peak current, drawn from te battery. The estimated average power consumption is 50% of the maximum. In order to operate for half an hour the battery must have a capacity of at least 2200 mAH ($0,5Hrs \times 50\% \times 8,4A$). Most important is that the battery can deliver high currents at any given moment. This capability is generally know als the discharge rate, or C-factor (eq. 9.2). Batteries discharged close to their maximum C-rating will heat up and not be able to deliver their full electric charge. In tab. 9.3 the different available battery types are stated, their C-rate and the needed cappacity to deliver the maximum current I_{peak}, discharged using their maximum C-rate. An indication of the power density and costs is also given [HAR]. Based on this tabel the Li-Poly battery technology is selected, due its very low weight and high C-rate, compensating for it's somewhat higher costs. In order to supply power to the base at least 2200 μAH needs to be installed, so the battery will be discharged at a 4C-rate when the peak current is demanded by the motors, improving the overall performance of the battery. The Polyquest PQ-B2600-HG 4S four-cell 2600μAH (14.8 V) Li-poly pack is selected as powersource for the mobile base, this pack can deliver up to 20 A continuously and weights 220 grams. The motors, amplifiers and step-down voltage regulator are all able to handle 14.8 V.

$$I_{peak} = C \times Capacity \tag{9.2}$$

9.5 Scheme

All components have to be connected. Using the documentation of the components the electrical scheme is designed (fig.9.4). A breadboard can be used to assemble all components.

Battery type	C-rating	capacity	energy density	costs
Sealed lead acid (SLA)	1 C	8400	very low	x
NiCd	2 C	4200	low	2x
NiMh	3 C	2800	moderate	2,5x
Li-Ion	1	8400	high	4x
Li-Poly	10 C	840	very high	5x

Table 9.3: battery specifications

It is recommended that two breadboards are used, separating the high current from the low current components. All components are connected using their pin-layout as found in their documentation [HCT], [LM5], [LM2], [LMD]. Please not that the PC104 I/O card must be connected using the PC104 bus to the main board. It will receive power and ground through this bus, if the PC104 main board is supplied with +5V and ground.

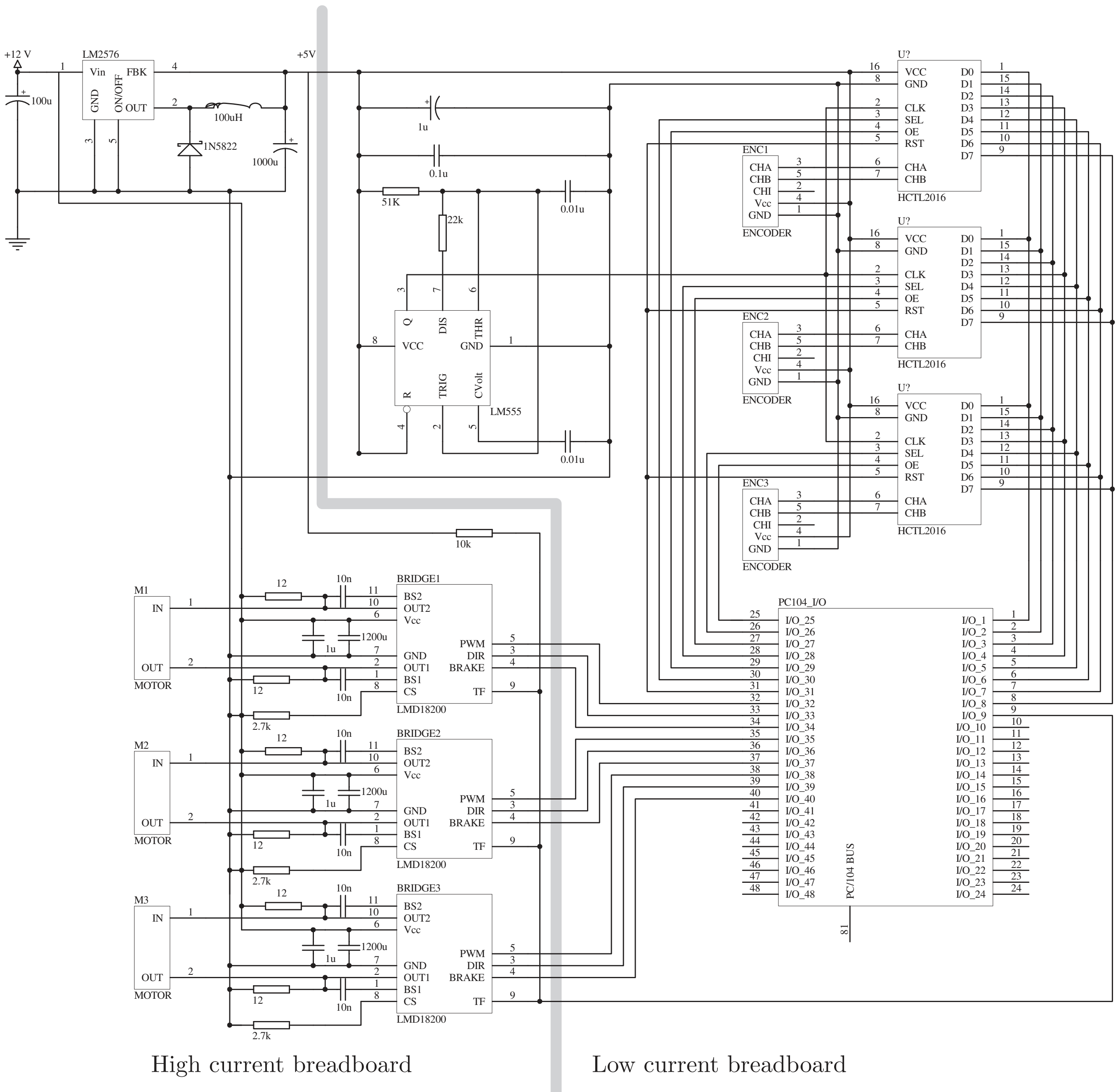

Figure 9.4: The electrical scheme for the omnidirectional base

Chapter 10

Frame design

All components are known and specified, so the frame can be designed. First of all, the total weight of all components is calculated and summarized in tab. 10.1. This shows that to keep the total base weight under 5 kg, the frame can weight no more than 2.8 kg, including all fasteners, bearings etc. The mobile base layout is designed on system level, three omniwheels need to be positioned at 120°. In order to keep te weight of te base as low as possible a sheet metal construction is preferred. A sheet metal construction, if well designed, will offer high stiffness while the weight can be kept relatively low [ROS]. Sheet metal is also easy to machine, especially using sheet aluminium. Aluminum will not only further enhance the lightweight properties of the base, but will also be insensitive to corrosion.

Component	qty	Dimension	total weight
Wheels	3	ø80 × 64 mm	0,84 kg
Motors	3	ø26 × 42 mm	0,34 kg
Gearheads	3	ø26 × 36,4 mm	0,35 kg
Encoders	3	ø30 × 18,3 mm	0,07 kg
PC/104 main board	1	ø26 × 36,4 mm	0,20 kg
PC/104 I/O board	1	ø26 × 36,4 mm	0,08 kg
Battery	1	96×62×22 mm	0,22 kg
Breadboards and electronics	-	-	0,1 kg
total			2,2 kg

Table 10.1: component mass and dimensions

10.1 Base layout

The three motor assemblies, each connected to their motor support plates, must be positioned at 120° relative to each other. The motor, gearbox and encoder assemblies will measure a combined length of 96.7 mm and should be positioned as close to the center of the base as possible to minimize the moment of inertia of the base and reduce overall dimensions. To hold the wheel units (wheel, shaft, bearing, motor, gearbox and encoder) in place relatieve to each other, can be achieved by installing them in on horizontal plate.

