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INSTITUT FÜR AUTOMATISIERUNGS- & REGELUNGSTECHNIK

Design and prototyping of an omnidirectional base for an indoor robot

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Abstract

Due to the increasing number of elderly people in our society and their wish to live independently at their homes as long as possible, the need for care attendants is drastically increasing. The foreseeable demand can only be satisfied by the development of personal service robots, who assist elderly people at everyday tasks.

At the moment several barriers prevent robotic assistants from resolving this problem in the field of elderly care. Besides the need for more elaborate sensors and actuators, important barriers are the current prices for mobile service robots and their necessary flexibility. Blue Danube Robotics GmbH aims to eliminate these barriers and develop a service robot helping elderly and handicapped people to live their lives at home. For the optimal use of the robot at home, an omnidirectional robot base is essential.

The design of the omnidirectional mobile base presented is based on the analysis of typical challenges arising from the robots environment. From this analysis and several design limitations a list of requirements was derived, ensuring the necessary flexibility of the robot in its environment. Based on this list the mobile base was designed and prototyped.

According to the developed design four drive modules, each consisting of two hydraulic rotary actuators and one hydraulic cylinder, enable the mobile platform to move the robot through the apartment. Due to the implementation of hydraulic cylinders the base design is capable of overcoming thresholds and single steps (up to 210 mm). The components of the supporting structure are designed to be assembled using wood connections. According to the design the surfaces are covered with a soft tactile material to detect collisions and at the same time to reduce the risk of injury.

Not all aspects of the design could be realized in the final prototype due to time limitations and manufacturing problems. A strategy to overcome single steps was developed and presented. The first prototype of the omnidirectional robot base is capable of climbing thresholds up to 20 mm and to drive on ramps. Due to its dimensions the base provides flexibility and can be used as an aid for standing up. The support structure uses eco-friendly material and allows easy maintenance. The mobile platform presented is capable of moving Blue Danube Robotics future robot through houses and apartments, bringing the robot one step closer to realization.

Kurzzusammenfassung

Auf Grund der steigenden Anzahl an älteren Personen in unserer Gesellschaft und deren Wunsch möglichst lange unabhängig zu Hause zu leben, steigt der Bedarf an Pflegepersonal drastisch an. Die voraussichtliche Nachfrage kann nur durch die Entwicklung von persönlichen Servicerobotern befriedigt werden, die älteren Menschen bei täglichen Aufgaben helfen.

Derzeit gibt es noch einige Hindernisse, die den Einsatz von Robotern in der Altenpflege unterbinden. Abgesehen von notwendigen Sensoren und Aktuatoren fehlen niedrige Preise und die nötige Flexibilität. Blue Danube Robotics GmbH zielt darauf ab diese Hindernisse zu beseitigen und einen Serviceroboter zu entwickeln der älteren Personen hilft zu Hause zu leben. Für die optimale Nutzung des Roboters zu Hause ist eine omnidirektionale Plattform essentiell.

Das Design der präsentierten mobilen Plattform basiert auf der Analyse typischer Herausforderungen, die auf Grund der Arbeitsumgebung auftreten. Von dieser Analyse und von einigen Designeinschränkungen wurde eine Liste von Anforderungen abgeleitet, die die notwendige Flexibilität des Roboters in seinem Umfeld sicherstellt. Auf Basis dieser Liste wurden ein Design und ein Prototyp der mobilen Roboterplattform erstellt.

Entsprechend dem Design ermöglichen vier Fahrmodule, die jeweils aus zwei hydraulischen Rotationsaktuatoren und einem Hydraulikzylinder bestehen, der mobilen Plattform den Roboter durch die Wohnung zu bewegen. Dank der Implementierung der Hydraulikzylinder ist die Plattform in der Lage Schwellen und einzelne Stufen (bis zu 210 mm) zu überwinden. Die Einzelteile der Tragestruktur können zusammengesteckt werden. Entsprechend dem Entwurf werden die Oberflächen mit einem weichen, taktilen Material verkleidet, welches Kollisionen detektiert und gleichzeitig das Verletzungsrisiko verringert.

Nicht alle Aspekte des Designs konnten im finalen Prototypen umgesetzt werden. Es wurde eine Strategie zum Überwinden einzelner Stufen präsentiert. Der erste Prototyp der omnidirektionalen Roboterplattform ist in der Lage Schwellen bis zu 20 mm zu überwinden und Rampen zu befahren. Wegen ihrer Abmaße erlaubt die Plattform Flexibilität und die Nutzung als Aufstehhilfe. Die Tragestruktur besteht aus umweltfreundlichem Material und erlaubt eine einfache Wartung. Die vorgestellte mobile Plattform kann den zukünftigen Roboter von Blue Danube Robotics durch Häuser und Wohnungen bewegen und bringt damit diesen Roboter seiner Umsetzung einen Schritt näher.

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Vienna, November 2015

Contents

1 Introduction **1**
1.1 Motivation: The Potential of Service Robots 2
1.2 Background 3
1.2.1 Blue Danube Robotics 3
1.2.2 BLUE 5
1.3 State of the Art 5
1.3.1 Humanoid Robots 6
Asimo 6
1.3.2 Wheeled Robots 7
RoNA 7
Rollin' Justin 8
Momaro 10
1.3.3 Tracked Robots 11
cRoNA 11
BEAR 12
AZIMUT 13
1.3.4 Comparison of Existing Mobility Concepts 13

2 Derivation of Techn. Requirements **18**
2.1 Problem Analysis 18
2.1.1 Analysis of an Apartment 18
Objects in the Way 18
Confined Spaces 19
Reach of the Hands 20
Uneven Floor 21
Floor Level Difference 21
Ramps 22
Interaction 23
Aid for Standing Up 23
Low Noise Level 23
Traveling Speed 24
2.1.2 Design Related Limitations 24
Part of a System 25

Maintenance and Servicing 25
Target Price 25
Company Image 25
2.2 Mobile Base Requirements 26
2.2.1 Motion Requirements 26
2.2.2 Geometrical Requirements 28
2.2.3 General Design Requirements 29
2.2.4 Target Market Requirements 31

3 Top Level Design 33
3.1 Functional Units and their Boundaries 33
3.1.1 Forming Functional Units 33
3.1.2 Motion System 33
3.1.3 Bearing Structure 35
3.1.4 Base Hull 36
3.1.5 Internal Components 37
3.2 Design Concept 37
3.2.1 Motion System 38
3.2.2 Bearing Structure 39
3.2.3 Base Hull 40
3.2.4 Internal Components 42

4 Low Level Design 43
4.1 Designing the Motion System 43
4.1.1 Sliding 44
4.1.2 Stepping 44
4.1.3 Rolling 45
4.1.4 Concept 51
4.2 Designing the Bearing Structure 55
4.2.1 Regular Polygon 56
4.2.2 Support Structure of a Mammal 57
4.2.3 Concept 58
4.3 Designing the Base Hull 60
4.4 Designing Internal Components 63
4.4.1 Hydraulic Pump 63
4.5 General Design Considerations 64
4.5.1 Structural Material 64
4.5.2 Hydraulic Fluid 65

5 Prototyping **67**
5.1 Hydraulic Sub System Prototypes 68
5.1.1 Hydraulic Pump 68
Replacing the DC Motor 68
Incorporation of an Impeller Pump 69
Changed Transmission 69
Simplified Setup 70
More Powerful Motor 71
Reintegration of the Planetary Gear 71
5.1.2 Hydraulic Cylinder 71
5.1.3 Slide Vane Actuator 74
5.1.4 Rotary Vane Actuator 79
5.1.5 Alternative to Hydraulic Rotary Actuators 82
5.2 Structural Sub Assemblies 83
5.2.1 Bearing Structure 83
5.2.2 Base Hull 87
PVC - Polyvinyl-Chloride 87
Glass Fiber Reinforced Polyester 87
Plywood 89
Selected Technique 91

6 Conclusion **92**
6.1 Final Setup 92
6.2 Lessons Learned 94
6.3 Improvements 96
6.3.1 Functional Improvements 96
Motion Capabilities 96
Actuator Prototype 96
Hydraulic Circuit 97
6.3.2 Improvements for Serial Production 97
6.4 Prospects 97

A Standing up from the ground **99**

List of Figures

1.1 Human and robot evolution 1
1.2 Design proposal #1 showing the service robot in various poses. . 4
1.3 Design proposal #2 showing service robot and components. . . . 4
1.4 ASIMO navigating through spinning obstacles 6
1.5 ASIMO Evolution 7
1.6 RoNA 8
1.7 RoNA stability system in action. 9
1.8 Rollin Justin 9
1.9 Rollin Justin robot base with variable footprint 10
1.10 Momaro 11
1.11 cRoNA 11
1.12 BEAR 12
1.13 BEAR drive module 14
1.14 AZIMUT: locomotion 15
1.15 AZIMUT: propulsion concept 16

2.1 Ordinary Apartment 19
2.2 Confined Spaces 20
2.3 Reach of a robot 21
2.4 Floor level difference 22
2.5 Standing up with aid 24
2.6 Holonomic motion, omnidirectional motion and limited steering angle 26

3.1 Mindmap showing functional units and requirements 34
3.2 First Design of the Motion System 39
3.3 First Design of the Bearing Structure 40
3.4 First Design of the Base Hull 41
3.5 First Design of the Distribution of the Internal Components . . 42

4.1 Mind map showing concepts for propulsion of ground vehicles . 43
4.2 Hexapod walking 45
4.3 Mind map showing different locomotion concepts based on rolling. 45
4.4 Comparison of a Mecanum wheel and an Omni-wheel 46

4.5 Attachment points of special wheels 47
4.6 Overrolling obstacles with common wheels and special wheels . . 48
4.7 Picture showing the Omni-Crawler and the Crawler-Vehicle . . . 49
4.8 Basic structure of the Omni-Ball 50
4.9 Correlation between overrolling torque, obstacle height and wheel radius 52
4.10 Mobile base with wheels with 210 mm diameter 53
4.11 A step by step strategy to climb single steps. 54
4.12 Proposed octahedronal, hexagonal and octagonal Structures . . 57
4.13 A design proposal inspired by the torso skeleton of mammals. . 58
4.14 Bearing Structure Design 59
4.15 Close up of the proposed design by Blue Danube Robotics . . . 60
4.16 Possibilities to conceal edges between adjacent parts 61
4.17 K2 Basic and custom hydraulic pump 65

5.1 Sketch illustrating the setup of the pump tests 68
5.2 Custom hydraulic pump including a booster pump 70
5.3 Custom hydraulic pump including a booster pump 71
5.4 Design of a Hydraulic Piston 73
5.5 Custom hydraulic cylinder 73
5.6 Piston size based on top height and stroke 75
5.7 Working Principle of a Slide Vane Actuator 75
5.8 Design of two Slide Vane Actuator 76
5.9 Working principle of Rotary Vane Actuator 80
5.10 Design of a Rotary Vane Actuator 81
5.11 First Prototype of the Bearing Structure 84
5.12 Redesign of the side ledges 85
5.13 Second Prototype of the Bearing Structure 86
5.14 Base Hull Prototype for one Side Cover 88
5.15 Bending wood 90

6.1 Prototype of the Drive Module 93
6.2 The prototype of the omnidirectional mobile robot base. 94

A.1 Standard Technique for Standing Up 99

List of Tables

1.1 Comparison of Robots 17

2.1 Contained Components 30

3.1 Requirements for the Motion System 35
3.2 Requirements for the Bearing Structure 36
3.3 Requirements for the Base Hull 37
3.4 Requirements for the Internal Components 38

4.1 Requirements for the Hydraulic Pump 63
4.2 Specifications for the Hydraulic Pump 64

5.1 Design Parameters for Slide Vane Actuators 78
5.2 Design Parameters for Rotary Vane Actuator 82

1 Introduction

Starting with the first use of knives and robes for hunting or building shelter, mankind has always striven to create more complex tools in order to simplify tasks. This continuous search for instruments and aids in combination with the human power of imagination enabled us to design and manufacture products we once only dreamed of. One of the biggest fascinations in all human cultures was and is to create an image of a human being which is capable of walking, talking, thinking and even feeling like its creator. Today we would call an aid like this a robot, maybe more precisely a humanoid. A humanoid service robot opens up incredible possibilities but also causes totally new dangers as Isaac Asimov illustrates in his famous collection of short stories named "I, Robot". [1] Today the fulfillment of this dream seems closer than ever before. Industrial robots take care of many production processes and domestic robots manage cleaning tasks autonomously at our homes. What once seemed an unrealistic dream might come into our houses in the next decades. Figure 1.1 [1] presents the classic illustration of the human evolution process with three additional silhouettes introducing robot development from a tiny helper to a complex machine.

[1] Picture taken from `http://3.bp.blogspot.com/-Nh9apTS5lkM/T8-6in_1JGI/AAAAAAAADE4/aUhqxsvSmJY/s640/Robot_Evolution.png`, ©33rdsquare

Figure 1.1: Human and robot evolution, ©33rdsquare

1.1 Motivation: The Potential of Service Robots

While most people know what an industrial robot does many of my friends do not know the term "service robot". I want to add a definition at this point to prevent confusion or misunderstanding. According to the IFR [2], which quotes the definition from the upcoming standard ISO-8373:2012 "Robots and robotic devices - Vocabulary", *"A service robot is a robot that performs useful tasks for humans or equipment excluding industrial automation application. Note: The classification of a robot into industrial robot or service robot is done according to its intended application."* [3].

At the present time several companies are developing service robots for households often called domestic robots. Today most domestic robots accomplish tasks like mowing the lawn or cleaning floors, windows or pools. These are tasks a robot can handle autonomously with hardly any interaction with other robots or human personal. Future service robots will be designed to interact with persons more frequently. As its name implies, the central goal of a service robot is to serve or support its user by taking over tasks similar to a coworker, personal assistant or household help. At the moment domestic robots take over one single task leaving users in need for many specialized robots instead of one robot assistant for all routine assignments. As we will see in the following section it seems to be just a matter of time until robots become a natural part of our households and of our daily routines like cars and smart phones already have. Although everyone would love to have a helping hand at home to do cleaning tasks the most promising target group are physically handicapped and elderly people, who require help with particular everyday routines in household. Where a human care giver is needed today, in future a personal robot assistant could help members of the target group to stay at home longer before moving to a care home or a retirement home. This business idea is especially promising because a robot which fulfills simple tasks semi-autonomously is able to support a human caregiver or to allow one carer to look after a number of people not only one by visiting them in turn instead of staying at one location. This reduces costs for care while still allowing patient monitoring as before. The robot can monitor vital signs and check the medication of a user just the same as human personnel. A service robot can take care of hygiene and relieve a human being of specific routine tasks of daily life to meet the wish of most people to stay at their homes as long as possible.

[2] IFR is an abbreviation for the International Federation of Robotics (`www.ifr.org`)
[3] Referring to [2], `http://www.ifr.org/service-robots/`

Importance of the Motion System The mobile base plays a significant role in a service robot's potential use because it enables the robot's mobility. In industrial production lines it is possible to deliver the objects, which need to be manipulated, directly to the robot. For service robots this is not possible, because in many cases it is part of the manipulation task. An adequate mobile base enables the service robot to compensate the limited mobility of its elderly or handicapped user, making it valuable for the user. A service robot, which can not move therefore is of little help. The field of operation for service robots are houses and apartments which are designed for human beings capable of walking, standing upright and reaching to the floor as well as to an average height of 1.75 m. Best of all would be a service robot capable of moving in this environment like a human being. Multiple challenges of the presented environment underlines the particular importance of an omnidirectional mobile base.

1.2 Background

To provide a better understanding of the requirements for the omnidirectional robot base it is necessary to shortly introduce Blue Danube Robotics and their visionary service robot BLUE.

1.2.1 Blue Danube Robotics

Blue Danube Robotics was founded in 2013 in Vienna, Austria with the vision *"To enable people to keep or regain autonomy and lead a self-determined life"* [4]. Following this vision the young and energetic team created the design for a personal robot assistant unofficially called BLUE, which is illustrated in Figure 1.2.

BLUE is designed to assist with simple everyday tasks like fetching objects, opening doors and handling beverages. Providing these and similar functions the robot assistant facilitates valuable support for elderly and physically handicapped people. At present day Blue Danube Robotics is also working on two sensor products named Airskin Safety and Airskin Sense [5], which have various fields of application from a low cost contact sensor to safety device preventing injuries in human robot collaboration.

[4] [3] `http://www.bluedanuberobotics.com/?page_id=168`

[5] ™Airskin Safety and ™Airskin Sense are registered trademarks by Blue Danube Robotics.-

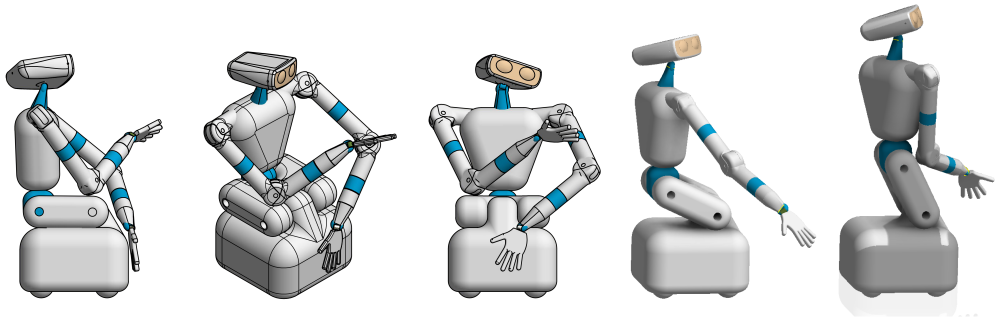


Figure 1.2: First design proposal showing the service robot in various poses. ©Blue Danube Robotics

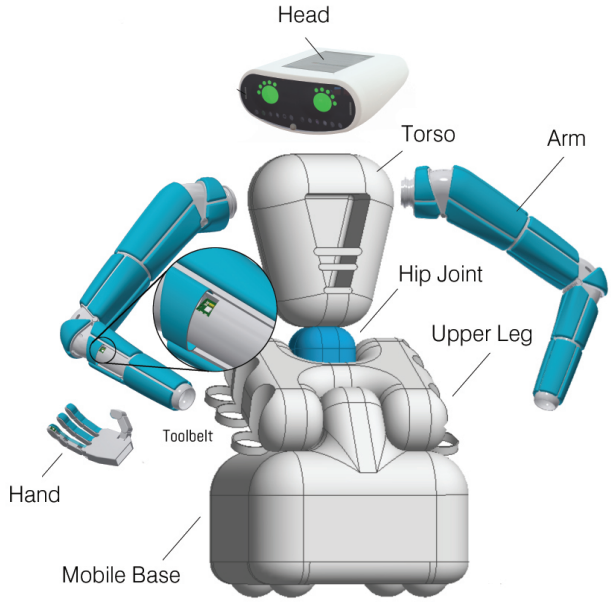


Figure 1.3: Second design proposal showing service robot and its sub-assemblies. ©Blue Danube Robotics

1.2.2 BLUE

Figure 1.3 shows the second design proposal of the robot. It illustrates a division of BLUE into components similar to human body parts. Due to the self-explaining character the sub-assemblies of BLUE are named after the respective parts of the human body. Using terms from human anatomy it could be said that BLUE consists of a head, a neck, a torso, two arms, two hands, a hip and one upper leg assembly. Instead of lower legs and feet the presented design features a box-shaped mobile base. This sub-assembly allows the service robot to move through various rooms of houses and apartments, which are on the same floor. Besides movement it provides stability for the robot's torso. Apart from the names also the functionality of the sub-assemblies are similar to human body parts. The hands are designed to allow several different grips giving the robot the opportunity to handle as many different objects as possible. The arms ensure the necessary reaching area from the ground to the most often used shelves. The head and neck assembly allows a flexible visual perception and interpretation as well as sound output of the robot. The torso works as a connector between the arms, the neck and the upper leg. It also contains several components for the purpose of actuation and information processing. The upper leg and hip function as flexible connection between torso and mobile base allowing the robot to turn, tilt and lift the torso. Although the arms are the most important components concerning the reaching area of the robot, the torso can be a valuable support when it comes to reaching sideways, to the ground or to a high shelf. Moving the torso also changes the position of the camera integrated in the robots head and thereby might give a better view of the environment. This thesis is dedicated to creating the first prototype of the mobile base of BLUE. To allow the robot to access all areas of apartments the base has to be capable of moving BLUE through confined spaces, around obstacles and over thresholds. It needs to be compact and extremely flexible to allow optimal operation. As Figure 1.2 and Figure 1.3 illustrate the first design of BLUE, the mobile base is not bound to look like the proposed designs or to use wheels or spheres for propulsion as the figures might imply. The omnidirectional mobile base could also make use of legs or other propulsion concepts as long as they provide an appropriate solution for BLUE's propulsion and comply with the requirements presented in Chapter 2.