A thin plate will offer excellent stiffness in its plane. It does however offer almost no resistance to forces applied perpendicular to it, like the weight of all components and payload, easily bending the plate. The bending stiffness of a plate is given by eq.10.1. The bending moment of inertia I for rectangular cross sections can be obtained from eq.10.2, with h representing the thickness of the plate, which generally is small for a thin plate.

$$k = \frac{3EI}{l^3} \tag{10.1}$$

$$I = \frac{bh^3}{12} \tag{10.2}$$

The bending stiffness can be dramatically increased by installing another plate at an offset distance, creating a design commonly known as a sandwich construction. The bending moment on the plate will now be divided in tension force in the bottom panel and a compression force in the upper plate. This concept requires another material or regular placed spacers between the two plates, in order to maintain the offset distance. Another commonly used technique to add stiffness to a thin plate is by increasing the bending moment of inertia I. This can be done by bending the edges of the plate 90° or by installing stiffening girders to the plate. Both concepts will be applied to enhance rigidity of the base. First the wheel shaft will be designed to derive stiffness requirements for the plate structure.

10.2 Shaft

The wheel must be connected to the secondary shaft of the gearbox, which is supported by two ball bearings in its housing. The bending moment applied on this shaft should not exceed 1,5 Nm, due to the short distance between both internal bearings [FAU]. While the contact point of the wheel and floor can be as far as 70 mm from the mounting face of the motor, transferring a load of 33 N per wheel, a bending moment of 2,5 Nm will be present on the gearbox shaft. There are two ways of reducing this bending moment.

10.2.1 Separate shafts

When the wheel is mounted on a separate shaft, suspended in its own bearings, there will be no bending moment applied to the gearbox at all. To connect the two shafts, each provided with its own two bearings, a flexible coupling must be used to compensate for any misalignment (fig. 10.1). This will require more components, involve more manufacturing processes, higher costs and results in a considerable larger base.

10.2.2 Internal degree of freedom

The second concept involves elongating the secondary gear shaft, by rigidly mounting the wheel shaft to the gearbox and the placement of a support bearing on the other side of the wheel. Three bearings on one shaft result in a over-determined design, introducing a bending moment itself when the bearings are not properly aligned and the shaft is designed to stiff. By constructing the shaft less stiff than the bearing support, introducing a internal degree of freedom, this will provide a simple design solution. To assure no large moments will be applied on the shaft due to misalignment of parts, a short analysis of applied moments and required tolerances will be carried out.

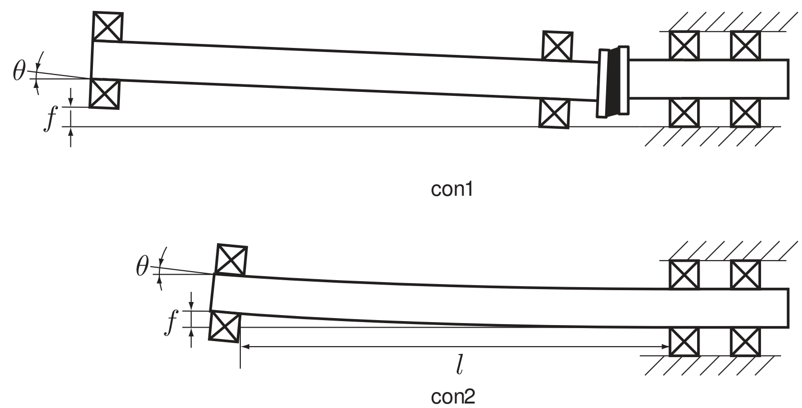

Figure 10.1: two design concepts for the shaft bearings

10.2.3 Shaft analysis

The wheel shaft can be modeled as a simple cantilever beam. All parts will be machined on numerical controlled (NC) machines, yielding a product accuracy of at least 0.05 mm. The maximum misalignment of two parts can therefore never exceed 0.1 mm, and will be considerably less if mounted properly. If the end of the wheel shaft is displaced w by 0.1 mm due to misalignment or bending of the supporting frame, the bending moment M applied on the clamped side of the cantilever can be calculated using eq.10.3 The moment of inertia of a rod can be calculated using eq. 10.4. The young's modulus of aluminum equals $70 \cdot 10^9\ Pa$, the shaft outer diameter will be the same als de wheel hub inner diameter, 8.4 mm.

$$M = w\frac{3EI_{rod}}{l^2} = 0.8Nm \tag{10.3}$$

$$I_{rod} = \frac{\pi d^4}{64} \tag{10.4}$$

This shows that the resulting maximum bending moment is 0.8 Nm, which is well acceptable and will be significantly lower by using the proper mounting procedure (appendix A).

10.2.4 Angular misalignment

The permissible angular misalignment between inner and outer rings of deep groove ball bearings lies between 5 and 10 minutes of arc [SKF], depending on bearing size. Within the manufacturing and mounting accuracy, the angular misalignment (θ) will remain under 4 minutes of arc, making the installation of self-aligning bearings unnecessary. The bearing inner diameter itself must be smaller then 8.4 mm allowing the bearing slide fit through the wheel hub.

10.2.5 Bearing

The bearing itself must be able to slide over the tread at the end of the shaft, while this thread must be kept as large as possible, enabling a high clamping force. The wheel will be press-fitted onto the shaft, since no keyed or spline connection is present in the wheel hub.

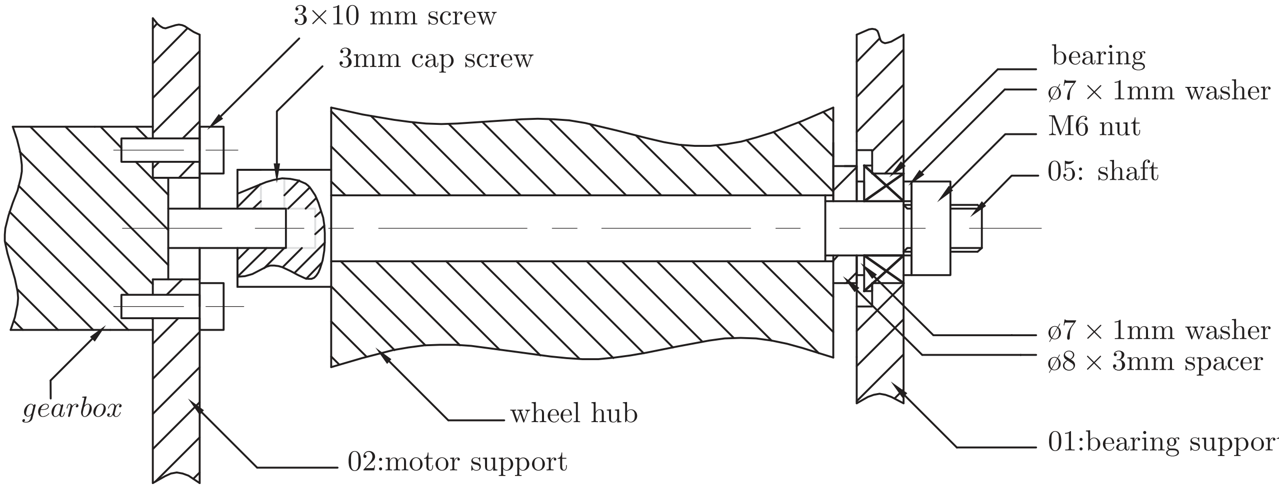

Figure 10.2: shaft assembly

In addition to the radial press fit, the wheel will be axial clamped to a stop collar, integrated in the shaft. This press force will be applied by a nut which not only fastens the wheel but also fix the entire shaft assembly to the moving part of the bearing. A 7 mm deep groove ball bearing is selected from stock, fulfilling all criteria. The shaft will be mounted to the gearbox using a M3 cap screw. The assembly is shown in fig. 10.2.

10.3 Plate structure

The only means to mount the motor assembly on any frame are provided by four threaded holes in the gearbox. A vertical aluminum plate will provide the motor support. The wheel will be press fitted onto a shaft, which extends from the gearbox secondary shaft through the wheel hub to the support bearing on the opposite side of the wheel. This bearing will also supported by a vertical aluminium plate. Both vertical plates will act stiffening girders once mounted on the baseplate and increase the base stiffness. It is important that the stiffness of the bearing support is high enough to prevent the shaft from applying a bending moment on the gearbox bearings. In order to prevent this, the displacement should not exceed 0.1 mm.

10.3.1 Base plate

A 2 mm aluminum plate is selected for the base plate. This one-piece base plate provides a geometric reference for all other components and is forming one side of the sandwich construction. All holes will be machined using a numerical controlled milling machine, providing accurate mounting holes for all other components.

10.3.2 Top plates

In order to maintain acces to all components, the top plate is divided into three identical sections. The top plates are bend over 90°, improving their stiffness and forming protective

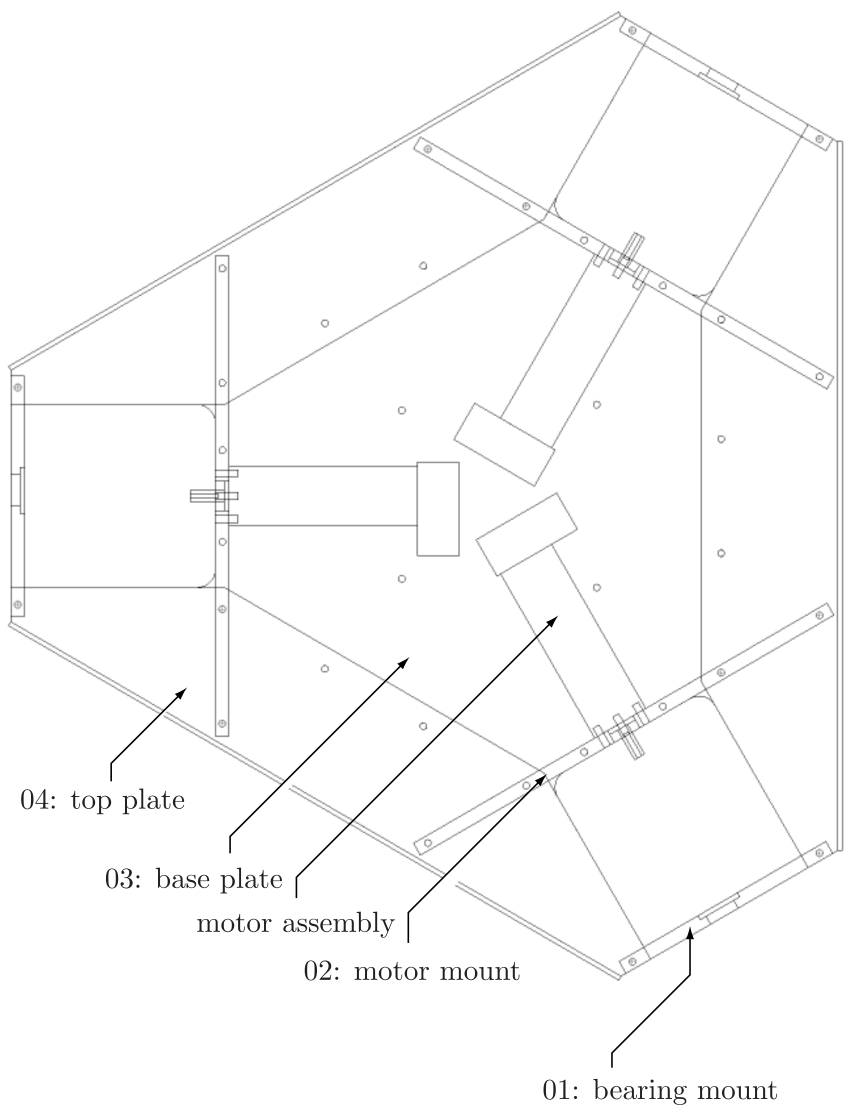

Figure 10.3: top view of the omnidirectional base

side panels. The top plates are manufactured out of 2 mm aluminum plates and can easily be demounted to add sensors or payload brackets.

10.3.3 Motor mounts

The motors are mounted in 6 mm aluminum plates, placed between the top and bottom plates. They provide a solid frame for mounting the motors and act as spacers and stiffening girders for the sandwich construction. The motor mounts require a thickness of at least 6 mm in order to use through-hole mounting of the base and top plates. The motor mount holes also provide a interface for mounting payload. The load will be located close to the wheels, reducing deformation of te base.

10.3.4 Bearing mounts

The ball bearings supporting the outer ends of the wheel shafts will be mounted in a 6 mm aluminum plate, similar to the motor mounts. The bearings will be press fitted in a precision milled central hole.

10.4 Frame analysis

It is important that the stiffness of the bearing support is high enough to prevent the shaft from applying a bending moment on the gearbox bearings. The maximum allowable bending moment requires the deflection of the bearing mount to be less than 0.1 mm. When one third of the base weight (10 kg) is supported by each wheel, a load of 33 N is applied, requiring a bending stiffness of arms supporting the bearing mount of at least 0.3×10^6 N/m.

10.4.1 stiffness

The top plate and base plate, transferring the weight of the base to the bearing supports, can be modeled as a simple cantilever beam, fixed at one side. By using eq.10.3, the bending stiffness of the sandwich construction is calculated. The bending moment of inertia I for a rectangular beam is given by eq.10.2 and equals 5.8×10^{-8} m^4 for the sandwich construction, at the outer most section where te smallest bending moment is applied. The free bending length l of the structure results in a bending stiffness of at least 5.7 kN/mm, satisfying the stiffness requirements of the frame.

10.4.2 weight

All parts are summarized in tab.10.4.2. The total weight of all parts equals 1.4 kg, bringing the total assembled weight of the base at 3.6 kg. Please note that some components, such as bolts, nuts and wiring is not taken into account in the weight calculation. Production drawings of all components can be found in C. All components are ordered and manufactured at the faculty of engineering workshop.