1.3 State of the Art

The number of propulsion concepts for robotic devices seems endless. From helicopter drones over walking and rolling vehicles to fish like swimming motions

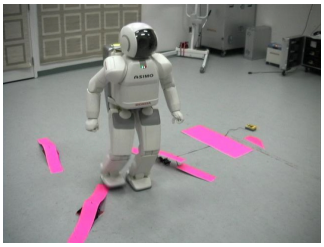


Figure 1.4: ASIMO navigating through spinning obstacles ©2007 IEEE, [4]

almost all motion concepts have been recreated to move robotic devices.

When it comes to service robots the existing propulsion systems can be divided in three categories, which are presented in this section. The following subsections present representatives of humanoid, wheeled and tracked service robots. The selection is based on their relevance for the design purpose as well as on the availability of information. Although a general information about the robots field of application and its skills will be given, the focus will be on the characteristics of its propulsion. The subsequent overview does not argue benefits and drawbacks of the three general concepts in detail as this topic is included in Section 4.1.

1.3.1 Humanoid Robots

Asimo

The most recognized bipedal humanoid robot is Honda's ASIMO, which is an abbreviation for Advanced Step in Innovative Mobility. The ASIMO robot is based on a robot development process started by Honda in 1986. It consists of seven experimental models (E0-E6) as well as three prototype models (P1-P3) as illustrated in Figure 1.5. The latest ASMIO robot was presented in December 2005 and is, according to the "ASIMO - Technical Information" [6], able *"to automatically perform the tasks of a receptionist or information guide and carry out delivery service."*[6, page 24] The bipedal walking mechanism allows ASIMO to walk dynamically at a maximum speed of 2.7 $\frac{\text{km}}{\text{h}}$. With the implemented running pattern ASIMO can achieve 6 $\frac{\text{km}}{\text{h}}$ when running straight and 5 $\frac{\text{km}}{\text{h}}$ when running a "circular pattern" with radius of 2.5 m. [6, page 24] According to the official web page of ASIMO [7] Honda's robot is currently capable of climbing stairs. The robot can also turn on the spot almost like a human being. It seems

[6] The document is available on the official ASIMO web page at: `http://asimo.honda.com/downloads/pdf/asimo-technical-information.pdf`, accessed on 16.09.2015

[7] Official web page of Honda ASIMO - `http://asimo.honda.com/asimo-history/`, accessed on 16.09.2015

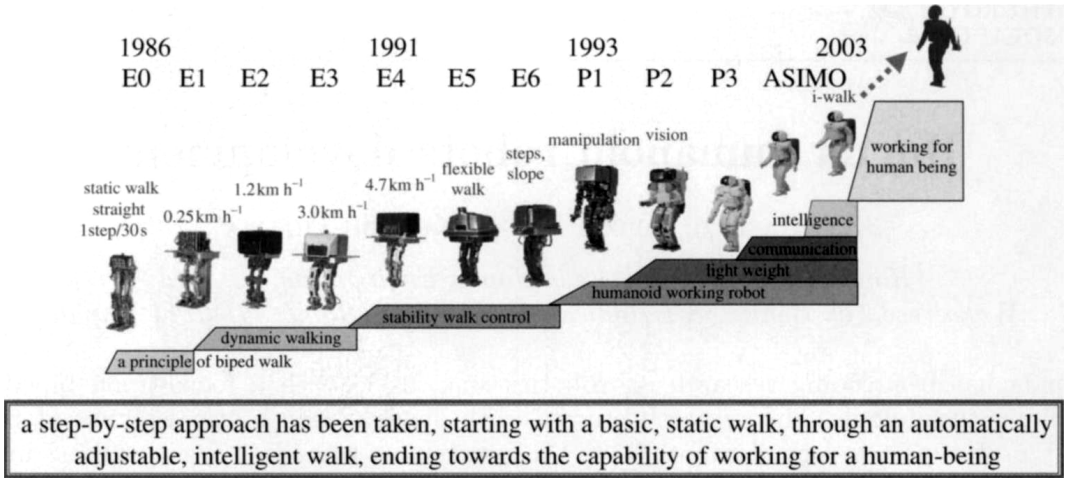


Figure 1.5: The Evolution of ASIMO and its bipedal walk.[5, page 12]

that ASIMO's hip joints do not allow as much rotation as its role model does. Therefore ASIMO has to take many small steps following a narrow circle, when it wants to turn on the spot. Although the most recognized humanoid features impressive specifications the robot has to stop from time to time to calculate the next movements which slows the robot down.

1.3.2 Wheeled Robots

RoNA

The Robot Nurse Assistant (RoNA) was developed by HSTAR Technologies, Inc. to take over frequent lifting and transferring activities in nursing profession. Figure 1.6 presents two designs of RoNA. While the design presented in Figure 1.6a [8] is presented on the official webpage, Figure 1.6b [9] illustrates the robots design used in the demonstration video. The development of RoNA is a reaction to the result of a study undertaken by a group of scientists headed by Terrence J. Stobbe. The study examines the relation between the frequency of lifting tasks and low back injuries of nurses and it confirms a significant correlation between patient lifting frequency and the examined symptoms [7]. RoNA provides a possible solution for nursing profession to prevent low back injury from lifting tasks.

The mobile platform for RoNA features four Mecanum wheels, enabling the

[8] The image is taken from `http://www.hstartech.com/images/research/RoNA%20carrying%20image.png`, ©HSTAR Technologies, Inc.

[9] The image is taken from `https://www.youtube.com/watch?feature=player_embedded&v=YqdQdUUSlp4`, ©HSTAR Technologies, Inc.

(a) RoNA model presented on web page

(b) RoNA model used in promotion video

Figure 1.6: Photography and rendering of RoNA the Robotic Nurse Assistant, all images ©HSTAR Technologies, Inc.

robot to move through the narrow space between patient beds. The specialty of RoNA is that it also features two stabilizers, which can be extended to gain higher stability during patient transfer. In order not to lose flexibility the stabilizers can be retracted into the robot base. Figure 1.7 [10] illustrates the process of extending the stabilizers.

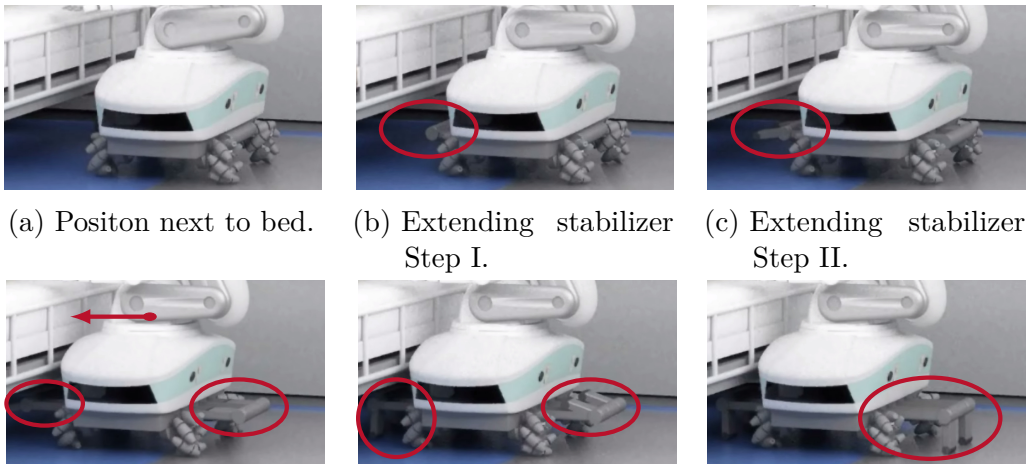
Rollin' Justin

The mobile humanoid robot "Rollin' Justin" was developed by German Aerospace Center (DLR[11])'s Robotics and Mechatronics Institute (DLR RM) for two purposes. First the mobile robot *"allows the implementation and demonstration of sophisticated control algorithms and dexterous manipulation."*[8, page 1, abstract] Secondly the mobile robot can be used to study important limitations and possible fields of application for mobile service robots. Rollin' Justin is mentioned in this section because DLR put much effort in the development of its mobile base. In the master thesis *"Design of a Mobile Robotic Platform with Variable Footprint"* Alexander N. Wilhelm focused on creating a stable platform for Justin, providing an appropriately big supporting polygon (footprint) for the manipulation of heavy objects as well as a slim contour, allowing access to confined spaces.

Figure 1.9a presents the mechanism used to combine these contrasts in one concept following the idea of a variable footprint. Figure 1.9b illustrates

[10] All sub figures of Figure 1.7 are screen shots taken `https://www.youtube.com/watch?feature=player_embedded&v=YqdQdUUSlp4`, accessed on 11.09.2015. Use with kind permission of HSTAR Technologies, Inc.

[11] DLR stands for "Deutsches Zentrum für Luft- und Raumfahrt"

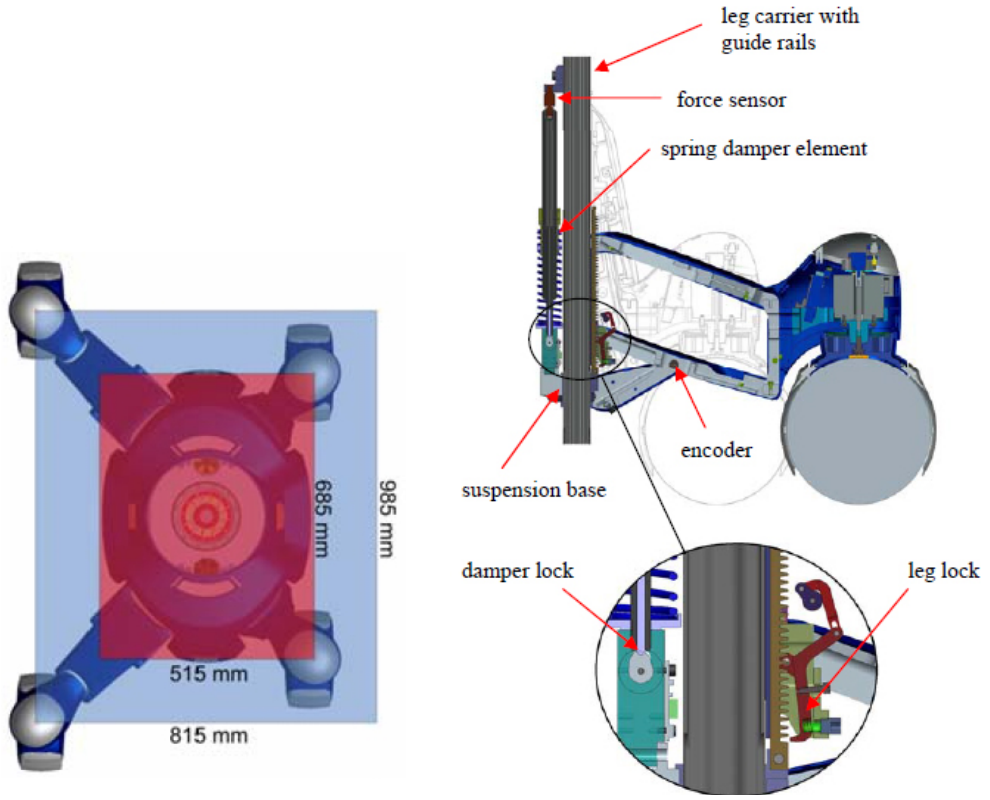


(a) Positon next to bed. (b) Extending stabilizer Step I. (c) Extending stabilizer Step II.

(d) Base rolls closer to the bed and extends second stabilizer (e) First stabilizer in position (f) Base is ready to lift a patient

Figure 1.7: RoNA stability system in action. The pictures are screen shots from an official promotion video ©HSTAR Technologies, Inc.

Figure 1.8: Rollin Justin ©2009 IEEE, [8]



(a) Rollin Justin maximum and minimum Footprint

(b) Rollin Justin mechanism for the variable footprint

Figure 1.9: Rollin Justin robot base with variable footprint, all images ©2009 IEEE, [8]

the minimum and maximum supporting polygon of the base. The presented mechanism does not require additional motors to vary the contact patch. It makes use of the drive engines in combination with a locking mechanism to adjust the footprint to the present needs.

Momaro

Momaro is a rescue robot developed by team NimbRo Rescue especially for the DARPA Robotics Challenge [12]. Team NimbRo is a subgroup of the Autonomous Intelligent Systems Group at the Computer Science Institute of University of Bonn [13]. The purpose of the robot design was to win the DARPA Robotics

[12] Official web page `http://www.theroboticschallenge.org/`

[13] News concerning Momaro can be found at `http://www.ais.uni-bonn.de/nimbro/Rescue/`

Figure 1.10: Momaro ©University Bonn

Challenge 2015, which tests the ability of all participating robots to assist humans at reacting on natural and man-made disasters. To test this capability the competing robots need to maneuver through a course while completing tasks on the way. As best European participants Team NimbRo Rescue finished the challenge 2015 as 4th in overall ranking.

Momaro makes use of a set of four legs, which each end in a pair of wheels. While the four pair of individually steered and driven wheels enable omnidirectional motion, the legs help the robot to overcome obstacles by lifting individual legs or the body of the robot. Lifting one leg after the other Momaro is even capable of climbing stairs by simply using its legs. The legs are made of carbon fiber springs providing a passive adaption to uneven surfaces. [9]

1.3.3 Tracked Robots

cRoNA

Figure 1.11: cRoNA picking up a wounded soldier, ©HSTAR Technologies, Inc.

Figure 1.12: BEAR - Battlefield Extraction Assistant Robot. The image was provided by Vecna Technologies, Inc. via mail, ©Vecna Technologies, Inc.

The combat Robotic Nursing Assistant short (CRoNA) could be described as a military version of the RoNA presented as a model for wheeled propulsion concepts. While HSTAR Technologies, Inc. developed RoNA for application in hospitals and nursing homes, cRoNA was developed to operate on battlefields or in other hazardous environments. Although the general idea of picking up a person and transferring it to a different location is the same for both products, cRoNA features two tracks for traveling off road, outside of buildings on a wide range of natural surfaces. cRoNA is built more robust and is capable of bending down to the ground to pick up persons in need of rescue from wherever they are lying, as Figure 1.11 [14] illustrates. Although tracked propulsion is ideal for loose ground, the described mobility system does not enable the robot to move sideways. This limitation is part of a tradeoff between holonomic motion and the ability to move on many different surfaces.

BEAR

A second example for a tracked mobile base is the Battlefield Extraction-Assist Robot (BEAR), presented in Figure 1.12. Vecna Technologies, Inc.[15] developed a search and rescue robot capable of finding injured human beings in dangerous environment. Bear is a cooperative project of Vecna Technologies and the US Army and aims to minimize human danger/injury at rescue operations. Bear is designed to lift and carry heavy objects, like injured soldiers or heavy objects which block the way over long distances. It makes use of high power hydraulics and a special tracked propulsion system to master its way through

[14] The rendering of cRoNA is available online at `http://www.hstartech.com/images/research/Combat_01.jpg`

[15] Vecna Technologies Inc. `http://www.vecna.com/`, accessed on

challenging terrain. Figure 1.13 [16] illustrates screenshots from a demonstration video showing how Bear uses its pair of each two tracks in different ways to better meet the current situation.

AZIMUT

AZIMUT is a mobile robot base designed by the LABORIUS-Research Laboratory on Mobile Robotics and Intelligent Systems which is a part of the Department of Electrical Engineering and Computer Engineering of the Université de Sherbrooke. Its unique propulsion concept allows the mobile base to cope with uneven terrain indoors and outdoor. The platform features a new, creative combination of legs, wheels and tracked propulsion, illustrated in Figure 1.14. AZIMUT has four similar propulsion modules. Each module features an asymmetric track, which can either be used like common tracks (see Figure 1.14 a) and Figure 1.14 g)) or which can be used in a four legged locomotion (indicated by Figure 1.14 h)). The sub-figures c), d) and f) aim to present possible steering movements allowing the robot to turn around when in legged mode or to drive on curved paths when using the tracks for motion. Additionally to these locomotion possibilities AZIMUT is also able to roll on wheels, which can be steered using the same mechanism.

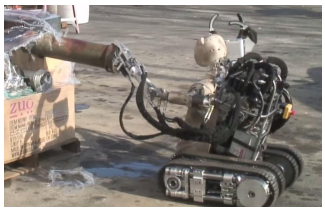
On Figure 1.15 the wheels can be seen next to the tracks on the thickest area of the leg. The chosen wheel diameter causes the robot to roll on its wheels instead of the tracks when it moves in positions similar to Figure 1.14 b) - f) combining the three most common locomotion concepts allows AZIMUT to move flexible and efficient on hard, even floor (using its wheels), climbing slopes and stairs as well as driving on soft ground (using tracks) and lifting its body to overcome obstacles (when walking on its legs). In some cases a combination of walking and rolling on the tracks might also be of use.

1.3.4 Comparison of Existing Mobility Concepts

The presented robots each poses a unique propulsion concept tailored for the robot's environment. While outdoor all-rounder rely on tracked propulsion, which limits their motion direction, indoor robots put emphasis on holonomic motion favoring wheels or legged motion.

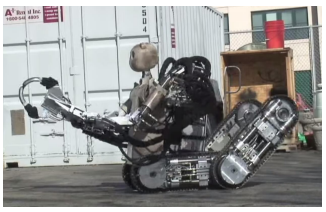
Table 1.1 gives a quick overview over six crucial parameters of the mobile base design. Focusing on the first three characteristics results in two designs, which seem to suit for the mobile base. ASIMO as well as Momaro are both able to cope with obstacles and stairs, while providing omnidirectional motion.

[16] Screen shots taken from the demonstration video `https://www.youtube.com/watch?v=8rdRxV-qn3w`, ©Vecna Technologies, Inc.

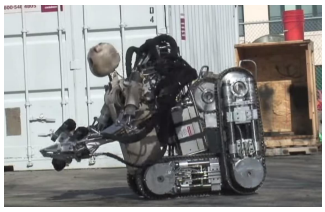


(a) Moving with minimum footprint.

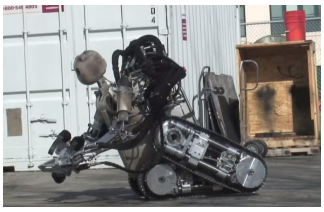
(b) Outside tracks oriented forward to better overcome obstacles.



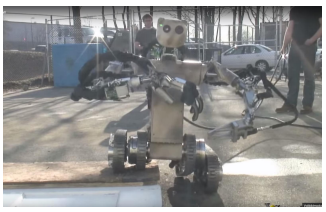
(c) Outside tracks oriented backward to overcome obstacles while diving backwards.



(d) Reorienting tracks from position c) to e)



(e) First stabilizer in position



(f) First stabilizer in position

(g) Base is ready to lift a patient

(h) BEAR lifts a human dummy onto a table balancing on the outer tracks.

Figure 1.13: Bear drive module. The pictures are screenshots from an official promotion video, all images ©Vecna Technologies, Inc.

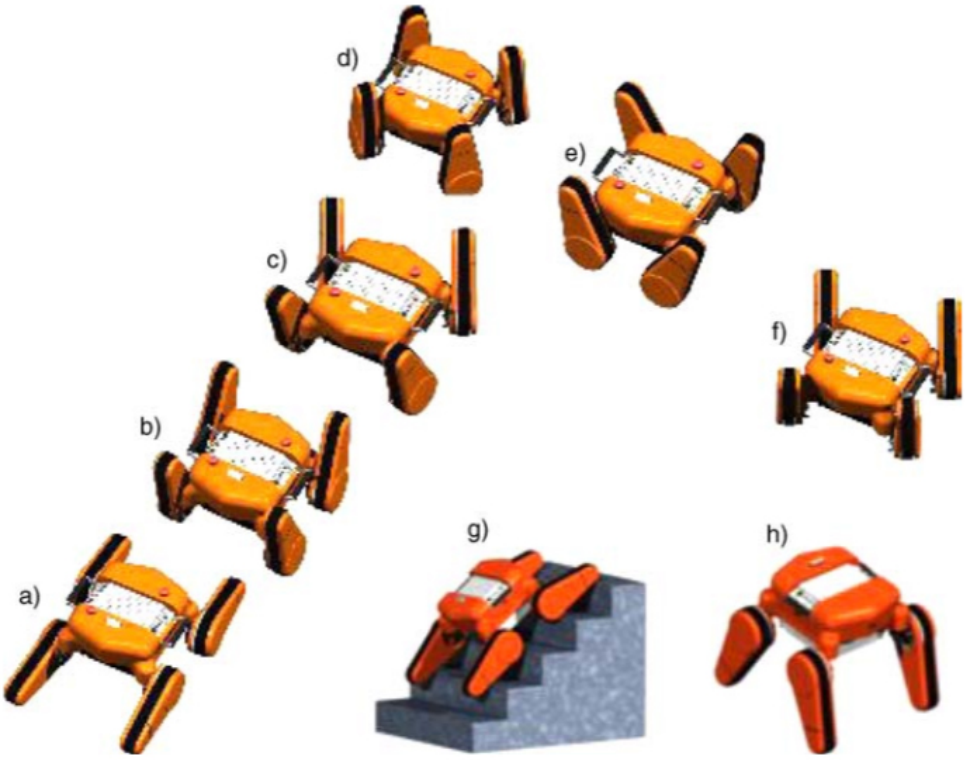


Figure 1.14: Mobile robot base AZIMUT and a variety of its locomotive skills. [10] with kind permission from Springer Science and Business Media.