Part number	name	qty	weight
01	bearing mount	3	0.066 kg
02	motor mount	3	0.136 kg
03	base plate	1	0.310 kg
04	top plate	3	0.140 kg
05	shaft	3	0.020 kg
	total		1.4 kg

Table 10.2: part summary

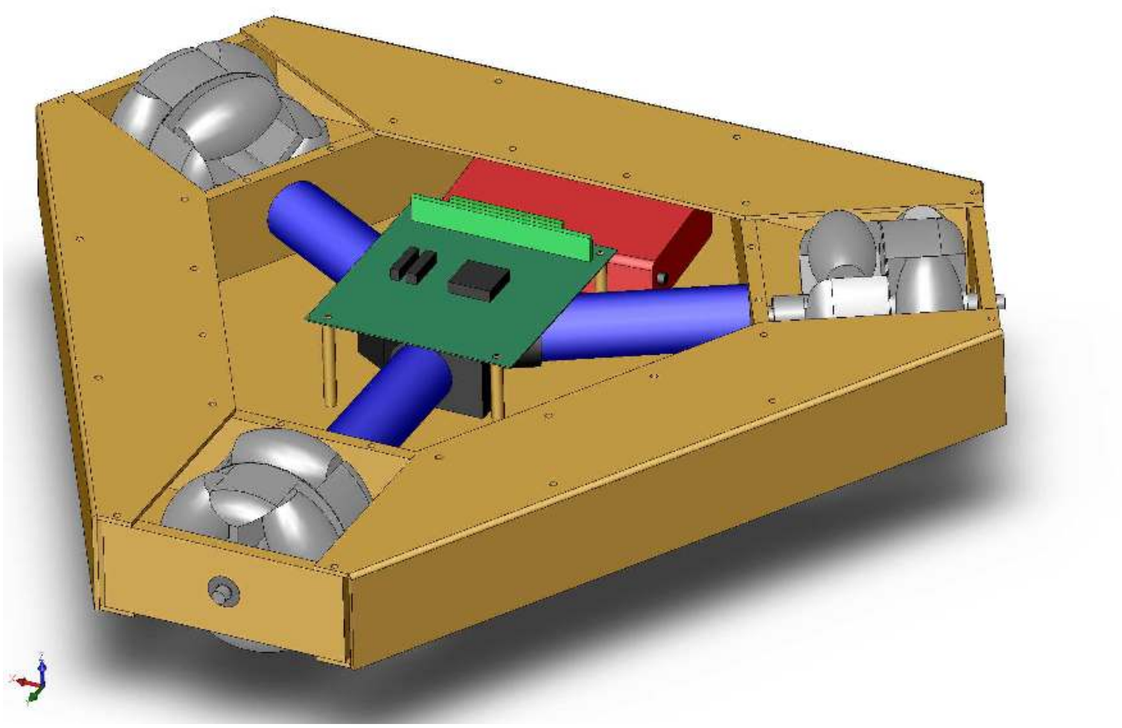

Figure 10.4: 3D CAD drawing of the assembled omnidirectional base

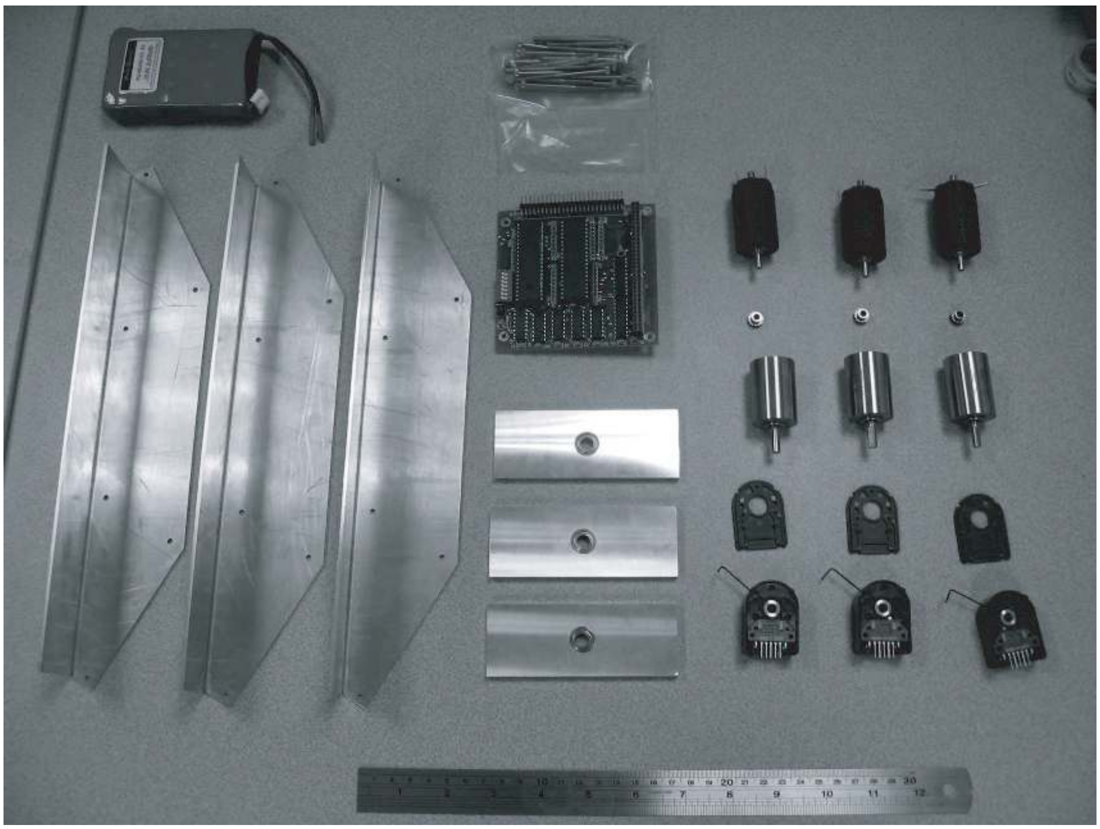

Figure 10.5: components of the omnidirectional base, ready for assembly

Chapter 11

conclusions and recommendations

11.1 conclusions

An omnidirection universal mobile platform has been designed, for testing newly developed autonomous navigation and localization algorithms. First, the specifications are derived for operating in a human-scale environment. Different concepts for achieving omnidirection mobility are evaluated and a omniwheel powered vehicle concept is selected as the most suitable system architecture for a low weight flexible platform. A kinematic and dynamic model are used to translate the system requirements to component specifications. The drivetrain, electrical system and robot frame are designed. All required components are ordered and manufactured. Due to delayed deliveries the mobile base could not be assembled before the end of this project.

11.2 recommendations

Future work on the omnidirectional base includes the assembly of all mechanical and electrical components. After all hardware and electronics are assembled, control software can be programmed. It is recommended to attract a embedded software engineer to program the basic control software to control the amplifiers and read out the position encoders, to enable autonomous mobility of the base. After testing the motion capabilities of the base navigation and localization software can be implemented on the omnidirectional universal mobile base.

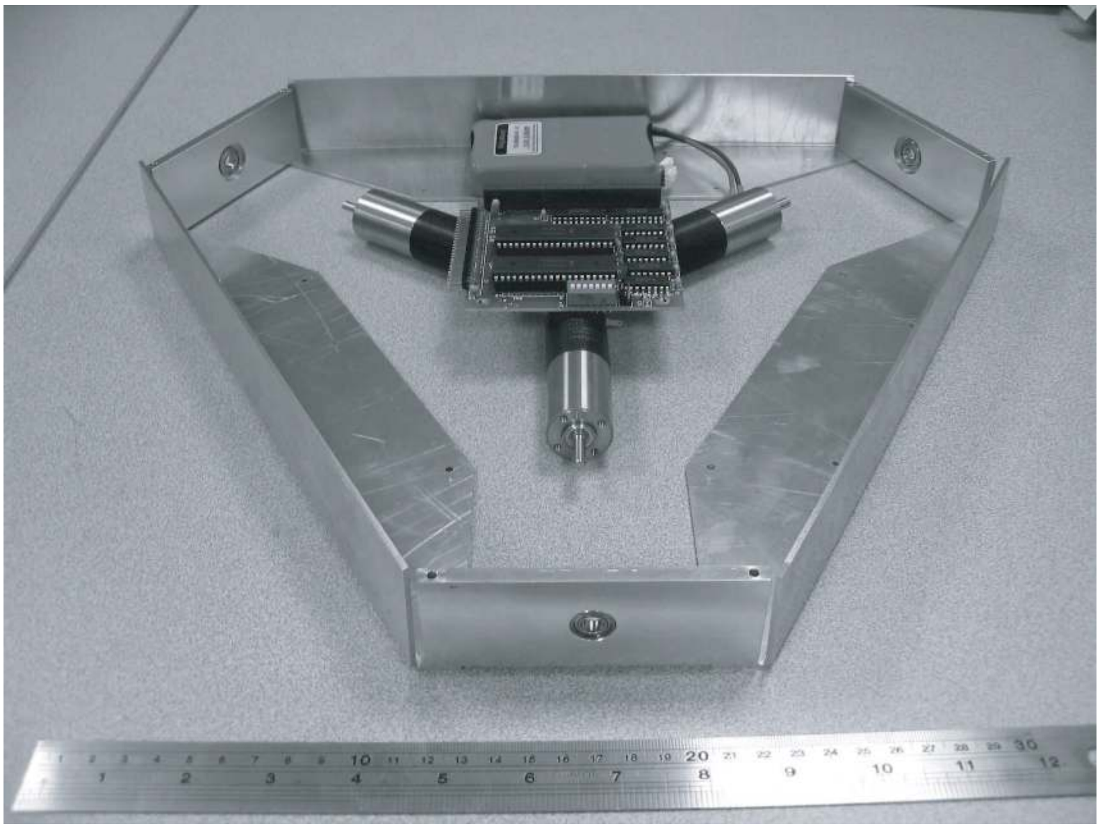

Figure 11.1: components of the omnidirectional base in final configuration (top plates positioned upside-down)

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[FAU] www.faulhaber.com

[WIK] www.wikepedia.nl, online encyclopedia

Appendix A

Assembly instructions

At the time of writing not all parts have arrived at the mechatronics and control lab or are manufactured. This is a short guide to assemble the mechanical components of the base.

A.1 Wheels

The wheels have not yet arrived. The shafts can not be manufactured until the exact dimension of the hub are known, due to the press-fit that has to be machined. When the wheels arrive, contact mr. Zhang (EA-04-5A) of the mechatronics and engineering lab and he will make sure the wheels arrive the manufacturing Lab. Once the shafts are manufactured, assemble the wheel and shaft to the bearing and bearingplate according to fig.A.1.

1. press the wheel on to its shaft, make sure the face of the wheelhub is pressed against the stop collar.
2. Add 3 mm of spacers (3 M8 washers of 1 mm thick) which can slide freely over the shaft
3. Add a ø7mm washer which fits the inner bearing shell
4. Slide the shaft through the bearing, which is pressed in the bearing mounting.
5. Apply another ø7mm washer
6. Fix the assembly with a m6 nut. Remember that the shaft is machined out of relatively soft aluminum when tightening the nut. This way the wheel is not only radial pressed onto the shaft, but an additional axial force is applied. Allowing for more torque to be transferred.

A.2 Base

Mounting all components to the baseplate is relatively easy.

1. Mount each gearbox onto the motor support plates, using four m3x10mm screws. make sure the heads are not higher than 3mm, to prevent them from touching the motor shaft.

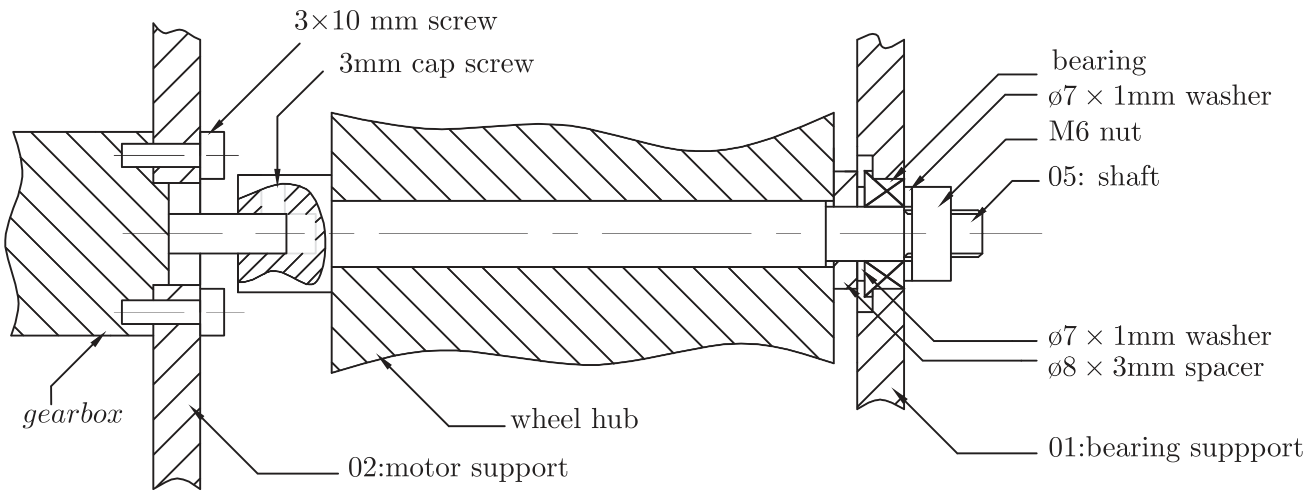


Figure A.1: shaft assembly

2. Use the supplied m3x50 hexagonal cap screws to mount the motor supports to the base, using the two holes holes nearest to the motor (fig.A.2 A). Make sure the mount is exactly flush and parallel with the front side of the wheel bay
3. Once all three motor supports are mounted, the top plates can be added and all other m3x50 cap screws can be inserted and fastened
4. Slide each wheel assembly into position, with the wheel shaft sliding over the motor shaft, aligning the flat section of the motor shaft with the cap screw in the wheel shaft.
5. Place the 3x50 mm hexagonal cap screws through the top plates, the bearing plate and the base plate(fig.A.2 B) . Do not fasten them fully yet
6. Fasten the capscrew in the wheelshaft, fixing the wheelshaft to the motor
7. Let the motor spin slowly, in order to align both shafts. By doing this the bearing mount will align with the gearbox.
8. Fasten the hexagonal head screws holding the bearing mount

A.3 Electronics

solder all components to a breadboard, according to the electrical scheme. Use two separate boards, one for the high current components and one for the 5V circuitry. Fasten the PC/104 stack above the motors, using isolated IC mounting pins. The breadboards can be fastened to the base using the additional holes in the base and top plates. Wire the motors and encoders to the amplifiers and I/O card, according the electrical scheme. Install the battery.