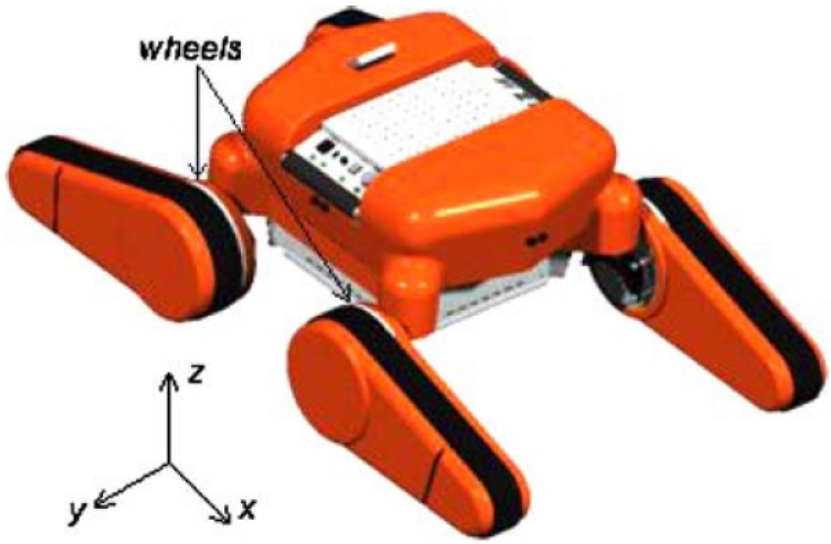


Figure 1.15: The AZIMUT base: A combination of legs, wheels and tracks. The orange legs can be rotated around the y-axis as well as 90 ° around the z-axis. The black ribbon on each leg represents a track. The arrows point to two of the four wheels. This image is reprinted from [10] with kind permission from Springer Science and Business Media.

Table 1.1: Comparison of the presented robots concerning motion and efficiency criteria. The fulfillment of a criterion in the authors perception is illustrated using the following symbols:
✓ - fulfilled, × - not fulfilled, O - no information.

	Walking	Rolling			Tracked		
	ASIMO	RoNA	Rollin' Justin	Momaro	cRoNA	Bear	AZIMUT
Omnidirectionality	✓	✓	✓	✓	×	×	O
obstacles $\geq$ 50mm	✓	×	×	✓	✓	✓	✓
stairways	✓	×	×	✓	✓	✓	✓
simple control	×	✓	✓	×	✓	✓	×
low cost	×	✓	O	×	O	×	×
energy efficient	×	✓	✓	✓	×	×	O

When focusing on the last three criteria, RoNA seems to be the best fitting candidate. At this point it is important to stress the fact, that the efficiency criteria have been rated by the author without further material supporting the ranking. This was necessary because no such data was available.

2 Derivation of Technical Requirements

2.1 Problem Analysis

The following chapter is dedicated to illustrate the technical requirements that arise from the environment of the mobile robot base of a domestic service robot, as well as specifications prescribed by the developing company and the stated product positioning.

For a better understanding Section 2.1 presents critical predictable situations. The numbers in square brackets indicate the requirements presented in Section 2.2.

2.1.1 Analysis of an Apartment

Most of the requirements of the mobile base derive from its environment. This makes it necessary to analyze typical difficulties that occur when a robot moves around in an ordinary apartment. To provide a common image of a flat for further thoughts, it is essential to state that most likely BLUE's environment will not be a perfectly clean apartment where every object is in its proper place on a shelf, or a cupboard. Instead of imagining a model apartment equipped with the latest technology and cleaned as we see it in architecture magazines, it would rather help to think of one's own apartment. Figure 2.1 illustrates the apartment of a test user from the Hobbit project[1].

Objects in the Way

Considering an inhabited apartment, there are always some everyday objects lying around on the table or on the floor, e. g. backpacks, shopping bags or handbags. As people get less agile at picking things up from the floor, it eventually becomes more exhausting for elderly users, therefore increasing the number of items on the ground. This observation shows that picking up

[1] For further information on the Hobbit project refer to `http://hobbit.acin.tuwien.ac.at/`.

Figure 2.1: The service robot Hobbit with its test user in an ordinary apartment. The picture is presented with kind permission of ACIN, Automation and Control Institute of TU Vienna.

objects is an important task for a service robot and underlines that in BLUE's environment items lying on the floor pose a foreseeable problem. To react to this environment the robot needs an appropriate obstacle localization system, which will not be integrated in the mobile base but in the robot's head and hence does not influence the design of the mobile base. After detecting an obstacle standing in the way, the robot can remove it. Obviously there will always be hindrances that the robot can not clear due to various limitations. Some objects might be too heavy, it might be impossible for the robot to get a safe grip on the object or the robot might need special tools to remove the obstacle e. g. in the case of a puddle of water or juice pouring out of a bottle, which got knocked over. To allow the robot to avoid the affected area, the base has to provide a certain degree of mobile flexibility to go around detected obstacles. [Requirement 1]

Confined Spaces

Another challenging aspect of the proposed environment are confined spaces, where the robot has to fit through. Figure 2.4 presents an image taken as part

Figure 2.2: Confined spaces occur in forms of doorways and corridors, the image is presented with kind permission of ACIN, Automation and Control Institute of TU Vienna.

of Hobbit Project[2] illustrating the robot and a doorway in the background. Even if there are no obstacles in the way, usually entrance rooms and corridors are narrow, challenging the robots flexibility and path planning ability. In this situation the base does not only need to feature an excellent mobility system to prevent collisions, but also have a compact shape to allow passing through confined spaces. [Requirement 1; Requirement 6]

Reach of the Hands

It might sound peculiar to mention the reaching span of the hands in the specifications for the mobile base, but although it is mostly determined by the design of the arms, their points of attachment as well as their length and flexibility, the design of the mobile base also has a noticeable influence. As mentioned before the operation of picking up objects and placing them somewhere else is a predictable task. Keeping in mind that the service robot's environment is an apartment makes the operation of placing objects on a table or picking up things from a table an obvious challenge. In this and similar cases

[2]For further information on the Hobbit project refere to `http://hobbit.acin.tuwien.ac.at/`

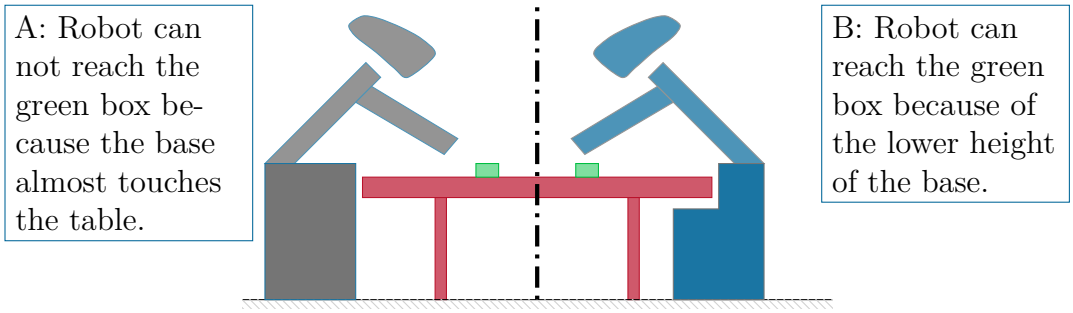


Figure 2.3: The reach of the robots hand on a table can be increased if its mobile base partially fits underneath the table because the distance between the torso joint and the edge of the table is decreased.

the reach of the robot's hands is increased if the mobile base fits (partially) underneath the table, so the torso can be positioned closer to the table. For a domestic service robot not only the horizontal reach is important. It is also necessary to reach down to the floor as well as up to one of the higher shelves of a cupboard. In this case the reach can be improved by a mechanism which lifts and lowers the whole torso of the robot. By modifying the vertical position of the torso not only the shoulder joints move closer to or further away from the floor, but also the cameras implemented in BLUE's head. This improves the robot's view on the objects he has to pick up or place.[Requirement 6; Requirement 13]

Uneven Floor

Especially in old buildings many apartment floors are not (perfectly) even due to several reasons. In most cases the ground is inclined from a higher level close to the walls to a lower level at the center of the room. In some cases the flooring also has irregularities conditioned by aging processes of the floor. The mobile base is required to assure sufficient stability and continuous surface contact of the propulsion system under these circumstances. [Requirement 5]

Floor Level Difference

Another challenge to a robot's motion system are thresholds, which need to be overcome. In many flats in old buildings there are floor level differences underneath almost every doorway or carpets on parquet floors or tile floors. To move across carpets or from one room to the next the robot has to get over these thresholds. Most obstacles of this sort are no higher than 20 mm. In some cases single steps with the same height as a step of a stair can be found.

Figure 2.4: These thresholds underneath the doorways represent common floor level difference.

A situation like this sometimes occurs when two apartments are merged. As small thresholds (x $\leq$ 20 mm) are more common than high ones (20 mm $\geq$ x $\leq$210 mm) it might be interesting to develop two separate strategies for the two types of floor level differences. The proper range of height for the two strategies is to be determined. Although the primary detection of floor level differences should be accomplished by the 3d camera system implemented in the robots head, strategically placed distance sensors should be included in the base to prevent the robot from tumbling down thresholds or stairs. [Requirement 2; Requirement 5; Requirement 10; Requirement 3; Requirement 16]

Ramps

As the aforementioned floor level differences pose a problem for wheelchair users their apartments have the advantage of having less or none of the stated thresholds, thus simplifying the movement from room to room. However, this benefit comes with a downside as well. The most common technique to make buildings barrier-free is to install ramps with an appropriate slope, simplifying the access for the wheelchair user to overcome them. As a result, BLUE needs to be able to travel on sloped surfaces as well. [Requirement 4; Requirement 7; Requirement 10]

Interaction

To ensure a safe interaction between the robot and its environment, consisting of objects, interior and most importantly human beings, the robot base design has to prevent hazards arising from the contact between the robot and its environment. Avoiding edges in the robot design reduces the risk to injure people or damage objects. Additional preventive measures proposed are the use of a soft coating, housing or covering in combination with sensors which detect even low pressure contact of the robot and its environment. [Requirement 15]

Aid for Standing Up

The most noticeable common problem for members of the target group of BLUE is their limited mobility. But besides this restriction most elderly or handicapped persons also have trouble standing up from the floor. Appendix A presents strategies for getting up from the ground after a fall. Either method requires a chair, wheel chair or at least another solid object the person can put it's weight onto. Although many useable objects are present in most apartments it would be a convenient if a proper item would come to the persons location. Up to now chairs and couches often were used as aids for standing up, as Figure 2.5 [3] illustrates. Since a service robot has to come to the person in case of a fall to check if medical help is needed, the robot is the perfect assistant for standing up from the ground if the patient was not injured. BLUE is not designed to lift a human being off the ground or to pull them back on their feet as a human might do, but the mobile base could be designed to take the place of a chair or stool in the usual procedure for getting up. An appropriate height as well as a maximum stability would be required. [Requirement 6]

Low Noise Level

Noise sensitivity will vary greatly depending on the person. While some enjoy their music loud, others might get a headache from the sound children make when they are playing next door. While it is common knowledge that a constantly high noise level at work can lead to long-term effects e. g. tinnitus or hearing loss, fewer people realize that the same and even more dangers arise from noise levels in family and private life. The noise pollution will not be comparable to the noise level in an industrial production plant, but a report from world health organization (WHO) shines a light on the health risks arising from traffic-related noise. The authors express the impact of traffic-related

[3] Screen shot from the video "How to get up from the floor (after a fall) - MacGyver style!" `https://www.youtube.com/watch?v=4ETgQD8QhZs&feature=youtu.be`,

Figure 2.5: Standing up after a fall with the aid of a couch. ©homeability.com

noise in Disability-adjusted life years (short DALY) and conclude as follows. "It is estimated that DALYs lost from environmental noise in the EU countries are 60 000 years for ischaemic heart disease, 45 000 years for cognitive impairment of children, 903 000 years for sleep disturbance, 21 000 years for tinnitus and 654 000 years for annoyance." [11, page 101] This result underlines the importance of a low noise level emitted by the mobile robot base. [Requirement 17]

Traveling Speed

It seems obvious, that it is important for the mobile robot to travel at an appropriate speed. Traveling too slow causes the robot to be in the way of human beings most of the time or might cause users to be on edge because it does not do tasks in the same time as they could. Traveling too fast can pose a threat as the robot might injure people or damage furniture due to the robots slow reactions. [Requirement 9]

2.1.2 Design Related Limitations

Besides the characteristics that the service robot has to fulfill to master the described environmental problems, there are a number of requirements the producing company imposes on the product and its design.

Part of a System

The mobile base can be considered the basic component of the service robot. Although it can not manipulate or navigate through its environment separated from attached parts, the mobile system is the biggest sub-assembly (in size) and therefore has to contain several components listed in Section 2.2. These items have to be housed in the base because of space and mass limitations in the other components. This allocation of the parts can also be used to guarantee a low center of mass, which improves a firm stand of the robot. [Requirement 12]

Maintenance and Servicing

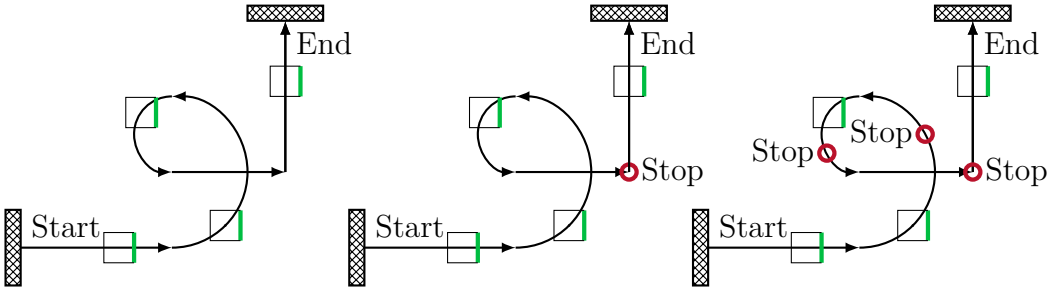
A crucial factor for a convenient operation of the service robot is a low maintenance rate and a good maintainability. The first point is quite obvious because if the robot does not require maintenance in short intervals the customer is happier, since the robot is always ready to use. In case of a technical problem, good maintainability supports fast and easy repair, therefore decreasing the time the robot is not operable. Due to BLUE's size and mass, it is necessary to fix problems and perform maintenance directly at the application site. As described in Section 2.1.1 (Confined Spaces) many apartments do not have much space where BLUE can be maintained. Within the design process it is necessary to keep in mind that both the number of tools as well as the space in the apartment, which can be used for removing, replacing or repairing components, is limited. [Requirement 14]

Target Price

According to the desired market positioning BLUE's target price is 18.000 €, giving everyone the opportunity to afford this service robot. Therefore the cost for the omnidirectional mobile base has to be below 1.000 €. [Requirement 18]

Company Image

Blue Danube Robotics is a young, innovative and ecoconscious company. It does not aim to follow the industrial trends considered with ecological awareness, but to be ahead of competitors. Hence a major design goal is to produce a robot with a small impact on the ecobalance, keeping in mind CO_2 footprints and energy consumption even at the early product design iterations (e. g. prototypes). [Requirement 19]



(a) Holonomic (b) Omnidirectional (c) limited steering angle

Figure 2.6: [a)] A holonomic vehicle can travel along the drawn path without stopping while the front of the base always faces in the same direction. [b)] An omnidirectional vehicle has to stop at the corner. If the drive actuator can only be rotated 360 ° or less in each direction around its mount, one more stop is required. [c)] With less than 180 ° in both directions another stop is needed.

2.2 Mobile Base Requirements

From the presented situations the following specifications for an omnidirectional mobile robot base can be derived.

2.2.1 Motion Requirements

Requirement 1 - Omnidirectionality
In order to ensure movement in confined spaces it is important to independently control as many degrees of freedom (DoF) as possible. The demand for omnidirectionality specifies the minimum required maneuverability of the mobile base.

To understand the term omnidirectional, it is important to conceive the meaning of holonomic movement. A holonomic motion system is capable of controlling all existing degrees of freedom independently. This means for a rigid body in a two dimensional space all 3 degrees of freedom (DoF) can be controlled separately. A platform mounted on 3 mecanum wheels, whose axes intersect at one point is capable of holonomic motion. A more intuitive model can be pictured when imagining a human being on her/his two legs. When a person travels on a planar surface without obstacles, she/he is capable of turning on the spot, moving forward, backward and to either side at any time. A human being could even walk on a rectangular path while it spins around its vertical body axis.

Any holonomic motion system is capable of doing this and even more compli-

cated movements. In short, holonomity provides maximum freedom for motion in the considered space. Although omnidirectionality seems to be exactly the same at first sight, there is a drastic difference. If you imagine a vehicle on 3 actively steered wheels, which can be actuated independent from each other, this platform is also capable of moving from any point in a horizontal two dimensional space to any other point (on this plane) following any arbitrary trajectory and it can still choose its orientation at any moment. But still the described vehicle is not capable of holonomic motion. If we consider a path with discontinuous curvature, the cart can not follow the trajectory without stopping at the points where the track curvature is discontinuous to reorient the wheels. This motion limitation derives from the fact that the vehicle motion is fixed by the current orientation of the wheels at every moment. As it turns out holonomic motion requires more complex mechanisms than omnidirectional move-ability, while it only has the advantage that the cart can follow any trajectory without the necessity to stop at some particular points. For the mobile base of a service robot this tradeoff seems more than acceptable.

Requirement 2 - Overcoming Obstacles
As most flats in Austria have small thresholds at some doorways, it is essential for a domestic robot to overcome these obstacles without help. Transforming this requirement to a technical specification is not as easy as it seems because the mentioned thresholds vary in height from 5 mm up to 210 mm, like steps of a stair. Based on the EU standard for electrically powered wheelchairs DIN EN 12184, the robot base has to be capable of overcoming obstacles with a maximum height of 50 mm. This matches the specifications for class B wheelchairs designated for indoor use but also capable of overcoming certain obstacles outdoors.

Requirement 3 - Single Step Climbing
Following up the last requirement further specifications need to be met concerning thresholds of more than 50 mm. To ensure that the mobile base can travel to any room in an apartment an appropriate maximum step height must be specified. For this thesis the robot is required to climb single single steps and thresholds with maximum height of 210 mm. This specification derives from the norm for "Stairs in buildings" currently valid in Germany (DIN 18065:2015). The value of 210 mm corresponds with the maximum height of steps inside an apartment as limited in the mentioned standard.

Requirement 4 - Driving on a Slope
One of the target groups for the mobile robot *BLUE* is handicapped people living on their own. It is often the case that their apartments have been adapted to make all rooms accessible by wheelchair. A standard solution to eliminate

single steps, thresholds or similar barriers is the installation of ramps, which makes sloped surfaces a predictable part of the robot's environment. Following the specifications for electrically powered wheelchairs, as presented in DIN EN 12184:2011, the mobile base is required to climb slopes up to 10% (equal to 5,71° or 0,10 rad). This obligation corresponds with the demanded dynamic stability for class C wheelchairs specified in the mentioned standard.

Requirement 5 - Surface Irregularities
Besides thresholds underneath doorways most apartment floors show deviations from horizontal planes. If they can neither be described as a removable object nor as part of a transition from one floor level to the next, they are called surface irregularities in this thesis. For reasons considering stability and motion it is necessary to equip the drive module with a spring and damping mechanism, which ensures surface contact of all propulsion devices in case of surface irregularities. Without further reasons than estimation the height to be compensated is set to 30 mm.

2.2.2 Geometrical Requirements

Requirement 6 - Outside Dimensions
A common problem with currently used/tested robot bases is that they can not turn around on their vertical axes when standing in narrow spaces e.g. a doorway. Combined with the limitation that most robots need to see where they are bound for, this results in robots being stuck when they can not pass the narrow place due to any reason. To work around this problem it is either possible to enable the robot to see the area behind it or to enable the robot to turn on the spot underneath a doorway. Following the second approach limits the outer dimensions of the mobile robot base to 500 x 500 x 500 mm. The vertical limit for the omnidirectional base derives from the demand that the base has to fit beneath a table and that it should be useable as an aid for standing up. In both cases a stool is a good model to determin the height of the mobile base because they can be placed underneath most tables and they can be used in the mentioned strategy for standing up.

Requirement 7 - Tilt Angle
Besides the ability of climbing a slope of 10 % the robot also needs to avoid falling over when standing or moving on a tilted plane. As the robot design is not yet finished, it is hard to implement the static and dynamic stability of the whole system in the design of its base unit. To lay a foundation for an upcoming calculation with the entire robot, it is required that the robot base alone does not turnover when standing on a sloped surface with 15 % (equals 8,53 ° or app. 0,149 rad).

Requirement 8 - Mass and Payload
To ensure the further use of the mobile platform, it is obligatory to fulfill all required motion specifications while carrying a payload. The robot is estimated to have a total mass of 60 kg including payload. To minimize energy consumption, the mass of the mobile robot base should be held low. It is important to keep in mind that this limitation is important for calculations concerning movements. For a static load the weight of a person is crucial. This scenario comes to life when BLUE acts as aid for standing up.

Requirement 9 - Maximum Traveling Speed
When talking about maximum traveling speed distinction must be drawn between maximum permitted traveling speed and maximum possible speed. As the maximum permitted tempo of the robot strongly depends on the traveling path and the robots field of view, it is subject to continuous changes. The maximum possible speed of the robot on the other hand is a fixed value, or more precisely a curve, taking into account different degrees of loading. Since this thesis does not deal with motion strategies or motion control the maximum possible traveling speed of the base is the subject of matter. The mobile base is required to reach the maximum possible traveling speed of 1 $\frac{\mathrm{m}}{\mathrm{s}}$ with 60 kg total mass (including payload).

Requirement 10 - Floor Clearance
To ensure floor contact of the propulsion system and no other part of the robot base in any scenario, it is necessary to calculate the distance between floor and the lowest components of the mobile base. Floor contact of any other component than the propulsion system may cause damage to the robot or prevent it from moving at all. Special focus has to be put on scenarios where the base is overcoming a threshold, uneven terrain or the edge of a ramp.

Requirement 11 - Underbody Protection
Additional to Requirement 10, it is important to prevent damage from unforeseeable floor contact of any components not belonging to the propulsion system. The proposed preventive measure is a cover similar to underbody protection on a car but with the additional mechanical stability to prevent damage to the base components.

2.2.3 General Design Requirements

Requirement 12 - Contained Components
With the overall goal of using the described mobility system as a base unit for a service robot, the structure is required to house several components, which are needed for mounting and operating the attached robot parts being two

Table 2.1: Contained Components

Component	Description	Dimension
Video Card	A Video Card is needed for processing camera data	120 x 220 x 30 mm^3
Main Board	Top level control	240 x 135 x 295 mm^3
Pump	DC powered hydraulic pump	200 x 100 x 100 mm^3
Pressure Tank	Container for pressurized hydraulic medium	4 L
Tank	Reservoir for unpressurized hydraulic medium	4 L
Battery	A 24 V 40A h Powersupply	394 x 175 x 190 mm^3
Recharger	Line powered Battery Recharger	170 x 70 x 50 mm^3

arms, two hands and a head. The components, which need to be housed, are listed in Table 2.1.

Requirement 13 - Knee and Upper Leg
As mentioned in Section 2.1.2 the mobile base is not planned and designed to function on its own. It is one part of a system which constitutes one robot capable of helping its user(s) with tasks of daily life. The "knee and upper leg" section of the robot base are the area at which other components will be attached to the omnidirectional robot base in future. During the definition of the boundaries of this project the supervisors and the author agreed on implementing a non functional simplified representation of the current design for the mechanical connection between the mobile base and the torso of the robot. This compromise allows a good representation while reducing the scope of this thesis.

Requirement 14 - Easy to Maintain
The mobile base has to allow easy maintenance, implying limited equipment in particular special tools needed to perform maintenance work, as well as a design to make maintenance possible in application areas like small apartments. The uses of fragile screwing connections, which run the risk of breaking, or loosing small components, are explicitly prohibited.

Requirement 15 - Soft Tactile Cover
Following the general concept of BLUE the mobile base has to be housed with a soft and tactile cover. The main purpose of this soft surface is to detect contact and reduce impact forces. The force detection is necessary to augment the video sensors at their task of perceiving the robot's environment. The

tactile surfaces can be used to detect collisions. Using this technology surface contacts outside of the field of view of the camera will be detected. To prevent people from harm and the environment from damage the sensor surfaces are required to be resilient. Blue Danube Robotics developed a product which was designed to meet all of these requirements. The product family is named AirSkin [4] and is split into AirSkin Safery and AirSkin Sense. While the first version is certified as an emergency stop, the second product is a soft tactile sensor, which can be attached to any robot or robotic device.

Requirement 16 - Cliff Sensors
Similar to the soft and tactile cover, the implementation of cliff sensors has to augment the video sensors to ensure the detection of thresholds and floor level differences. The consequences of rolling over a threshold without detecting it can be fatal, the implementation of sensors for the prevention of such incidents is important.

Requirement 17 - Low Noise Level
When it comes to noise level most people think the lower the noise pollution the better, which is correct generally speaking. Following this idea the mobile robot base as well as the rest of BLUE's components shall emit a minimum amount of sound and noise especially when the robot does not move, is in standby waiting for it's next task or charging it's battery. With this requirement no target value will be formulated because the target is minimization. Referring to the Austrian decree concerning noise and vibration (VOLV) [12, page 2, §5.1] the noise level within apartments and recreation rooms has to be below 50 dB. Although the decree concerns workplaces it is used as closest related regulation. For sake of completeness I want to add that a certain level of noise can have a positive influence on the acceptance of users for the service robot because most human beings are shocked to suddenly see a person which they did not hear coming into the room. It would be to expect that the noiseless appearance of a service robot will lead to similar reactions. In any case with current technology I do not see any danger that this problem will arise due to processor fans and rolling noise

2.2.4 Target Market Requirements

Requirement 18 - Economical Production
To distinguish the designed service robot from competing products Blue Danube Robotics wants it to be available at a low price. This economic objective is a total price of 18.000 €, setting the target costs of the mobile base to 1.000 €, excluding a selection of components, particularly the video card.

[4] The AirSkin product family is a registered trademark of Blue Danube Robotics OG

Requirement 19 - Ecobalance
During construction and material selection a minimum environmental burden has to be emphasized. Through selection of local resources as well as ecofriendly production processes, the negative impact of the product on the environment has to be kept in mind over the whole life cycle. The focus must lie on the consumer product, not on the prototypes, but to provide the best results, ecological awareness has to influence design considerations even at the early development phases. Some explicit suggestions from the supervising team are the use of recyclable biodegradable materials like wood or wood-fiber reinforced polylactide from local fabrication.

3 Top Level Design

3.1 Functional Units and their Boundaries

To meet all requirements it is reasonable to form sub-assemblies each dedicated and designed to meet a group of related requirements. While most of the specifications listed in Section 2.2 only influence the design of one functional unit, some specifications affect multiple sub-assemblies of the omnidirectional mobile base.

3.1.1 Forming Functional Units

To simplify the definition of functional units it is helpful to group the requirements. There are numerous possibilities to combine the specification. One possibility was presented by the structure of Section 2.2. Using this approach it is an obvious decision to create one sub-assembly covering the specifications listed in section Motion Requirements and another one covering the specifications of Geometrical Requirements. The first functional unit is called *motion system*, as it deals with all specifications concerning the movement of the base. The second sub-assembly dealing with geometrical properties is named *bearing structure* but could also be called chassis referring to automotive industries. These two functional units cover the most important attributes of the mobile base by providing the possibility to move and giving stability. Additional to these two sub-assemblies two less noticeable function units are defined. Namely these are the *base hull* and the *internal components*. The last system contains all components, which are needed on board either because they are listed in Table 2.1 (presented in Requirement 12) or because one of the other three functional units needs it as peripheral environment.

3.1.2 Motion System

To ensure the desired move-ability this motion system is designed focusing on the requirements listed in Table 3.1. The first five requirements are the primary requirements for this functional unit because they define its minimum capabilities. The developed motion system has to provide omnidirectional

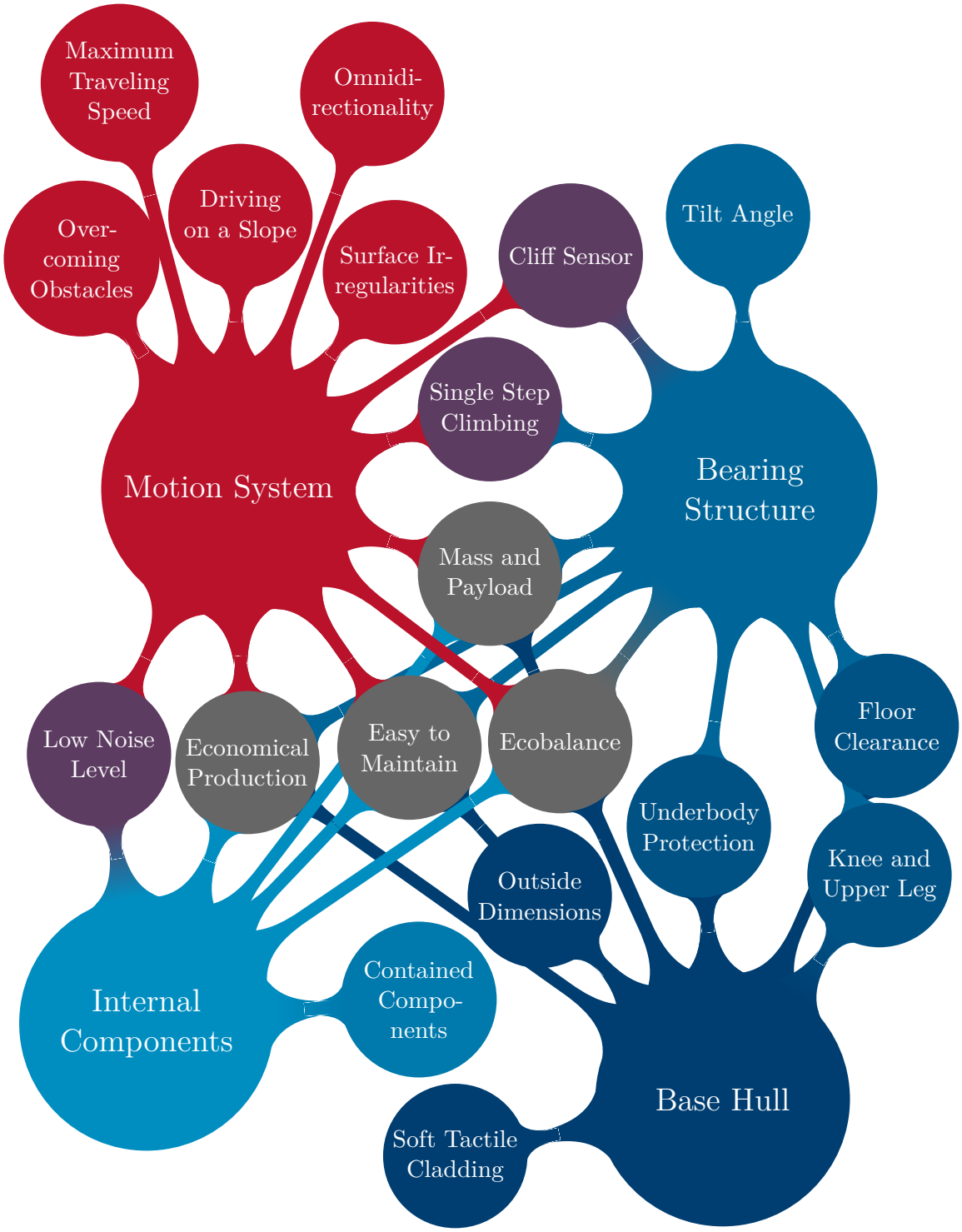


Figure 3.1: Mindmap showing the presented requirements in relation to the proposed functional units.

Table 3.1: Requirements for the Motion System

Requirement	Specification	Ref.
Omnidirectionality	Capable of omnidirectional movement	Req. 1
Overcoming Obstacles	Get over 50 mm high obstacles	Req. 2
Single Step Climbing	Climb single steps up to 210 mm	Req. 3
Driving on a Slope	Climb a slope of 10 %	Req. 4
Surface Irregularities	Cope with irregularities of 30 mm	Req. 5
Mass and Payload	Carry a payload of 60 kg	Req. 8
Maximum Traveling Speed	Traveling speed can not exceed 1 $\frac{m}{s}$	Req. 9
Easy to Maintain	Maintained by few and simple steps	Req. 14
Cliff Sensors	Implementation of min. 4 cliff sensors	Req. 16
Low Noise Level	Noise Level below 50 dB	Req. 17
Economical Production	Production costs less than 1000 €	Req. 18
Ecobalance	Minimum environmental burden	Req. 19

movement while overcoming surface irregularities, getting over obstacles with maximum height of 50 mm as well as single steps of 210 mm or climbing a slope of 10 %. Every propulsion concept which can not meet all of these requirements is unsuitable for the presented purpose. Additionally to these five items three more requirements from different sections have been added to the list. Although all specifications presented in Section 2.2 influence the design of each and every component to a certain degree, the last three items in Table 3.1 seem to be more important than the non-listed requirements and can be referred to as secondary requirements for the purpose of designing an optimal motion system for the omnidirectional robot base. The specified mass and payload influence the power of the actuators while Requirement 14 (easy to maintain) makes a modular solution reasonable. Economical production leads the construction towards existing concepts based on simple components. Last but not least ecobalance emphasizes a design that causes low energy consumption during usage.

3.1.3 Bearing Structure

Besides motion also stability is a critical aspect of the omnidirectional mobile base. To ensure sufficient properties the support structure of the mobile base has to comply with the following requirements. First of all the structure is required to support 60 kg payload additionally to the mass of the mobile base

Table 3.2: Requirements for the Bearing Structure

Requirement	Specification	Ref.
Single Step Climbing	Climb single steps up to 210 mm	Req. 3
Tilt Angle	Must not fall over when tilted 15 °	Req. 7
Mass and Payload	Carry a payload of 60 kg	Req. 8
Floor Clearance	Distance between body and floor is 50 mm	Req. 10
Underbody Protection	Floor contact must not deal damage	Req. 11
Knee and Upper Leg	Consider later attachment of a upper leg component	Req. 13
Easy to Maintain	Maintained by few and simple steps	Req. 14
Cliff Sensors	Implementation of min. 4 cliff sensors	Req. 16
Economical Production	Production costs less than 1000 €	Req. 18
Ecobalance	Minimum environmental burden	Req. 19

itself. This demand is tightened when combined with the request that the base has to withstand the changed load distribution on a sloped surface (with 15 °) or with the static stresses and strains effected by the strategy to overcome single steps presented in Figure 4.11. Providing stability also includes the task of mechanically connecting the drive modules to ensure the proper functioning of the motion system. Furthermore the bearing structure has to ensure 50 mm clearance between an even floor and the lowest parts of the mobile base despite components of the motion system. The construction of the support structure has to be designed to fit all components listed in Table 2.1 in the base as well as to allow easy maintenance. The demand for Economical Production leads the construction towards the use of simple production techniques as well as reasonable priced materials and towards a low number of parts. Last but not least Ecobalance emphasizes the use of eco-friendly materials.

3.1.4 Base Hull

The main requirements for the base hull are the outer dimensions, the easy maintainability and the soft and tactile cover as concluded in Table 3.3. While the outside dimensions and the soft tactile covering have a clear impact on the design, the influence of Requirement 14 is less obvious to see. In accordance with the design of the bearing structure the base hull has to feature the possibility of an easy access to the contained components. Furthermore the base hull has to be designed regarding the bearing structure to ensure the proper functioning

Table 3.3: Requirements for the Base Hull

Requirement	Specification	Ref.
Outside Dimensions	Maximum shape of 500 x 500 x 500 mm^3	Req. 6
Mass and Payload	Carry a payload of 60 kg	Req. 8
Floor Clearance	Distance between body and floor is 50 mm	Req. 10
Underbody Protection	Floor contact must not deal damage	Req. 11
Knee and Upper Leg	Consider later attachment of a upper leg component	Req. 13
Easy to Maintain	Maintained by few and simple steps	Req. 14
Soft Tactile Cover	Surfaces covered with soft tactile sensor	Req. 15
Economical Production	Production costs less than 1000 €	Req. 18
Ecobalance	Minimum environmental burden	Req. 19

of the floor clearance and under-body protecting measures.

3.1.5 Internal Components

The internal components consist of the contained components listed in Table 2.1 and several other parts which have to be implemented in the mobile base to allow its proper functioning like valves for the hydraulic system or cabling. The most important task in this functional group is the selection and the efficient distribution of the components inside the base. As most of the parts are prescribed, the task of selecting proper components is subsidiary. Besides geometrical properties, other interdependencies between the parts have to be taken into account. One example is that the placement of the hydraulic pump above the video card or the main board bears the risk of fatal damage in case of pump leakage. The ideal placement also has to take into account maintainability in the sense, that big components block the access to the parts behind them.

3.2 Design Concept

To simplify further discussions about a solution to the complex set of problems the following section presents an early stage concept for the omnidirectional robot base in compliance with the requirements listed in Section 2.2. In order to find a sufficient design the complex problem was divided into small design tasks. The subsequent system is a conglomerate of the optimal solutions to

Table 3.4: Requirements for the Internal Components

Requirement	Specification	Ref.
Mass and Payload	Carry a payload of 60 kg	Req. 8
Contained Components	Store components listed in Table 2.1	Req. 12
Easy to Maintain	Maintained by few and simple steps	Req. 14
Low Noise Level	Noise level below 50 dB	Req. 17
Economical Production	Production costs less than 1000 €	Req. 18
Ecobalance	Minimum environmental burden	Req. 19

these smaller design tasks, each taking into account only the most important circumstances.

3.2.1 Motion System

As a direct consequence of the demand for an omnidirectional mobile base the design does not show a preferred motion direction. Following the considerations presented in the next chapter the motion system consists of four identical drive modules. Each of these sub assemblies consists of a wheel, two hydraulic slide vane actuators, one hydraulic piston, two linear slides, a number of ball bearings and several parts designed to attach all parts together. Figure 3.2 presents the alignment of the mentioned components for each drive module as well as the positioning of the modules inside the robot base. One of the rotary actuators is used to drive the wheel. To reduce the number of components for transmission motor and wheel are aligned coaxial. Furthermore to minimize the required space the hydraulic actuator is located inside of the wheel. The second slide vane actuator is used to rotate the wheel along the vertical axle implementing a steering movement of the wheel. Last but not least a double acting hydraulic piston actuator is attached between the mounting structure of the drive module and the bearing structure. By varying the distance between wheel axle and fastening point at the bearing structure this actuator can lift each wheel individually and thus enables the mobile base to climb single steps and thresholds. The linear slides absorb transverse forces.