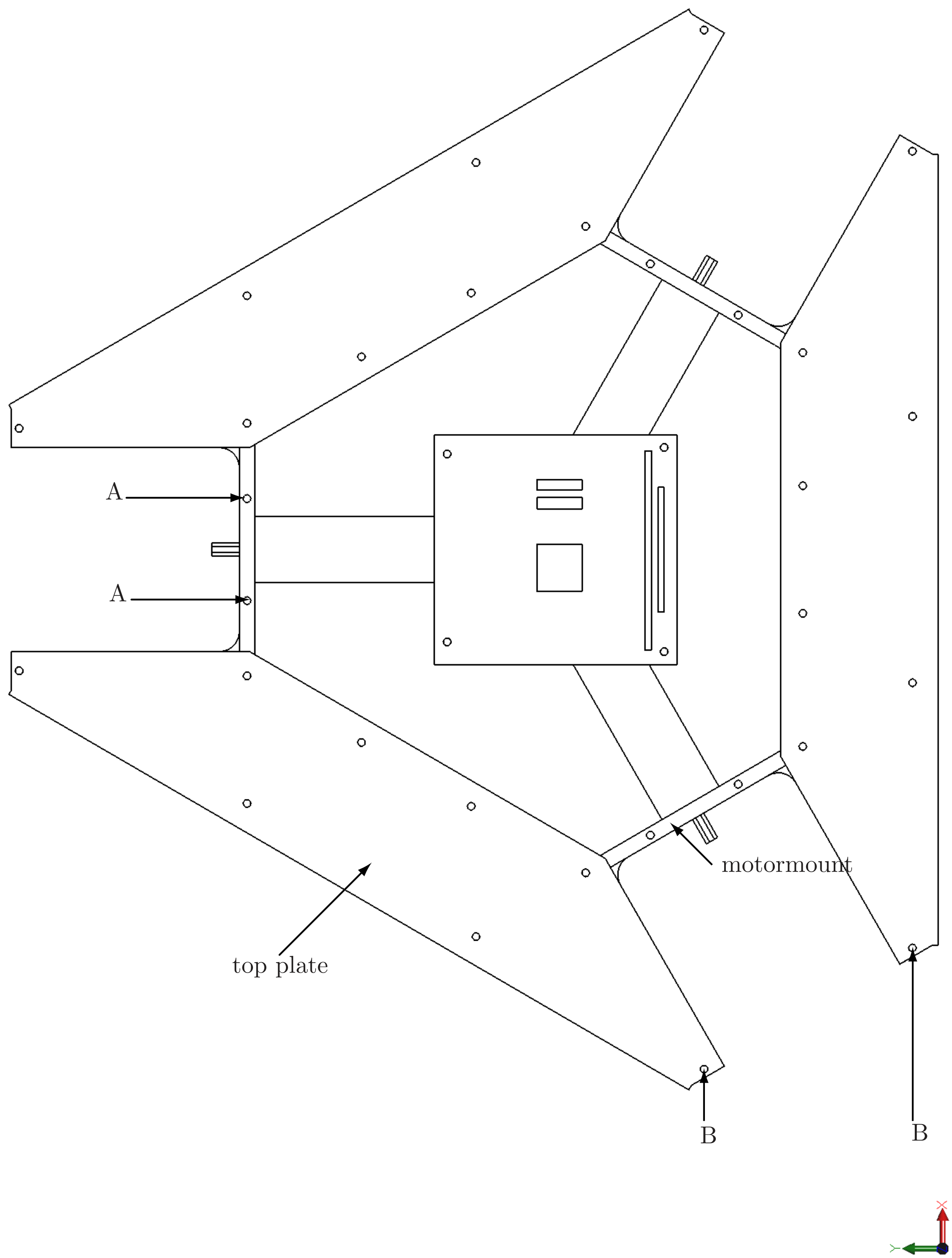


Figure A.2: assembly overview

Appendix B

Omnibase components

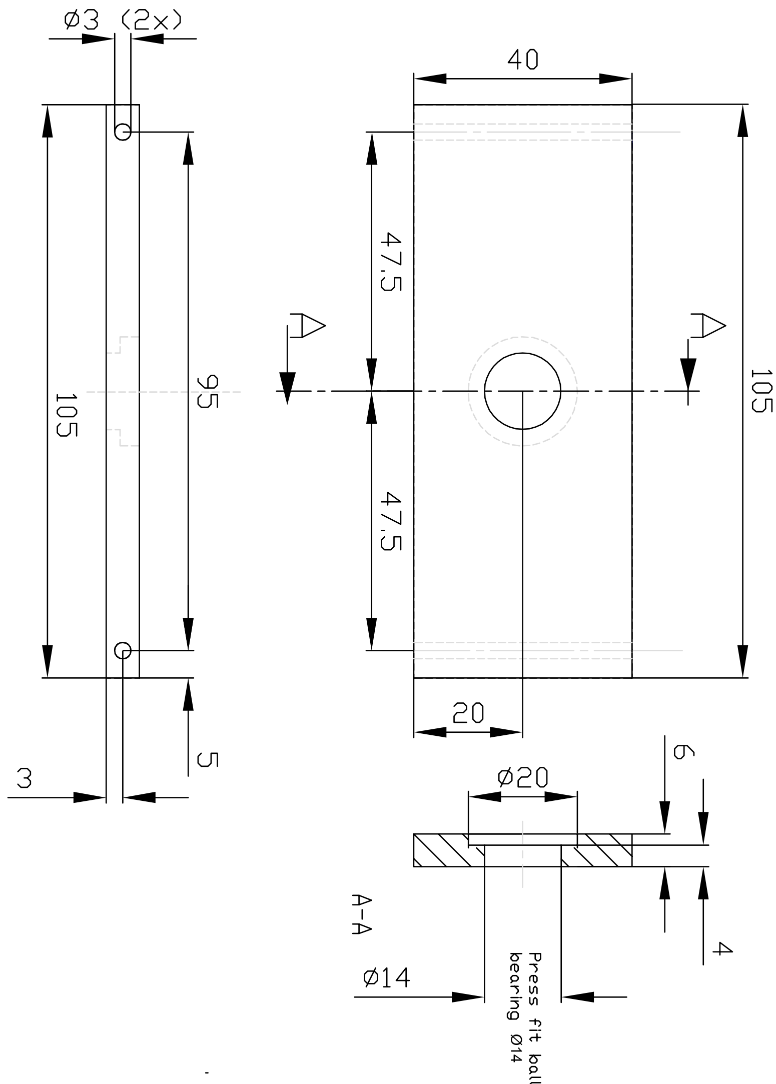
vendor	product	qty	comment
Drive			
Faulhaber	DC-Micromotor 2642 012 CR	3	DC brush motor 12V
Faulhaber	Gearhead 26/1 S (14:1)	3	All steel, ratio 14:1
Faulhaber	Encoder HEDM 5500 B	3	Optical 1000 lines
Electrical			
measurement computing.com	PC104/DIO48	1	I/O card
-	LM2576	1	3A voltage regulator
-	LM555	1	Timer
-	HCTL2016	3	Quadrature Encoder Counter
acroname.com	LMD18200	3	3A H-bridge
-	Coil 100μH	1	High current
-	Capacitor 1200μF	3	
-	Capacitor 1000μF	1	
-	Capacitor 100μF	1	
-	Capacitor 1μF	4	
-	Capacitor 100nF	1	
-	Capacitor 10nF	8	
-	Diode 1N5822	1	
-	Resistor 51kΩ	1	
-	Resistor 22kΩ	1	
-	Resistor 10kΩ	1	
-	Resistor 2.7kΩ	3	
-	Resistor 12Ω	3	
Mechanical			
acroname.com	NARP 8cm 3-Pack	1	3 polyurethane omniwheels
Power			
robotcombat.com	ET LiPoly Charger	1	2500 mAh charger
robotcombat.com	14.8V 2600mAh battery	1	14.8V 4cell LiPoly

Appendix C

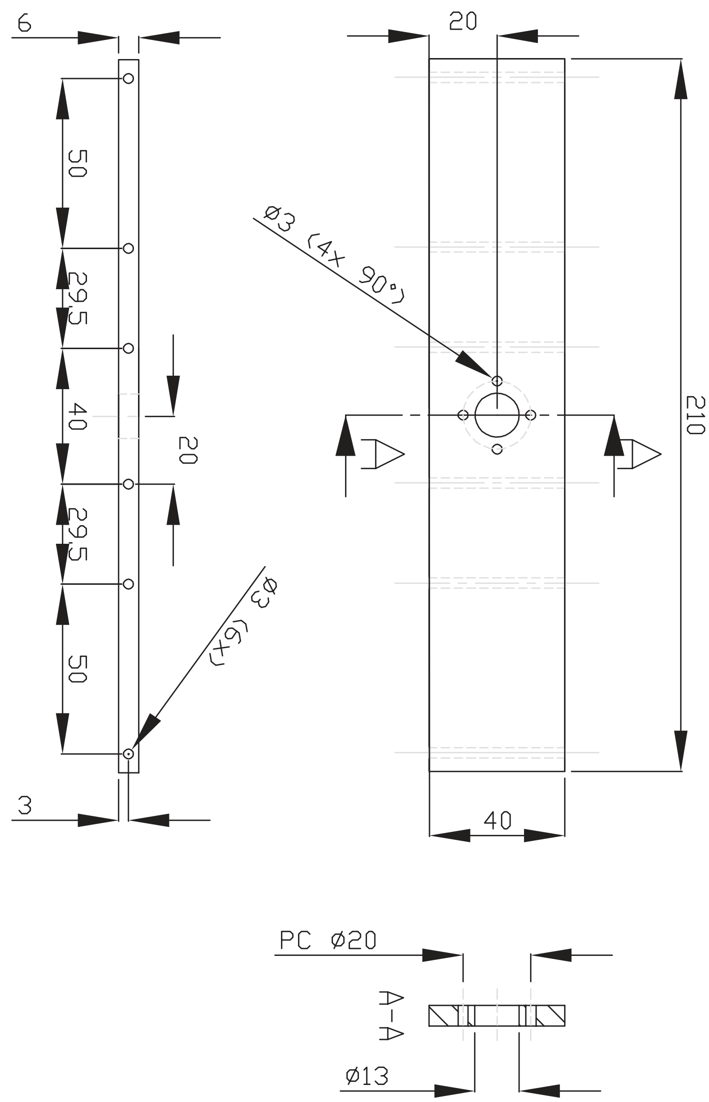
Drawings

This appendix contains all production drawings of the parts on the following pages.

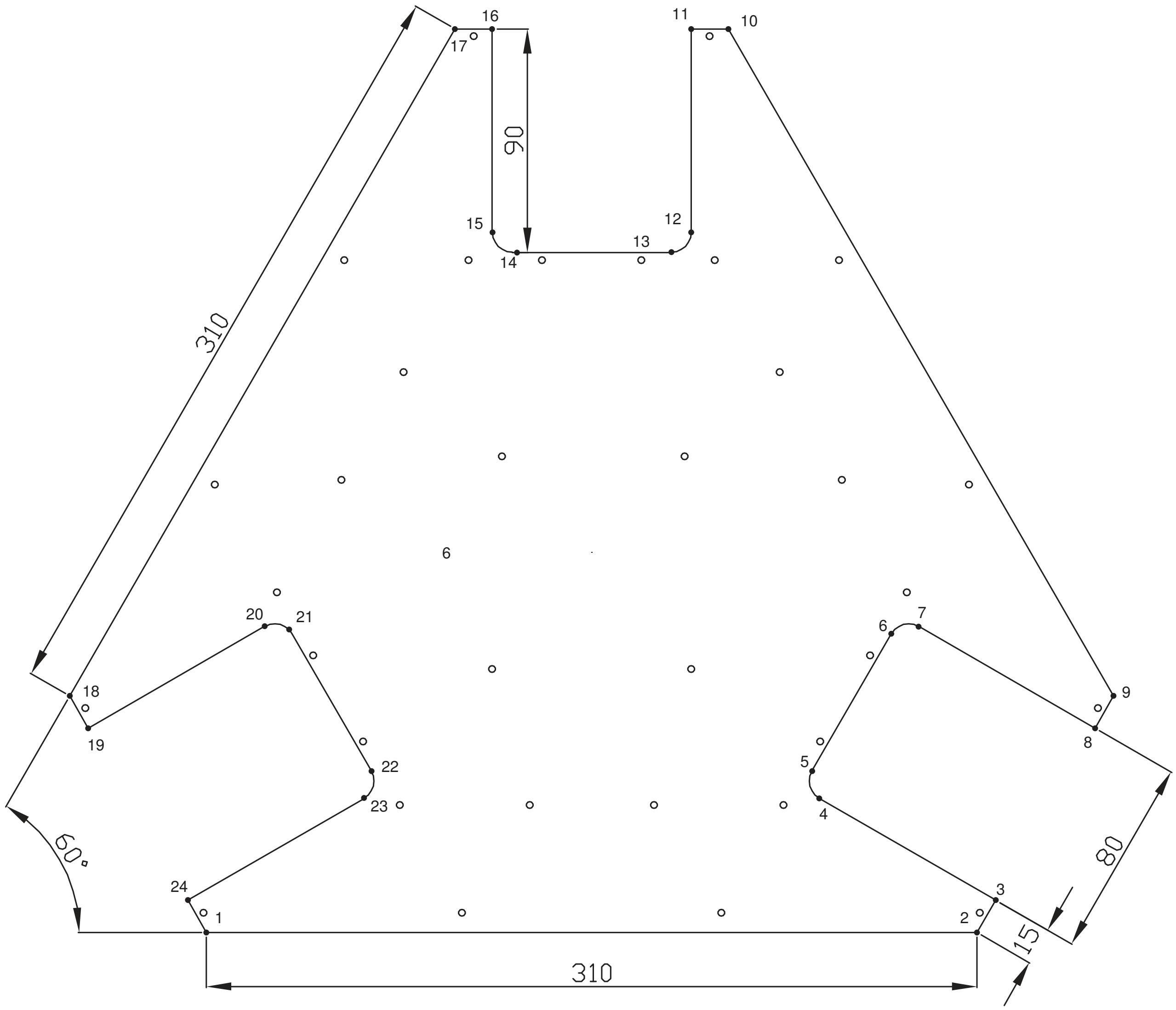
Part	01: Bearing mount
Quantity	3
Material	Aluminum
Outer dimensions	105×40×6mm
Weight	0.066 kg



Part	02: Motor mount
Quantity	3
Material	Aluminum, 6 mm
Outer dimensions	210×40×6mm
Weight	0.136 kg



Part	03: Base plate
Quantity	1
Material	Aluminum, 2 mm
Outer dimensions	420×264×2mm
Weight	0.310 kg