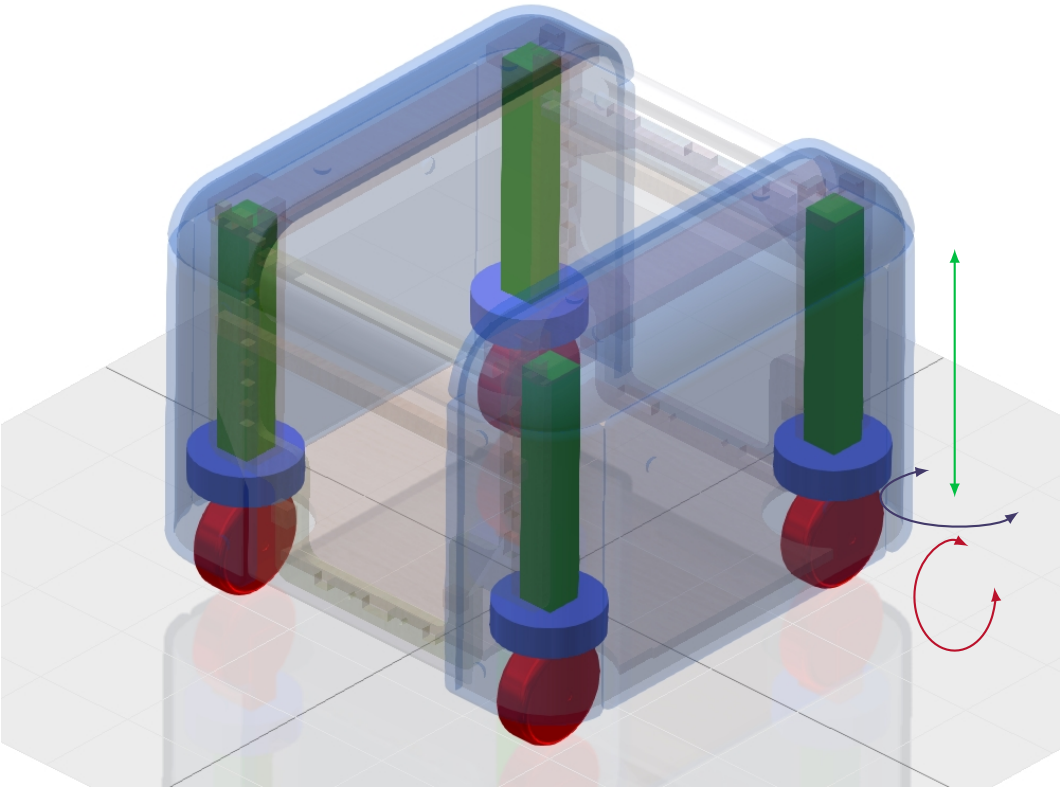


Figure 3.2: First design of the motion system showing the positioning of the four similar drive modules within the mobile base. The colored arrows illustrate the direction of movement of the three actuators implemented in each drive module.

3.2.2 Bearing Structure

The first design of the bearing structure consists of eleven wooden pieces which can be assembled simply by inserting fitting sections similar to dovetail joints common in carpenter products. The assembly consists of seven different parts which all can be produced using simple 2d CNC contour cutting steps, making production less demanding. To prevent assembling the parts wrongly they are designed to fit only in one position.

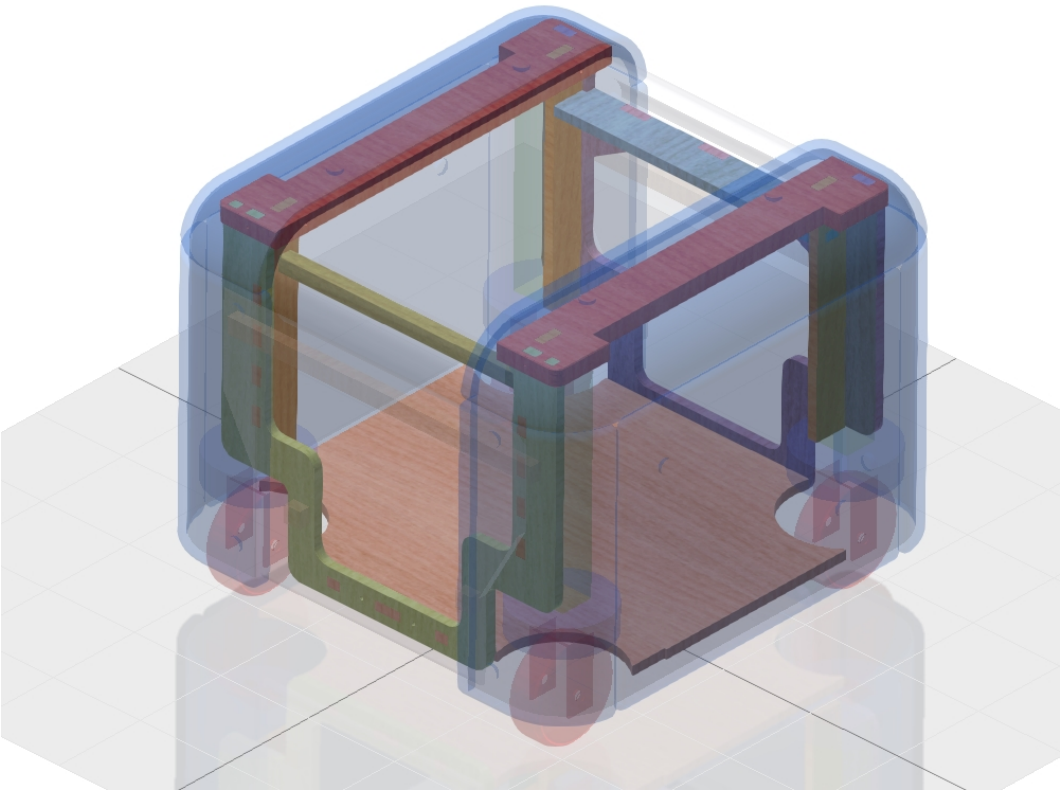


Figure 3.3: First design of the bearing structure assembled of seven different contour-cut parts, using a form-fit design to reduce the chance of wrong assembly.

3.2.3 Base Hull

The first design of the Hull of the mobile base is focused on limiting the potential to do damage or to injure users. Means to this goal are rounded edges, soft contact surfaces and a minimum gap between the upper leg and the base hull to reduce the risk of pinching fingers or other body parts. The first design presented consists of two shields attached to the bearing structure to cover the front and back side of the base, a non-actuated upper leg and hip and two assemblies for covering the sides and the drive modules. Each of the side covers can be removed easily and consists of one frame shape and four soft and tactile components attached to it. In Figure 3.4 the tactile surfaces are colored in blue, while white components consist of painted wood.

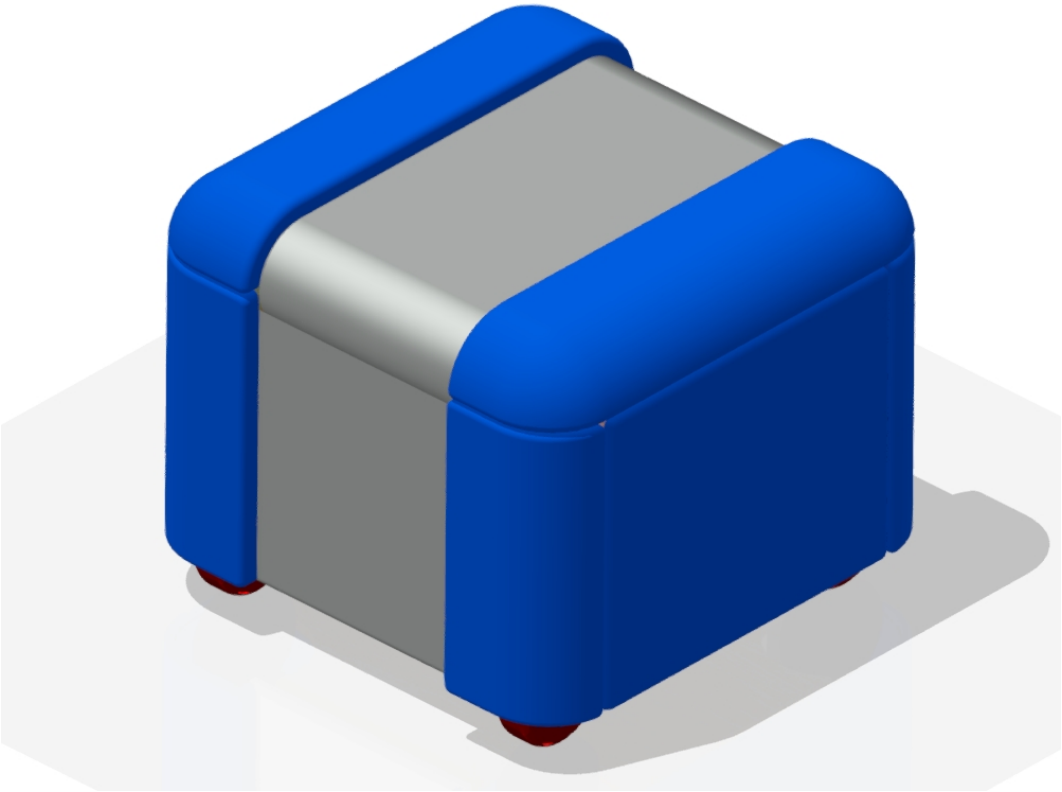


Figure 3.4: First design of the base hull. Components in white color are made of painted wood, while blue parts are covered with soft tactile cover.

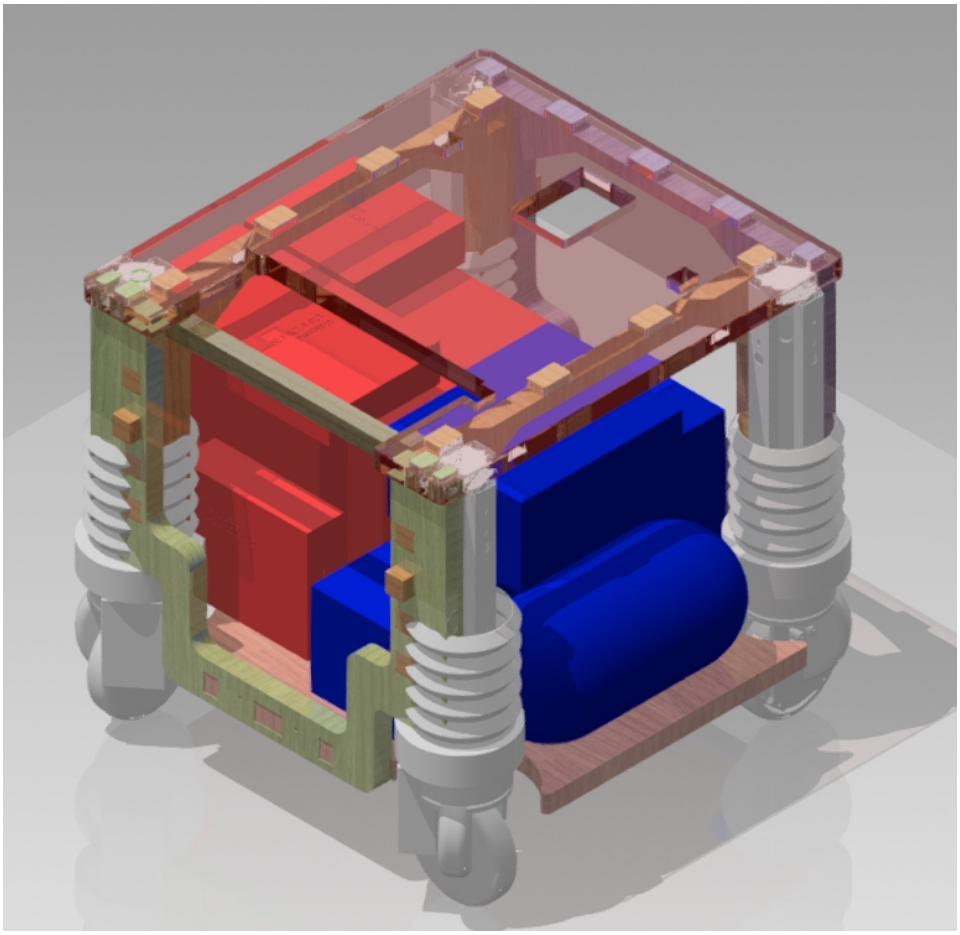


Figure 3.5: First distribution design of the internal components showing electrical components in red, hydraulic components in blue. The components are presented in simplified shapes.

3.2.4 Internal Components

To optimize the distribution of the internal components the focus was laid on the separation of hydraulic and electric components to reduce the risk of damage due to leakage. The installation of a wooden screen between hydraulic and electric components was planned, but discarded, because it contradicts the idea of easy maintainability and the risk of critical leakage was rated low.

4 Low Level Design

4.1 Designing the Motion System

To understand the first design concept of the motion system described in Section 3.2.1 a basic overview over mobility concepts is the chosen starting point. Figure 4.1 provides a systematic overview over possible concepts for locomotion used in mobile robots. Each and every movement strategy presented has its advantages. To find the best fitting concept is the first step to designing a suitable motion system. For a systematic analysis the following three sections each discuss one tree of the mindmap presented in Figure 4.1 and its representatives.

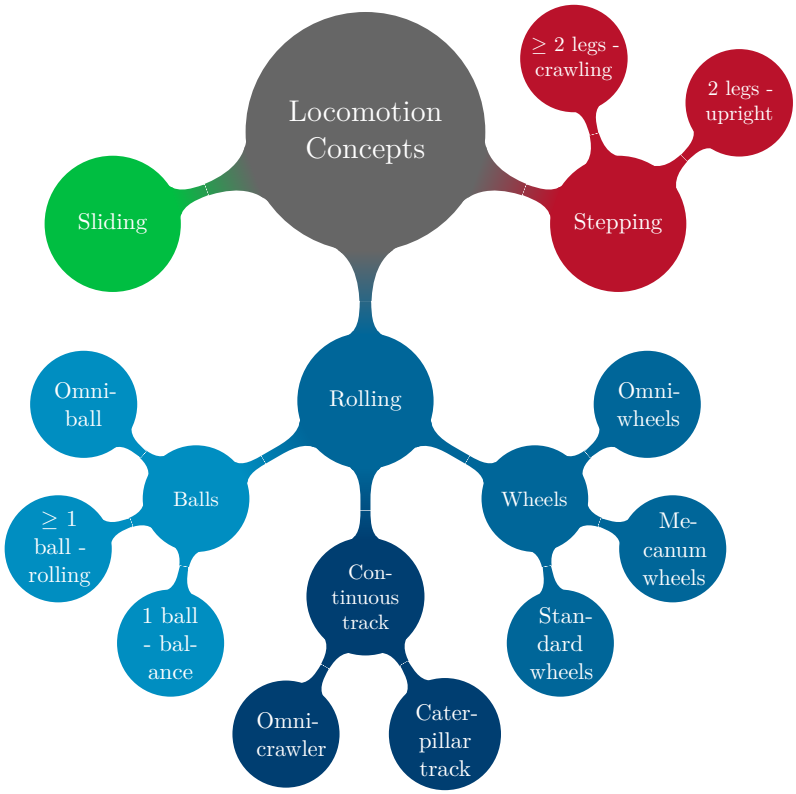


Figure 4.1: Mind map showing concepts for propulsion of ground vehicles

4.1.1 Sliding

Sliding or skating is a very efficient locomotion concept for cross-country skiing and ice skating but not fitting for the presented scenarios. Although it provides the possibility to move in any direction it is very ineffective on common apartment floors. As we all noticed several times textile fabric, like the one our socks are made of, slides perfectly well on parquet floor but can hardly slide on a carpeted floor. This example demonstrates that there are some material combinations which enable sufficiently low friction for sliding locomotion but there is no material, which can achieve this effect with all floor materials in common housings.

Another issue with sliding as movement concept is that slopes have an excessive influence on the speed and effort for the motion. Watching a biathlon or a cross-country ski race the differences in tempo on a sloped surface and on horizontal course sections can be studied easily. Although there are certain material combinations which would provide an effortless propulsion locomotion concepts based on sliding are quite inefficient on an average mixture of floor materials. Additionally steps preventing undesired motion on sloped surfaces would be required.

4.1.2 Stepping

Apartments are designed for human beings. Keeping this fact in mind it seems a great idea to design a service robot with the ability to move in the same way as its owner. As a consequence of this approach varying floors, thresholds beneath doorways, surface irregularities and slopes do no longer pose insurmountable obstacles. Instead of climbing a single step, as stated in Requirement 3, a bipedal robot would be able to ascend a stairway just like a human. The drawbacks to this overwhelming concept are difficult mechanisms and the need for an extremely elaborate control system. A specially challenging task is to keep balance during movement. To decrease the control effort for holding the balance the number of feet used in the motion system can be increased. One especially popular design concept for robots is the so called hexapod named for its six legs. This concept allows several gait patterns, amongst them a very simple gait where two sets of legs (three legs per set) are moved in turn. Because the three legs with their three contact points provide a stable standing at any time as long as the projection of the center of mass lies within the spanned triangle. Despite this drastic simplification the hexapod concept is complex compared to Section 4.1.3 locomotion.

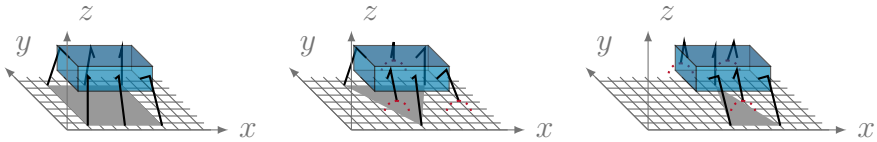


Figure 4.2: Hexapod walking

4.1.3 Rolling

In contrast to Sliding and Stepping the mechanisms for most propulsion concepts based on Rolling can be described as well-engineered. While rolling over thresholds can pose a problem, traveling on horizontal surfaces or on slopes can be accomplished easily. To compensate surface irregularities spring damping units are applied in wheel suspensions. Figure 4.3 illustrates an overview over existing concepts summarized under the term rolling.

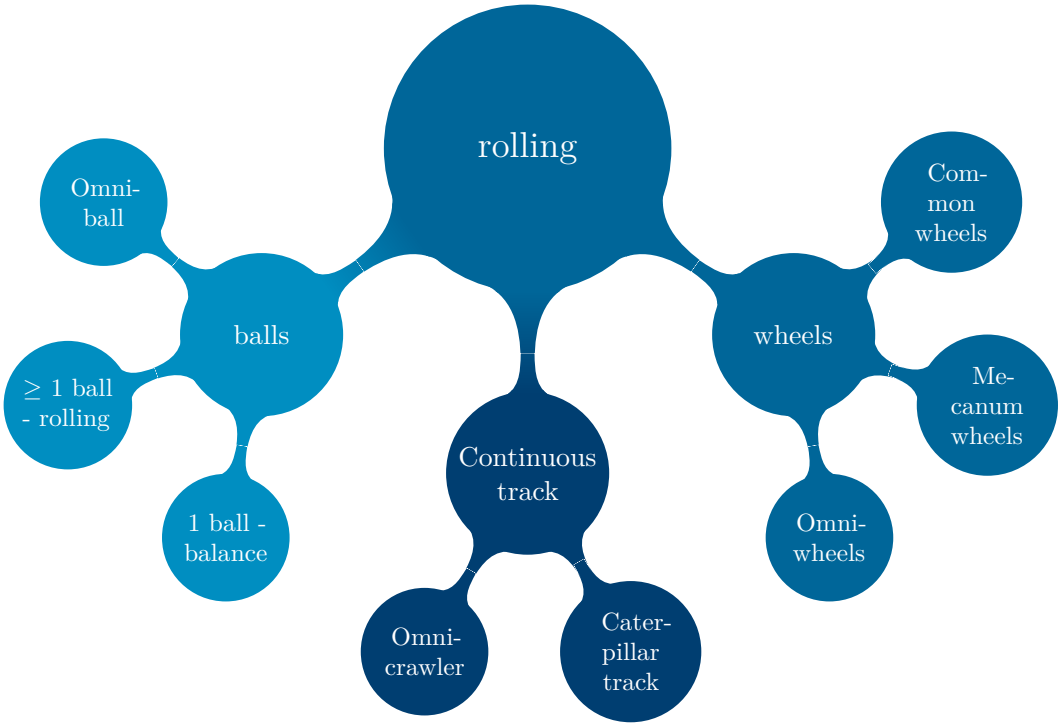


Figure 4.3: Mind map showing different locomotion concepts based on rolling.

When we usually mention this word most people think of motorcycles, bicycles, cars or sometimes tricycles. In more general terms in our minds we see the image of a vehicle on two, three or four wheels, with one or two of them actively steered.