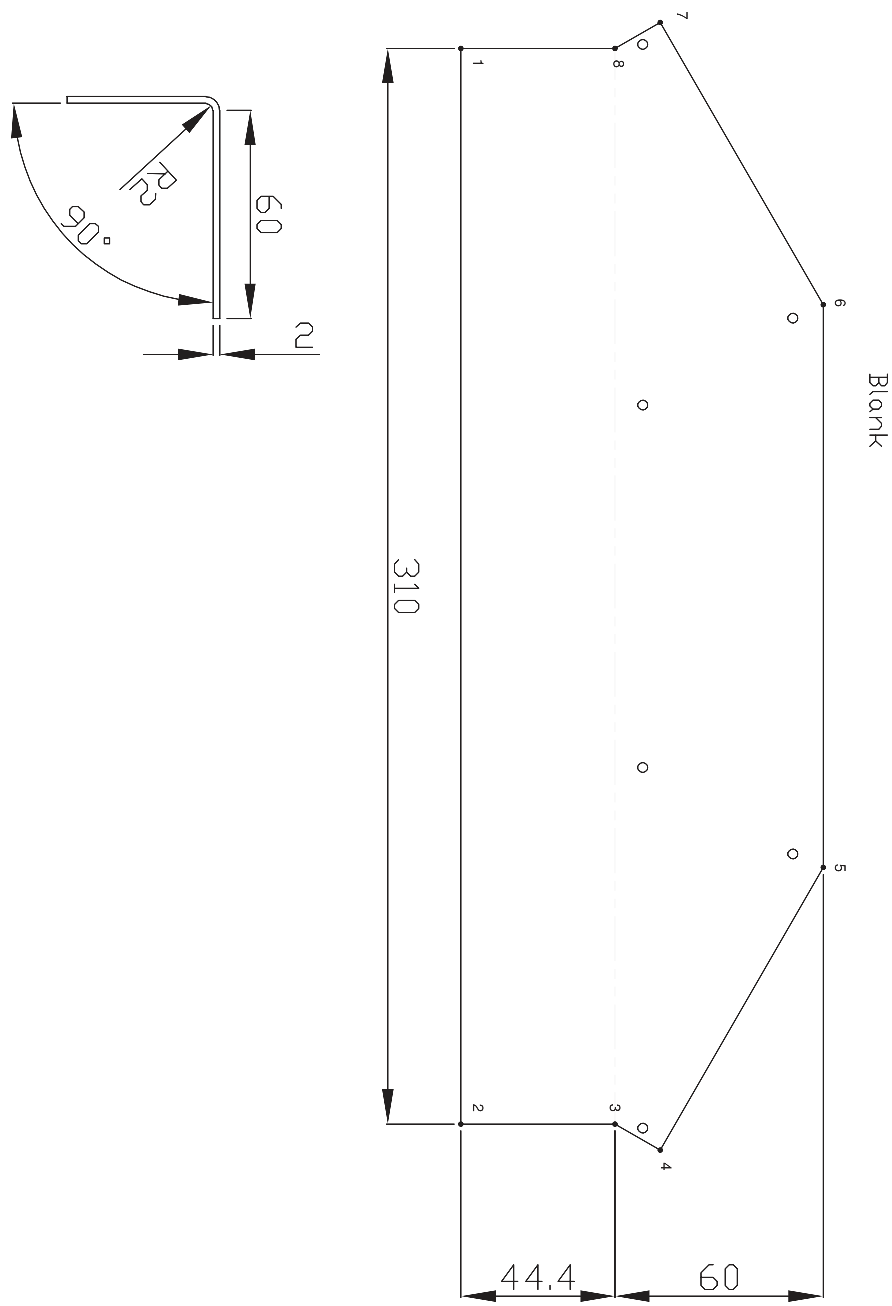
1	X= 0.00	Y= 0.00	Z= 0.00
2	X= 310.00	Y= 0.00	Z= 0.00
3	X= 317.50	Y= 12.99	Z= 0.00
4	X= 246.48	Y= 53.99	Z= 0.00
5	X= 243.56	Y= 64.92	Z= 0.00
6	X= 275.56	Y= 120.35	Z= 0.00
7	X= 286.48	Y= 123.28	Z= 0.00
8	X= 357.50	Y= 82.27	Z= 0.00
9	X= 365.00	Y= 95.26	Z= 0.00
10	X= 210.00	Y= 363.73	Z= 0.00
11	X= 195.00	Y= 363.73	Z= 0.00
12	X= 195.00	Y= 281.73	Z= 0.00
13	X= 187.00	Y= 273.73	Z= 0.00
14	X= 123.00	Y= 273.73	Z= 0.00
15	X= 115.00	Y= 281.73	Z= 0.00
16	X= 115.00	Y= 363.73	Z= 0.00
17	X= 100.00	Y= 363.73	Z= 0.00
18	X= -55.00	Y= 95.26	Z= 0.00
19	X= -47.50	Y= 82.27	Z= 0.00
20	X= 23.52	Y= 123.28	Z= 0.00
21	X= 34.44	Y= 120.35	Z= 0.00
22	X= 66.44	Y= 64.92	Z= 0.00
23	X= 63.52	Y= 53.99	Z= 0.00
24	X= -7.50	Y= 12.99	Z= 0.00

Table C.1: Base plate contour coordinate listing

X= -1.15	Y= 8.00	Z= 0.00
X= 102.79	Y= 8.00	Z= 0.00
X= 207.21	Y= 8.00	Z= 0.00
X= 311.15	Y= 8.00	Z= 0.00
X= 232.21	Y= 51.27	Z= 0.00
X= 180.00	Y= 51.27	Z= 0.00
X= 130.00	Y= 51.27	Z= 0.00
X= 77.79	Y= 51.27	Z= 0.00
X= 63.04	Y= 76.81	Z= 0.00
X= 246.96	Y= 76.81	Z= 0.00
X= 266.96	Y= 111.46	Z= 0.00
X= 195.00	Y= 106.00	Z= 0.00
X= 114.99	Y= 106.00	Z= 0.00
X= 43.04	Y= 111.46	Z= 0.00
X= -48.65	Y= 90.27	Z= 0.00
X= 28.29	Y= 137.00	Z= 0.00
X= 281.71	Y= 137.00	Z= 0.00
X= 358.65	Y= 90.27	Z= 0.00
X= 306.71	Y= 180.30	Z= 0.00
X= 255.60	Y= 182.22	Z= 0.00
X= 192.46	Y= 191.73	Z= 0.00
X= 118.80	Y= 191.73	Z= 0.00
X= 54.40	Y= 182.22	Z= 0.00
X= 3.29	Y= 180.30	Z= 0.00
X= 79.40	Y= 225.52	Z= 0.00
X= 230.60	Y= 225.52	Z= 0.00
X= 254.50	Y= 270.73	Z= 0.00
X= 204.50	Y= 270.73	Z= 0.00
X= 175.00	Y= 270.73	Z= 0.00
X= 135.00	Y= 270.73	Z= 0.00
X= 105.50	Y= 270.73	Z= 0.00
X= 55.50	Y= 270.73	Z= 0.00
X= 107.50	Y= 360.73	Z= 0.00
X= 202.50	Y= 360.73	Z= 0.00

Table C.2: Baseplate drilling coordinates listing (through holes, ø3 mm)

Part	04: Top plate
Quantity	3
Material	Aluminum
Outer dimensions	325×104.4×6mm
Weight	0.140 kg



1	X= 0.00	Y= 0.00	Z= 0.00
2	X= 0.00	Y= -44.40	Z= 0.00
3	X= 310.00	Y= -44.40	Z= 0.00
4	X= 310.00	Y= 0.00	Z= 0.00
5	X= 317.50	Y= 12.99	Z= 0.00
6	X= 236.07	Y= 60.00	Z= 0.00
7	X= 73.92	Y= 60.00	Z= 0.00
8	X= -7.50	Y= 12.99	Z= 0.00

Table C.3: Top plate contour coordinate listing

X= -1.15	Y= 8.00	Z= 0.00
X= 102.77	Y= 8.00	Z= 0.00
X= 207.23	Y= 8.00	Z= 0.00
x= 311.15	Y= 8.00	Z= 0.00
X= 232.23	Y= 51.30	Z= 0.00
X= 77.79	Y= 51.30	Z= 0.00

Table C.4: Top plate drilling coordinates listing (through holes, ø3 mm)

Part	05: Shaft
Quantity	3
Material	Aluminum
Outer dimensions	ø15mm×110
Weight	0.02 kg