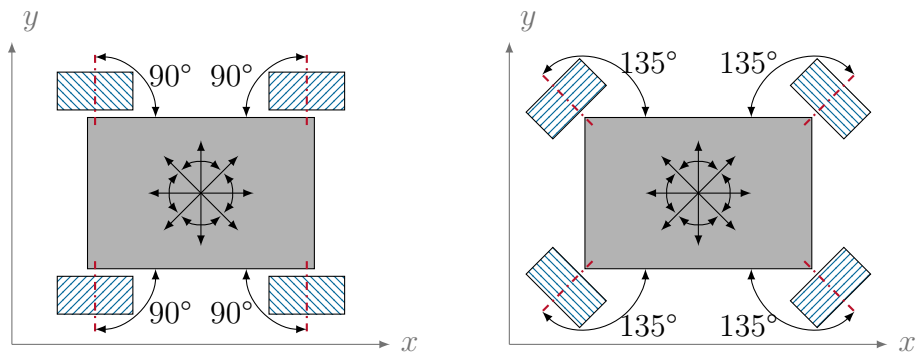
(a) Mecanum wheel from Nexus Robot [13]

(b) Omni wheel from Nexus Robot [14]

Figure 4.4: Comparison of a Mecanum wheel and an Omni-wheel both from Nexus Robotics

Referring to Figure 4.3 these descriptions would fit to the entry "Standard wheels". In general the use of wheels drastically reduces the amount of energy needed to move loads sideways on horizontal surfaces. The effort to move a wheeled object in the direction of the wheel axes is not reduced because the wheel can not roll in this direction. In contrast to these wheels Mecanum wheels and Omni-wheels, concluded as "special wheels" can be shoved in transverse direction to their rotational axis. To achieve this flexibility the contact surface of special wheels is equipped with rollers. The difference between Mecanum and Omni-wheels is the angle between the wheel motor axle and the axes of the rollers as Figure 4.4 illustrates. The most remarkable benefit of special wheels is that they enable a mobile base to move omnidirectionally with a minimum of three wheels using only their drive motors if the wheels are positioned appropriately.

Figure 4.5 illustrates the position and angle in which four special wheels of each type need to be attached to a rectangular shaped chassis. To achieve omnidirectionality using standard wheels several conditions have to be fulfilled, one of them is the installation of one steering actuator for each driving motor used for propulsion. At first the reduced number of actuators seems very tempting. This concept seems to reduce mass and lower the production price of the base. But this first conclusion does not take into account that the engines used for bases with special wheels need to be more powerful. This is because with the application of Omni-wheels the propulsion in each direction is performed by two engines instead of four. The use of Mecanum wheels on the other hand causes opposing contact forces, which have a similar result. Standard wheels require an additional steering engine and a more difficult suspension. The benefit of steered wheels over non steered special wheels is their ability to roll over bigger objects regardless of the motion direction



(a) Mecanum wheels are attached to the cart similar to standard wheels without the steering mechanism at the front axles, but considering passive rollers.

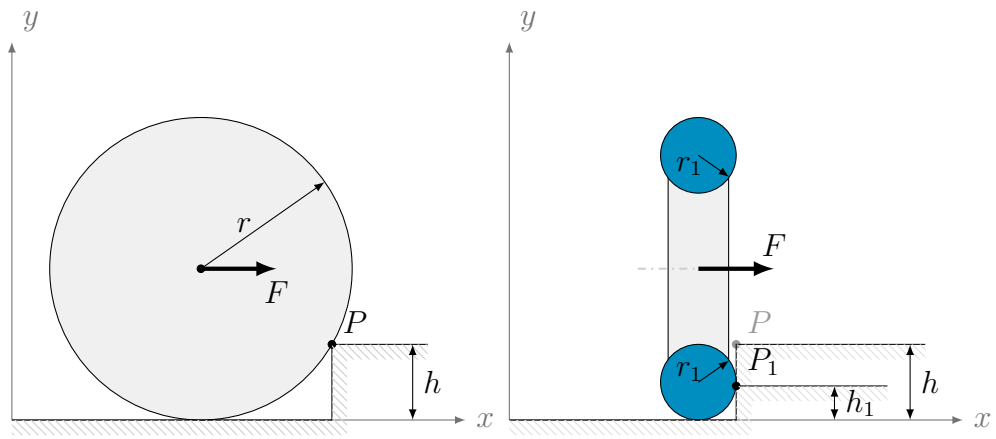
(b) Omni-wheels have to be mounted 135° from the lateral surface to realize the same result. They also don't require a steering mechanism.

Figure 4.5: Picture showing the mounting places for omnidirectional mobile bases using special wheels. As indicated by the blue stripes the passive rollers on the wheels are positioned 90° or 0° from each other regardless of the applied special wheel. This orientation allows each pair of wheels to actuate one direction

because the wheel axles always point 90° from the motion direction.

Figure 4.6 aims to illustrate this problem by presenting two wheels of the same size (one a common and the other a special wheel). The dark blue circles in Figure 4.6b represent the passive rollers of the special wheel, which are important for determining the necessary torque for rolling over an obstacle.

Up to this point the only elements discussed for rolling motion were wheels. Figure 4.3 also presents continuous tracks and ball based rolling. The most common application of continuous tracks are heavy off-road vehicles like tanks, or snow groomer. As continuous tracks cause high friction and a high noise level when the vehicle is rotating/changing its movement direction a use of this technology seems beyond question. The most common reason for their use is that due to their large area of surface contact heavy machines can be moved off roads, enabling tanks to drive through deserts without bogging in sand. A drawback of conventional continuous tracks is that they do not provide omnidirectional motion. In 2008 a team of scientists headed by K. Tadakuma published an article titled "Crawler Vehicle with Circular Cross-Section Unit to Realize Sideways Motion" [15]. The presented technology enables a vehicle with continuous track to move sideways providing the necessary flexibility to realize omnidirectional motion. Although this technology complies with



(a) A common wheel rolling over an obstacle.

(b) An Omni-wheel pused over an obstacle.

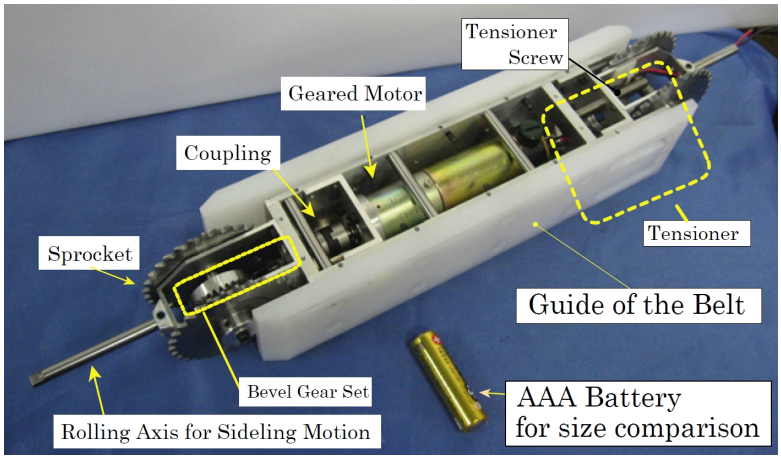
Figure 4.6: A common wheel has to overcome obstacles in its motion direction. An Omni-wheel in contrast is sometimes pushed over an obstacle lateral to its actuated motion direction. This causes the surmountable object height to fall below the radius of the passive rollers on the omni wheel.

Requirement 1, it is not the optimum choice for the design problem at hand because continuous tracks need more space and have a lower efficiency than wheels.

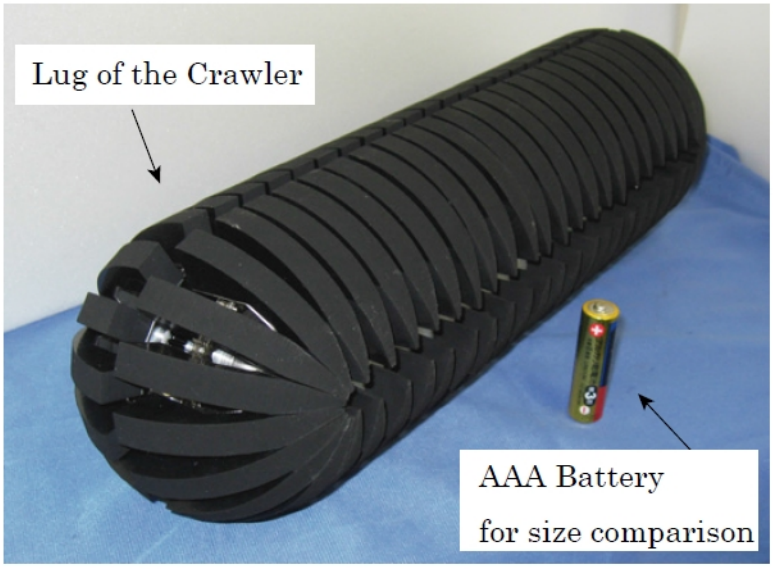
Figure 4.7 presents one continuous track for omnidirectional motion called Omni-Crawler, as well as a vehicle propulsed by two of these tracks. The Omni-Crawler can only provide active rotation in the same direction as a common continuous track, enabling the vehicle to drive forward and backward as well as to rotate around its vertical axes. The Crawler Unit is equipped with a motor, which actuates the Crawler Tracks (labeled "Normal Crawling Motion" in Figure 4.7c) from inside. Sidewards motion is facilitated by the circular cross section of the Omni-Crawler track, but this motion is not actuated from inside the Crawler, but rather by a motor located on top of the Crawler Vehicle labeled "Motor for Rolling Motion". Several other arrangements of Crawler Units can be made to provide omnidirectional motion with only one actuated axis per Omni-Crawler.[1]

The last of the concepts presented in this section is describes the use of balls instead of wheels. This idea also seems appealing because spheres can rotate around any axle which crosses the center of the sphere. This characteristic

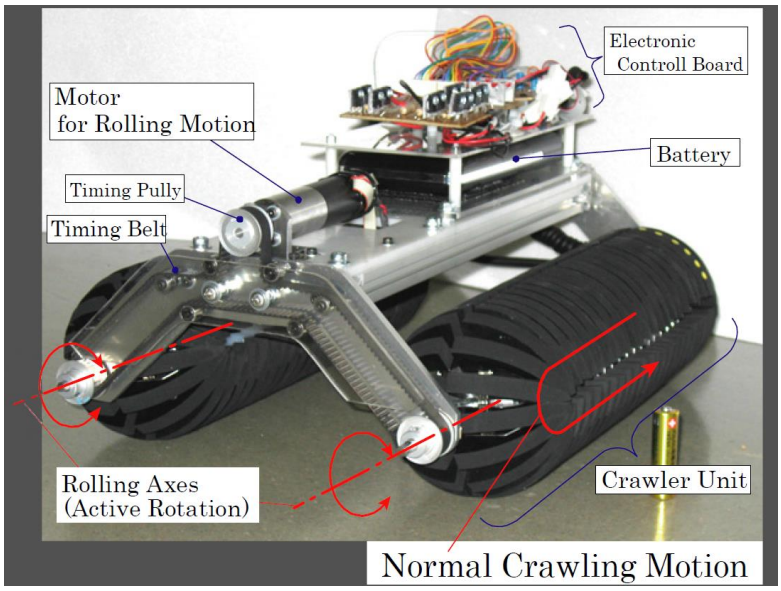
[1]For some different examples for Omni-Crawler Vehicles please see [15, page 2425]



(a) Internal composition of the Omni-Crawler, ©by IEEE, 2008



(b) An assembled Omni-Crawler Unit without Rolling Axis for Sideling Motion. , ©by IEEE, 2008



(c) Basic structure of the Crawler-Vehicle, ©by IEEE, 2008

Figure 4.7: Omni-Crawler and Crawler-Vehicle designed by a team of scientists headed by K. Tadakuma and published 2008, [15], all images ©by IEEE, 2008

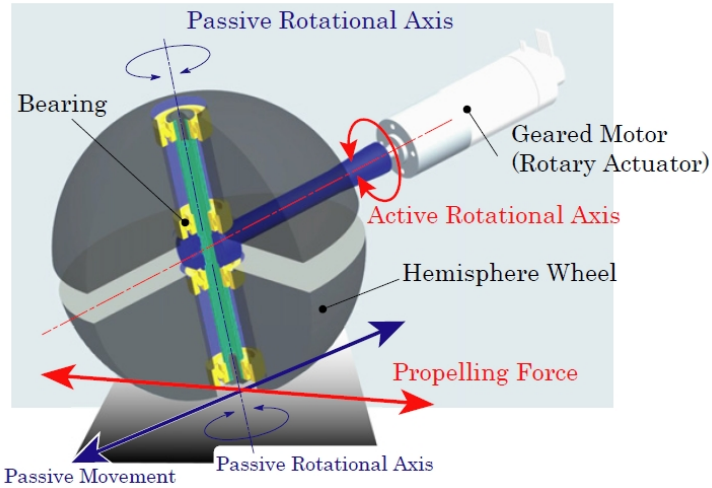


Figure 4.8: Basic structure of the Omni-Ball. Two hemispheres are mounted on a freely rotatable axis. The actuated axis is perpendicular to the mentioned passive axis, allowing passive motion in one direction and active motion in the perpendicular motion. taken from [15] ©by IEEE, 2008

enables vehicles on spheres to be capable of holonomic move-ability independently of their arrangement. The problems that arise from the use of balls in stead of wheels are that in contrast to continuous tracks the contact area is very small and that it is a very difficult endeavor to realize an efficient force transmission from the actuators to the sphere as well as from the sphere to the ground. To improve the efficiency of the power transmission from the motor to the sphere an Omni-Ball can be used.

Figure 4.8 presents the so called Omni-ball, which allows control of the rotation around one (active) rotation axis, while passive rotation around the second axis is maintained. The appealing idea of controlling rotational movements around both marked axes of a sphere leads to a similar problem as the use of wheels and special wheels for omnidirectional motion. Either the ball is driven by an Omni-wheel which can be reoriented to select the direction of active motion or more than one Omni-wheel needs to be applied to allow omnidirectional motion by superposing two motions.

Concluding we can state that the use of a ball as rolling element instead of a wheel leads to a smaller contact surface, and thereby reduces friction. Despite this benefit ball based rolling adds the difficult task of transmitting drive torque to the sphere, allows no reduction of actuators and does not simplify the construction of an omnidirectional mobile robot base compared to a design

using common wheels or special wheels.

4.1.4 Concept

Based on the above described advantages and disadvantages of the several locomotion concepts we decided to use four independently steered common wheels with their steering axle directly above the center of mass of each wheel, because of their low price, their simple kinematics, the low control and energy effort. Despite its huge potential the omnidirectional robot base will not aim to imitate AZIMUT (presented in Section 1.3.3) due to the high anticipated costs as well as the need for excessive development. This design decision enables the robot base to travel omnidirectionally on even surfaces and slopes using one actuator per wheel for driving and one actuator per wheel for steering each wheel. (Resulting in eight actuators, four for steering and four for driving.) Using wheels also enables the mobile base to roll over obstacles smaller than the radius of the wheels. Figure 4.9 presents a diagram showing the characteristics of the torque depending on the ratio of obstacle height and wheel radius as well as a sketch containing the respective dimensions. The results presented in Figure 4.9 base on the following considerations.

For overrolling an obstacle with the height h using a wheel with radius r it is necessary, that the contact force F_2 is zero so the wheel can lift off from the lower level and rotate around point P to reach the higher level. It is taken that no sliding appears during this movement. Else the depicted case would be much more difficult. By formulating the equilibrium of momenta around point P the following equation can be formulated.

$$\sum M_{\mathrm{P}} = 0 : M - m * g * d = 0 \tag{4.1}$$

Reformulating this equation gives $M = m * g * d$. Based on the Pythagorean theorem the distance d can be described using the threshold height h and the radius r.

$$\begin{aligned} d =& \sqrt{r^2 - (r-h)^2} \\ =& \sqrt{2 * r * h - h^2} \end{aligned} \tag{4.2}$$

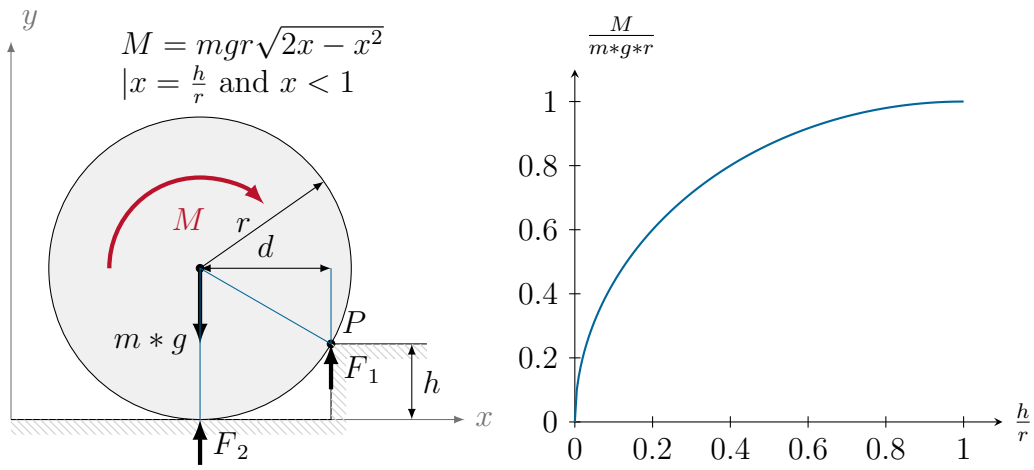
By introducing the relation $x = h/r$, (4.2) rearranges to

$$d = r * \sqrt{2 * x - x^2} \tag{4.3}$$

with implementation of (4.3) to (4.1) the momentum M can be expressed as

$$M = m * g * r * \sqrt{2 * x - x^2} \qquad \text{or} \qquad \frac{M}{m * g * r} = \sqrt{2 * x - x^2} \tag{4.4}$$

As (4.4) is based on the Pythagorean theorem, the formula is only valid for $h < r$ because else r is no longer the hypothenuse of the triangle consisting of r, h and d, resulting in a different mathematical relationship than presentend in (4.2).



(a) Sketch of the Overrolling problem.

(b) Diagram of the Overrolling problem.

Figure 4.9: Sketch and diagram illustrate the correlation between necessary torque M for rolling over an obstacle and the ratio of obstacle height h and wheel radius r with constant mass m and constant wheel radius r.

Using the presented relation it is possible to calculate the maximum obstacle height a vehicle can roll over after determining the torque provided by the actuator as well as the wheel radius. To comply with Single Step Climbing [Requirement 3] wheels with a radius $r \geq 210$mm would be required. Besides other disadvantages steering motions with wheels with 420 mm diameter would require too much space. Figure 4.10 illustrates a mobile base with spheres allowing to roll over 105 mm. It is easy to see, that spheres with double the diameter will overlap and thereby block each others movement. It is quite evident that a different approach is needed to enable the mobile base to climb a single step. Due to the need for hydraulic components in the robot's arm all required peripheral components of a hydraulic circuit have to be on board making the use of hydraulic pistons for climbing single steps obvious. A single double acting piston between each wheel and the support structure of the mobile base represents a simple solution because hydraulic actuators show a high force-to-size-ratio. To climb a single step the motion system would lift the robot to the height of the upper step, then drive closer to the edge of the

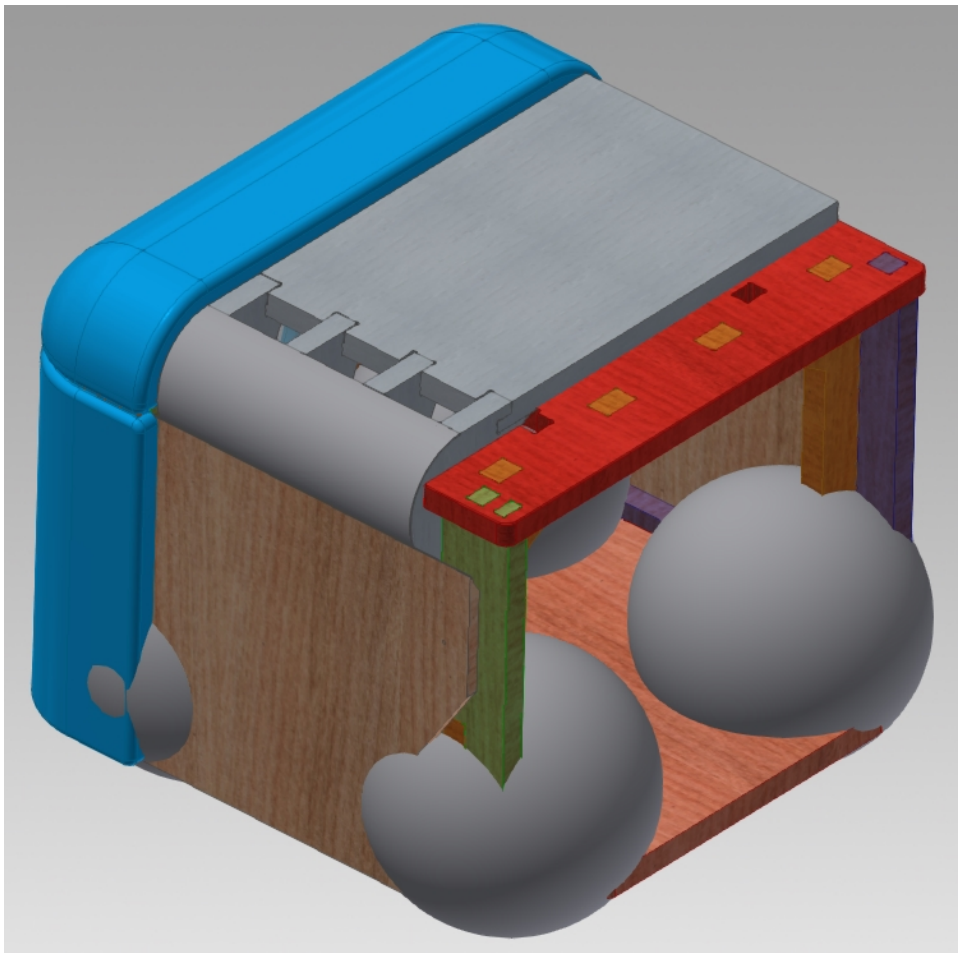
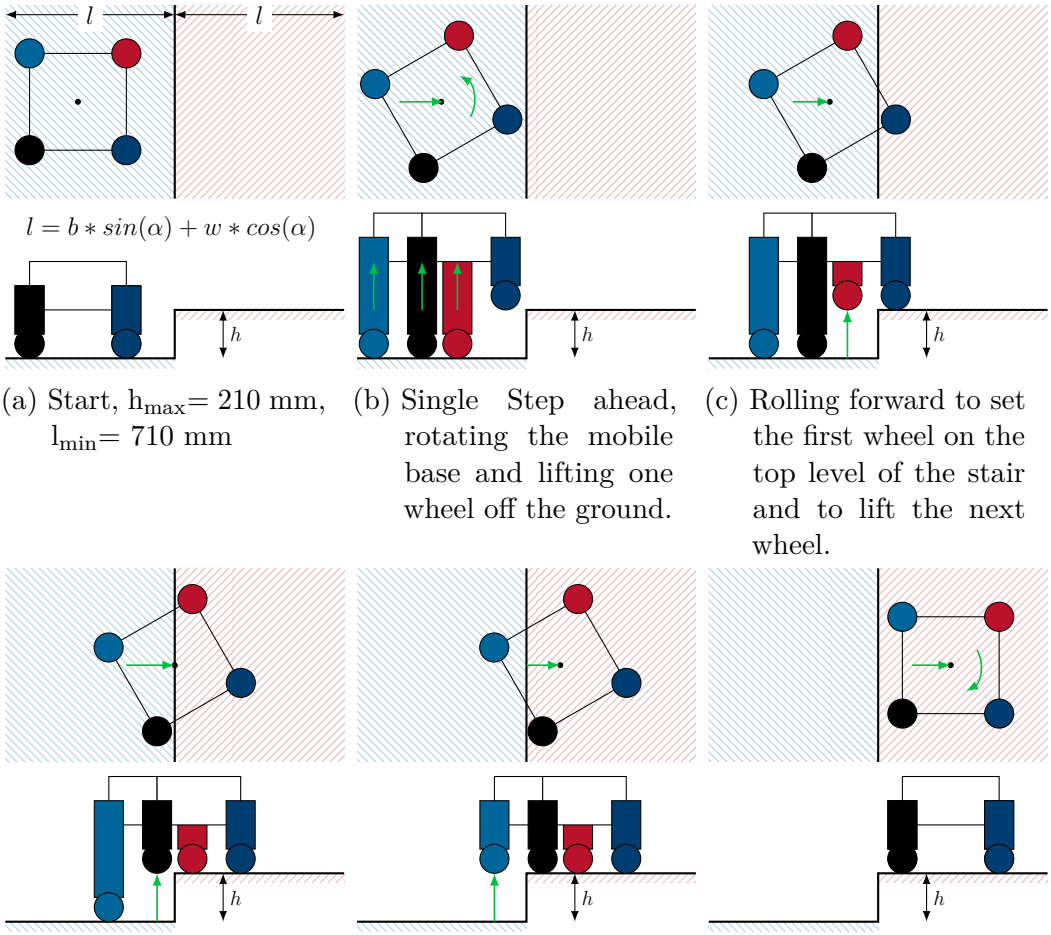


Figure 4.10: The four balls illustrate the space problems due to limited outside dimensions when using wheels with 210 mm diameter.

step, pull the closest wheel up and roll forward so the wheel can be lowered onto the upper surface of the step. Then the remaining three wheels would also be placed on the top level of the step following a similar procedure. If the horizontal distance between two or more steps is larger than the length presented in Figure 4.11 more than one step can be climbed, each at a time.



(a) Start, h_{max}= 210 mm, l_{min}= 710 mm

(b) Single Step ahead, rotating the mobile base and lifting one wheel off the ground.

(c) Rolling forward to set the first wheel on the top level of the stair and to lift the next wheel.

(d) Repeating the step before with wheel two and three.

(e) Repeating the step before with wheel three and four.

(f) Setting all four wheels on the top level.

Figure 4.11: A step by step strategy to climb single steps.

Obviously this strategy for climbing a step is based on the robot's ability to lift one wheel off the ground. Demanding a stable position at any time causes the motion system to feature at least four wheels. For reasons of stability it is of advantage to position the four wheels in one horizontal plane as far from each other as possible to create a maximum contact patch. According to

Requirement 6 the robots shape in a topview is limited by a rectangle. With this boundary the maximum distance between four points (the center points of the rotations) is achieved when the four points each lie in one corner of the boundary rectangle. Taking into account that the wheels are required to stay inside the boundaries as well the wheels are shifted inwards until they fully fit inside the bounding rectangle. With a perfectly balanced robot design the center of mass would theoretically lie directly on top of the intersection of two diagonals of the rectangle. When the robot now lifts one of the four wheels off the ground the center of mass is above the boundary of the new contact patch leaving the robot in a semi-stable state where a slight impulse in the appropriate direction would cause the robot to loose balance. To remedy this problem the easiest solution to implement would be to lift the robot base to a position where the base is in a tilted position with respect to a horizontal plane. This movement helps to shift the center of mass towards the center of the contact patch, providing a higher stability. A different approach making use of the (later on) attached robot parts could shift the center of gravity by changing the position of the torso. By leaning forward, backward or sideways the center of mass of the entire robot changes its position. To determine the exact correlation between the position of the center of mass and the position of the torso mass distribution of both components is needed. At present this information is not available which is why we confine ourselves to mentioning to mention this solution without evaluating it further. Another benefit of using hydraulic pistons to achieve Single Step Climbing is that the implementation of a spring-and-damper effect demanded in Requirement 5 (Surface Irregularities) is possible by adapting the hydraulic circuit controlling the pistons to show a similar behaviour as the hydro-pneumatic suspension designed by Citroen engineers. [16]

4.2 Designing the Bearing Structure

While the number of concepts for a robot's locomotion are relatively low the variety of possible support structures seems endless. Looking at competing service robots to find out their solution to this omnipresent problem does not lead to a lot of information or ideas. On one hand the Support Structure is seldom a sub-assembly that can easily be reconstructed by looking at a robot from outside and on the other hand it is usually neither a group of components the producer wants to boast with, nor one the user wants to receive information about. To circumvent this lack of design examples, bio-mimicry seems to provide a solid foundation. Taking nature's ingenious concepts as a source for solution to similar problems brings the following examples for

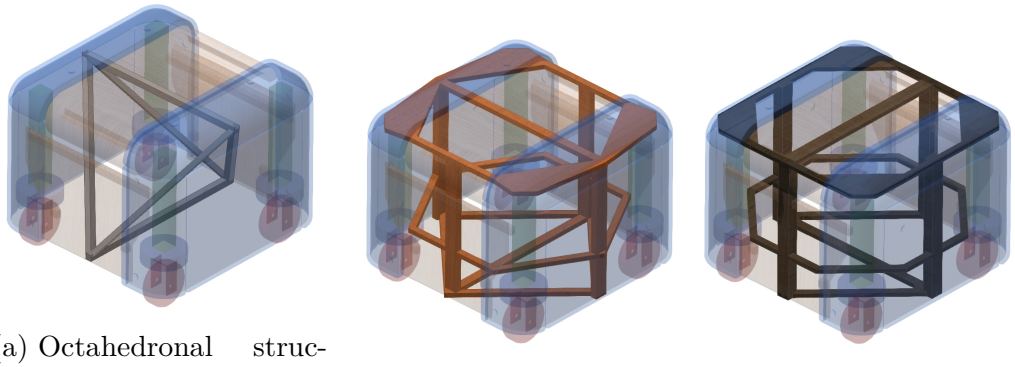
bearing structures to mind. The micro structure of the bones of vertebrates can absorb a huge amount of energy and support high loads before breaking, while a skeleton made of bones with this micro-structure is light enough to allow birds to fly. Another remarkable product of evolution is the shell of an egg. It protects its content while consisting of a minimum mass.

Both these evolutionary supporting and protective structures mentioned find use in products. Framework concepts for bridges come closest to the interlinked structures of bones while monocoque designs, for planes and racing cars, mimic an egg. With the set of requirements presented in Table 3.2 two concepts have been evaluated.

4.2.1 Regular Polygon

The structures of crystalline materials feature several regular polygons. The most stable example is the octahedron which can be found in the crystal structure of diamonds. Although this structure is one of the hardest meaning that it can withstand high pressure before breaking, it also is one of the most brittle geometrical arrangements. Despite this a octahedronal bearing structure would have interlinking parts which would not comply with Requirement 14 (Easy to Maintain) and would also complicate the placement of the components inside the mobile base. As Requirement 6 limits the size of the mobile base and the contained components require the maximum space inside the base, the design has to find a fitting trade-off between maximum stability and the best geometrical structure for component placement and maintainability. A better fitting design should have all components of the supporting structure located close to the base hull without blocking the access to the components inside. This goal can be reached by creating window like supporting frames with enough space in between to fit a battery through. For further evaluation two prismatic shapes with regular fundamental structures are added. Namely these are a hexagonal prism and an octagonal prism. Figure 4.12 illustrates the octahedral shape as well as the two prismatic shapes inscribed in the first design of the base hull. The hexagonal and the octagonal prism both present a better connect-ability for the drive modules. While a hexagonal structure can be equipped with mounting pieces to attach four drive modules, an octagonal structure can even integrate the drive modules by integrating them as vertical links. This has the benefit of fewer parts but also the drawback that the stability of the bearing structure is drastically reduced when drive modules are removed during maintenance.

Both prismatic design proposals for the bearing structure presented in Figure 4.12 consist of horizontal connections and vertical links. The horizontal connections are ordered in three plane which are located at different heights.



(a) Octahedronal structure (b) Hexagonal structure (c) Octagonal structure

Figure 4.12: Proposed designes for a support structure inscribed in the first design of the base shell. Including the connection points for the drive units.

The horizontal links of the higher two levels are arranged in a hexagonal or octagonal shape, which gives the three dimensional structure its name. On the lowest plane the horizontal connections form a rectangular shape. All three horizontal structures are connected by vertical links. The bearing structure would be stable enough with two of the horizontal structures and their vertically connecting parts. The choice for an arrangement with horizontal links on three different levels is based on the attempt to maximize the space useable for storing components while at the same time allowing a simple attachment of the drive modules to the bearing structure. The horizontal connections on the middle plane allow a simple linkage of the drive modules to the bearing structure. Arranging these horizontal connections closer to the ground (at a lower level) is not possible as moving parts of the drive module would collide with the structure. With the implementation of a rectangular structure at the lowest level the space for placing components is maximized while collisions of drive module and bearing structure are prevented.

4.2.2 Support Structure of a Mammal

A totally different approach is presented in Figure 4.13. Based on the formulation given in Section 3.1.3 the bearing structure can be described as a rigid structure providing stability and shielding the enclosed space. It features defined points where actuators for locomotion are attached. This formulation of the key aspects of the bearing structure of the mobile robot base shows several similarities to the skeletal structure. The skeleton provides stability to a mammals body. All muscles of the motor system are anchored at bones

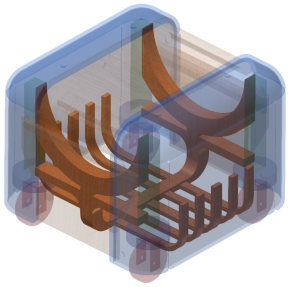


Figure 4.13: A design proposal inspired by the torso skeleton of mammals.

in some cases via tendons. There is even a part of the skeleton shielding the entrails namely the thorax. After noticing these similarities a support structure designed like the rib-cage looks promising, as the contained components require a stronger fixation than the internal organs of mammals. Adapting to this need the thorax structure is placed as if the living entity was lying on its back so the ribs can be used to place the contained components. Figure 4.13 shows a first design proposal following this approach. It is noticeable that the presented design does not feature a horizontal stabilization at the top level of the bearing structure. This improves the maintainability of the mobile base but it also has negative effects on the stability of the structure.

4.2.3 Concept

Neither of the proposed concepts is a satisfying solution for the bearing structure. Up until now all design proposals are composed of bars, because of the sources of inspiration. Especially for the bottom of the structure a single wooden panel seems more suitable. With this adjustment the number of parts is reduced while the component can also function as an underbody protection and allow a more flexible placement of the contained components. On the top level of the bearing structure a compromise between the prismatic proposals and the skeleton design seems promising. As the mammal inspired structure (presented in Figure 4.13) has no links on this level at all, this design might prove unstable. On the other hand the prismatic constructions do not easily comply with Requirement 13 because the support structure is blocking the rotational movement of the upper leg. With an additional link between the front drive modules the mammal structure gains higher stability. This link can be used as rotational axis for the rotational movement of the upper leg. Similar to this connection a link between the two backside drive modules increases stability and can be used as hip is rested on this connection when it is in lowered position. To allow easy access to the contained components from both sides the vertical components

are only connected to the bottom panel on the front and back side not on the other two sides. To avoid the need for a middle level as in the prismatic proposals the front and back components are shaped to leave room for the elongation movement of the piston. All components are designed to allow only one reasonable assemblage because of the use of form-fit connections which are designed to fit in only one place. The vertical components of the structure create an L-shape to help positioning the drive modules and to allow a rigid fixture. Figure 4.14 shows the structure configuration including the proposed improvements.

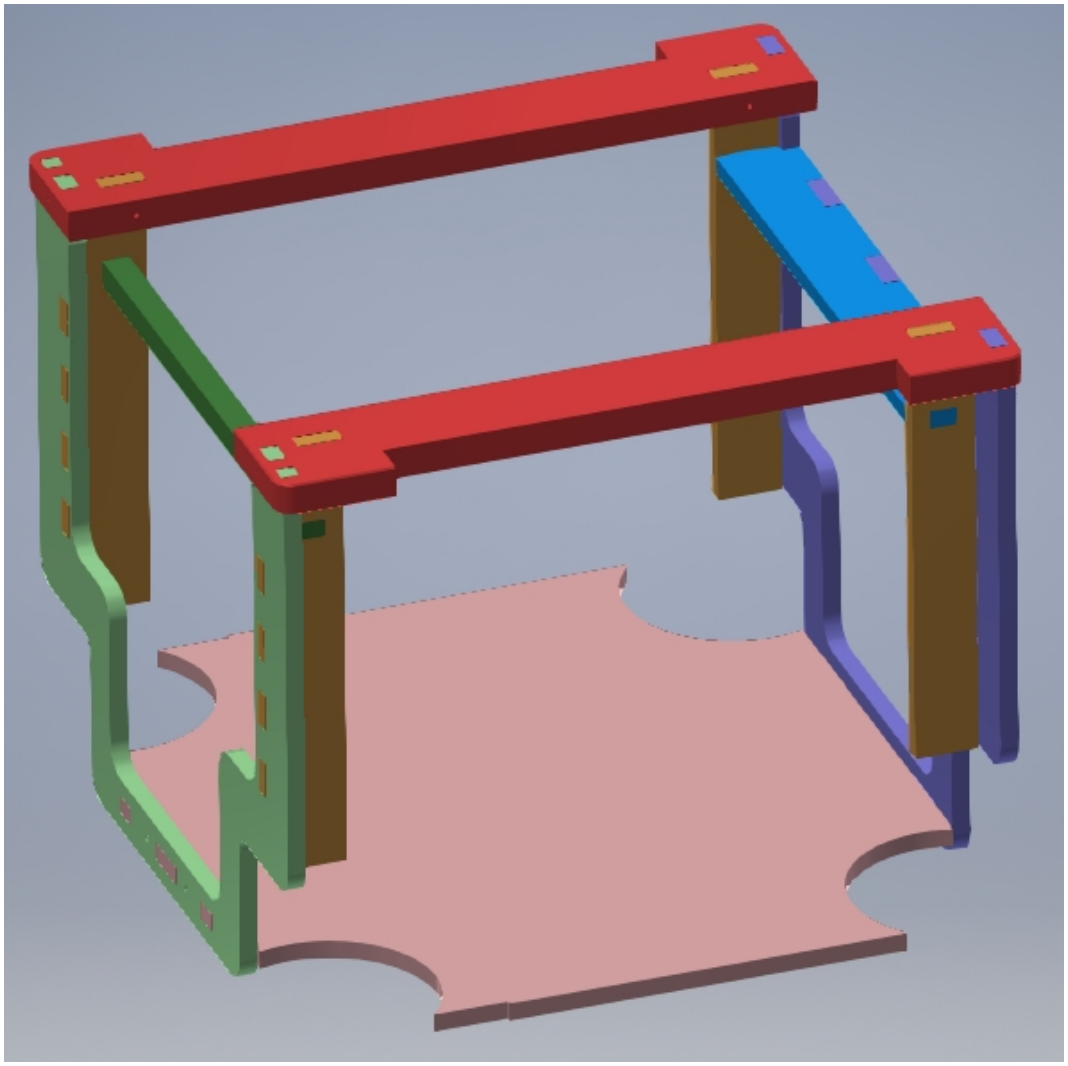


Figure 4.14: Bearing structure design including improvements

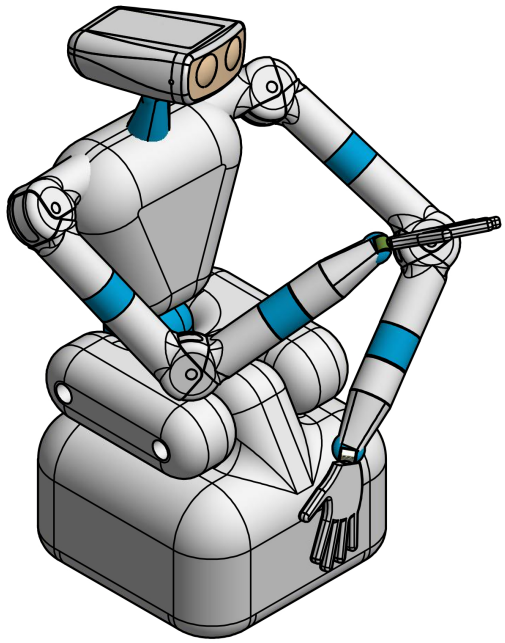
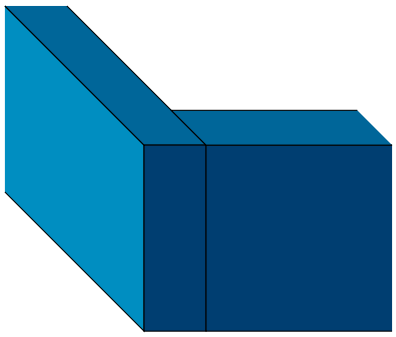


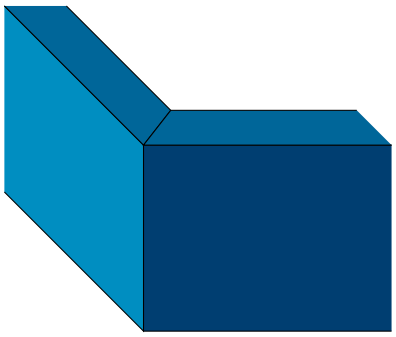
Figure 4.15: Close up of the proposed design by Blue Danube Robotics

4.3 Designing the Base Hull

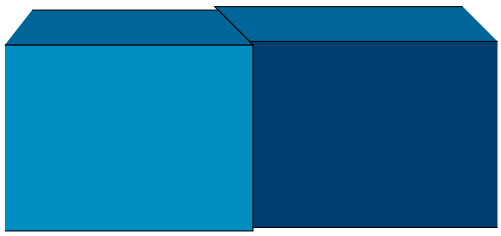
In contrast to motion system and bearing structure this functional unit is not only designed regarding functional requirements but has to fulfill aesthetic criteria. Starting with the functional terms fixed in Table 3.3 and guided by the design presented in Figure 4.15 the first design aims to bridge the gap between functional and aesthetic by stressing different surface functionalities while integrating all functional units to one shape. To allow a box shape with rounded corners but without gaps or visible edge to edge connections maintenance flaps and similar openings have to be placed deliberately. The easiest way to circumvent visible component edges is to design the cover parts in a fashion that they meet at the corners because there would be an edge anyway. If the two components have a proper chamfer the edge to edge effect is hardly visible. The problem with the proposed design is that there are no edges because this decreases the risk for injuries. As a result the best solution to hide maintenance flaps simply is to have none. This sounds impossible at first because one of the requirements demands easy maintainability which implies that repair and maintenance works are to be expected. But rather than prohibiting maintenance the task is to eliminate flaps and other openings in the hull. To realize this it is necessary to remove specific components of the base hull for maintenance works or repairs. To comply with the mentioned requirement



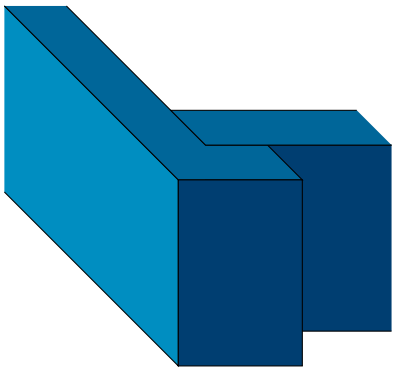
(a) Visible edge at joining



(b) Less noticable joining egde



(c) Edge to edge joining



(d) Proposed joining method

Figure 4.16: A variety of possibilities to conceal gaps and annoying edges between components of the base hull.

it is essential to allow an easy and quick way to remove the components, which block the maintenance opening. As the knee blocks a wide area on the front side and the actuator for the upper leg is likely to block the back side the base hull design provides maintenance access from the left as well as the right hand side of the mobile base.

Following this concept the base hull consists of two fixed cover panels for the front and backside cover and two removable covers for either side of the mobile base. Additionally several small parts have been added to improve assembling. Most of these mounting aids can be implemented in existing elements in the next design. To conceal the areas where two components come together the design makes use of another trick. Rather than trying to perfectly align the surfaces of two adjacent parts, the adjacent surfaces are joined at an angle of 90 °. This creates two edges where none has been before, but one is set at a specific position so it can not pose any hazard and the other edge is covered by a soft sensitive material. Combining the above presented ideas leaves the mobile base with a hull design which covers all sides except for the top and the bottom of the base. Referring to the First Design of the Bearing Structure, the bottom of the mobile robot does not require an additional covering as the bottom panel of the bearing structure already protects the components of the mobile base against harm from this direction. On the top of the base the upper leg will cover most of the area. To limit the risk of pinching a finger or another body part the side covers are designed to end adjacent to the upper leg and are equipped with soft sensors. Furthermore a gaiter seal is mounted at the sides of the upper leg and knee section. For implementation of the soft and tactile surface the use of ™AirSkin Sense is reasonable as it is an easy solution designed to meet all requirements for the soft cover of the mobile base. To reduce costs the presented design anticipates that the front and back cover as well as the knee do not require touch sensors because no critical situations could be found where these surfaces are the only parts of the robot to have contact with an obstacle, except for a table leg. Both of the side hulls need to detect touches on all sides. The sensitive surface has to be split into sensor areas because each sensor can only detect a contact, but can not specify the impact point of the touch. The chosen trade-off between low number of sensors and high tactile resolution leads to a system of four sensor pads on both side covers (resulting in eight sensor pads in total). With these sensors the robot base can detect obstacles in any moving direction as well as a touch on the top surface left and right of the upper leg.

4.4 Designing Internal Components

As most of the internal components are available parts, no designing is needed. Battery, micro controller boards, main board and video card are purchased parts. When it comes to the hydraulic pump no suitable part could be found for a reasonable price. To circumvent the design and production of an entire new pump, a Kärcher hydraulic pump was modified to being moved by a DC motor. Several ideas concerning a new type of fluid pressure tank have been developed but could not be realized due to time limitations.

4.4.1 Hydraulic Pump

From the start of this thesis the need for a hydraulic pump was predetermined because of the use of hydraulic actuators in attached robot parts. The search for a suitable device was defined as part of this thesis. The requirement profile for an on-board pump is depicted in Table 4.1

Table 4.1: Requirements for the Hydraulic Pump

Requirement Name	**Specification**
Supply Voltage	12 V DC
Minimum Pressure	20 bar
Maximum Pressure	50 bar
Minimum Fluid Flow	3.13 $\frac{\text{L}}{\text{min}}$
Maximum Price	150 €

The most significant parameters are the 12V DC power supply and a hydraulic system pressure of 20 to 50 bar. In the absence of a hydraulic pump complying to the specifications listed in Table 4.1, a customized solution was created. Due to the price limitation a low budget high-pressure cleaner from Kärcher [2] was selected. The product is commonly used in gardens or private garages and therefor is powered by line voltage. For a use inside the mobile robot the pump was disassembled and the original 220 V AC engine was replaced by a 12 V DC motor. Although first tests using a 100 W 12V motor were unsuccessful because the pump was not able to reach the required minimum pressure and minimum flow, the use of the more powerful electric motor with 120 W fulfilled

[2] Kärcher K2 Basic for information see `https://www.kaercher.com/at/home-garden/hochdruckreiniger/k-2-basic-16731500.html`

Table 4.2: Specifications for the Hydraulic Pump

Specification	**Quantity**
Dimensions	
Length	350 mm
Width	100 mm
Height	140 mm
Hydraulics	
Max. Pressure	30 bar
Max. Flow	2.4 $\frac{l}{min}$
Electrics	
Max. Voltage	12 V

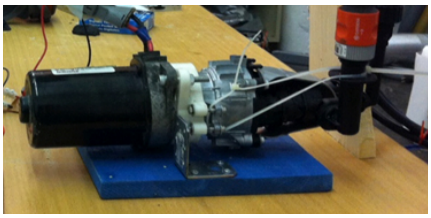
the requirements. This combination resulted in a hydraulic pump as presented in Table 4.2

4.5 General Design Considerations

4.5.1 Structural Material

The ideal material for a robot component strongly depends on the part itself and on its requirements. Looking at the automotive industries many materials from steel, to polymers, foams and leatherette are in use within one product. Up to now most service robots are a combination of support structures made of aluminium and covers made of plastics or soft rubbers. The use of aluminium for prototypes is often limited to simple geometrical shapes using aluminium profile systems which are interlinked using screw connectors. Apart from this, aluminium is a material which requires a high energy input for its production. The use of timber instead of aluminium provides several benefits. The first being its price. Wood, in our case plywood, is cheap than aluminium and steel. Furthermore it is easier to manufacture and join structural components using timber because no welding tools or bending machines are needed. This allows the design of supporting structures to use customized components rather than standard parts. Using plywood means selecting "local" resource and eco-friendly material at the same time, as asked in Requirement 19.

(a) Kaercher K2 Basic, ©Kärcher [17]



(b) Picture of the customized hydraulic pump

Figure 4.17: K2 Basic and custom hydraulic pump

4.5.2 Hydraulic Fluid

As already mentioned various components of the robot are moved by hydraulic actuators. Despite the omnipresent problem of preventing leakage the choice for a hydraulic system over an electric system is based on the following characteristics.

Hydraulic systems provide an integrated cooling as the pressure fluid can also be used for heat transfer. Hydraulic circuits feature an overload protection by means of integrated pressure relieve valves. For a service robot this characteristic can be used to implement a safety function called compliant actuation. Compliance in the case describes actuators or actuated components which give way to objects or body parts which are blocking their motion without doing them harm. Furthermore hydraulic actuators have a good power to weight ratio and provide high linear forces.[18, page 18] When it comes to mobility the mass of the machine is always essential. In this case the power to weight ratio is a key aspect for actuator selection.

General reasons for the use of water over oil are the lower price, a better availability and a much better environmental compatibility.

More important in this application is that in case of leakage, which can not be excluded, water is preferable to oil. Leaking oil in an apartments is unacceptable, due to the increased danger of slipping compared to water. Furthermore oil leaves permanent stains on many carpets and floors. Long

term contact with hydraulic oils[3] can cause skin irritations and dermatitis.

Water has a lower viscosity than most hydraulic oils and therefore lower friction losses in the same pipe. This means that the diameter of the pipes can be reduced while keeping pressure losses at the same level using water instead of oil. Last but not least oil has a higher heat capacity than water. This results in a bigger amount of thermal energy stored in oil. But it also leads to a slower cooling rate. The reason for the use of oil in most cooling cycles derives from the low boiling point of water compared to the used oil.

[3] e. g. see safety data sheets from Castrol [19], Chevron [20] and Pirtek [21]

5 Prototyping

As prototyping was an important part of this thesis, I want to give a short overview over the machines available for the prototyping process. This short description should give a basic understanding for possibilities and limitations arising from the set of tools.

The most extensively used machine is the CNC milling machine. The available tool, an *EAS(Y)440 KG PRO*[1], is equipped with a *Kress 1050 FME*[2] milling engine and is capable of milling wood, plastic and aluminium. The CNC mill was used to produce all components of the bearing structure as well as components of the hydraulic rotary actuators.

For the production of the piston head, the piston rod and other rotationally symmetrical components, an *Optimum Optiturn TU 2404V*[3] lathe was used. Due to its construction the lathe is capable of processing wood, plastics and aluminium without difficulties. During lathing the piston rod, made of stainless steel, a short clamping length and sharp tool tips were necessary to achieve the required accuracy.

The last special machines used during prototyping are two 3d printers. The *Ultimaker Original*[4] was used to produce relatively small parts (approximately 30 mm x 30 mm x 50 mm) like e. g. gears for the pump assemblies. For larger parts the *Profi3DMaker*[5] was used due to its higher printing speed.

Besides these specialized tools, common workshop tools including a heat gun were used during prototyping.

[1] The specifications of the EAS(Y)440 KG PRO CNC milling machine can be accessed at `http://www.easgmbh.de/CNC-Maschinen/Fraesmaschinen/EASY_KG_PRO/440`

[2] The specifications of the Kress 1050 FME milling engine can be accessed at `http://www.kress-elektrik.com/Elektrowerkzeuge.71+M5d4d51cec4a.0.html?&tx_commerce_pi1%5BcatUid%5D=17&tx_commerce_pi1%5BshowUid%5D=1035`

[3] The specifications of the Optimum Optiturn TU 2404V lathe can be found at `http://www.optimum-maschinen.de/produkte/drehmaschinen/optiturn-tu-2004v/index.html`

[4] The specifications of the Ultimaker Original can be found at `https://ultimaker.com/en/products/ultimaker-original`

[5] The specifications of the Profi3DMaker can be accessed at `http://www.3dfactories.com/3d-printers/profi3dmaker/`

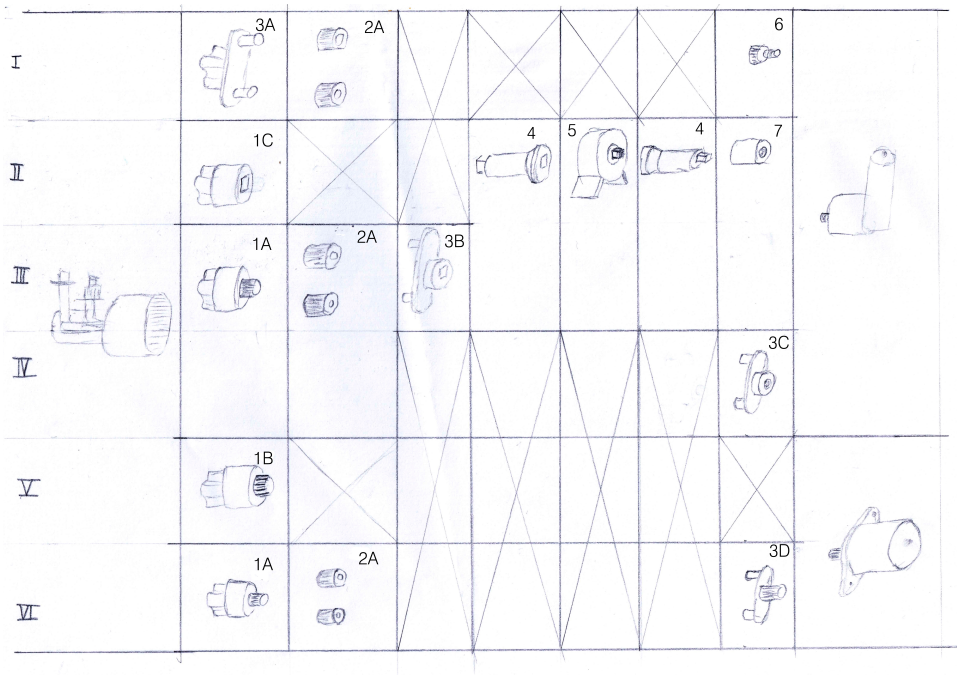


Figure 5.1: This sketch illustrates the setup of the pump tests. Each row represents the components used for the respective test setup. Numbers and letters help to distinguish similar from identic components.

5.1 Hydraulic Sub System Prototypes

5.1.1 Hydraulic Pump

The following trials were implemented to find a working propulsion for the piston pump unit of the Kärcher K2 Basic. Figure 5.1 shows the assemblies used in the six tests. Besides the test of two different engines the transmitting components have also been varied to find the optimum solution available.

#I Replacing the DC Motor

In the first test the AC motor was replaced by 12 V, 40 W motor. To mechanically connect these two components a gear wheel was designed based on the gear mounted on the original motor. The original planetary gear was maintained. The connector was 3d printed and required reworks especially at the tooth flanks. The first test failed, as neither a significant flow nor a remarkable pressure rise could be noticed. To test the function of the Kärcher

Pump unit a drill machine from Bosch[6] was used to propel the pump, which lead to both significant flow and pressure.

A research concerning piston pumps provided information that common piston pumps have problems with sucking in water. Usual use of the K2 Basic requires a connection to the water pipeline, which delivers water at a pressure of 3 to 5 bar [7]. A test setup in which the water reservoir was positioned 1.5 m above the pump lead to a better performance of the pump in combination with a drilling machine for its propulsion. Apart from this the test setup created output using a cordless screw driver [8] with less power than the drilling machine.

#II Incorporation of an Impeller Pump

As the final setup in the mobile base does not allow a vertical distance of 1.5 m between the pump and the water tank, the use of a booster pump was obvious. The purpose of the booster pump was to raise the water pressure at the input of the piston pump. Due to its fitting characteristics an impeller pump was modified and installed to raise the input pressure for the piston pump. The setup for test #II featured the wiper engine, which actuated both the impeller booster pump as well as the piston pump. During this test the impeller pump and the piston pump were driven at the same speed. Following the idea that the input pressure was restricting the output of the first setup, the assembly presented in Figure 5.2 did not make use of the planetary gear connection implemented in the original pump. With the presented modifications the pump assembly showed improved output flow using the wiper engine compared to previous tests with the same motor. The vertical distance between water reservoir and pump was reduced to 10 mm resulting in a water flow higher than the 1.5 m setup propulsed by the wiper engine.

#III Changed Transmission

To improve the test setup #II (Incorporation of an Impeller Pump) the operating speed of the piston pump in relation to the impeller pump was increased using the planetary gear. Mechanical analysis revealed that, given the fact that the ring gear is fixed, the optimum use of the existing components is made when the arm of the planetary gear is moved by the engine and the pump was connected to the sun gear. According to the diameters this combination resulted in a transmission ratio approximately 5.16.

[6] The product name of the drilling machine is *Bosch PSB 500 RE*

[7] pressure level referring to Wiener Netze GmbH `https://www.wien.gv.at/wienwasser/versorgung/rohrnetz/`

[8] The product name of the cordless screw driver is *Bosch PSR 960*

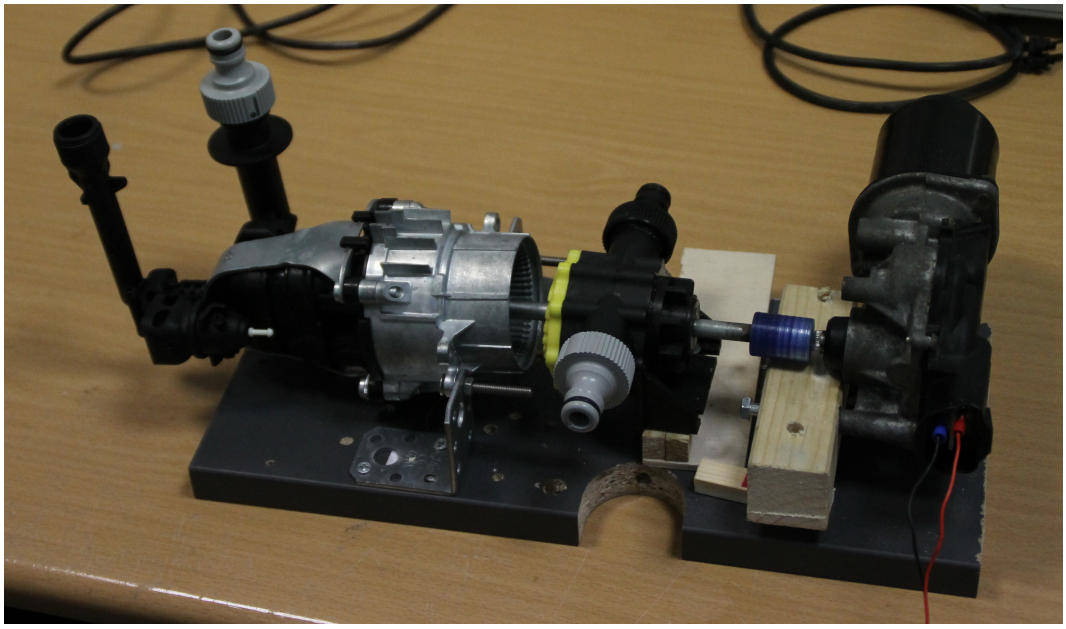


Figure 5.2: Custom hydraulic pump test assembly #II including an impeller booster pump

This test setup was the first which actually lead to an increased flow, but still not enough for our use. The measurement was made by collecting the water transported by the pump assembly in two and a half minutes in a tank. Dividing volume over time resulted in a flow of 0.32 $\frac{\mathrm{l}}{\mathrm{min}}$ which is way too little for the robot base.

#IV Simplified Setup

To test the influence of propulsion speed and input pressure, test #IV (Simplified Setup) was undertaken using the same transmission as in the previous test, but without the use of the impeller pump for pressure boost. Repeating the measurement described in test #III (Changed Transmission) resulted in a reduced flow of 0.28 $\frac{\mathrm{l}}{\mathrm{min}}$. As expected the output flow decreased compared to the pump assembly with booster pump. Nevertheless the output flow of 0.28 $\frac{\mathrm{l}}{\mathrm{min}}$ is comparable to the output for test #III and clearly more than the results of test #I and #II, which both featured a much slower propulsion due to a different transmission. These test results indicate that the propulsion speed of the pump is more important than the input pressure. Based on this understanding a faster and more powerful motor was chosen to further increase the output flow of the pump assembly.

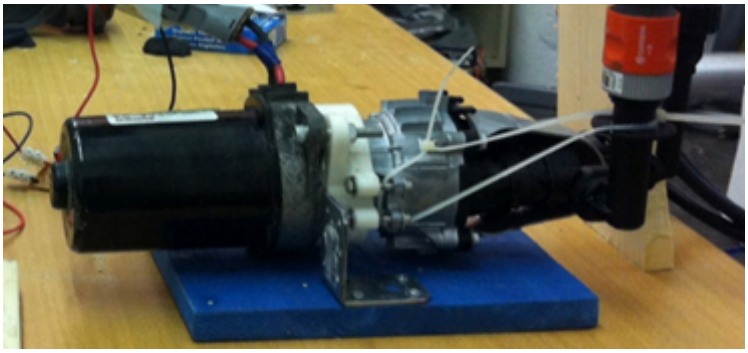


Figure 5.3: Custom hydraulic pump test assembly #II including an impeller booster pump

#V More Powerful Motor

The search for a more powerful 12 V motor lead to the use of a 12 V, 150 W motor. Due to the size of this motor and the space limitations inside of the base the test setup for test #V (More Powerful Motor) consisted of the piston pump, a connector part and the steer engine. Neither the impeller booster pump nor the planetary gear were in use. The same test as conducted before with setup #III (Changed Transmission) and #IV (Simplified Setup) resulted in a significantly higher water output of 2.4 $\frac{\mathrm{l}}{\mathrm{min}}$.

#VI Reintegration of the Planetary Gear

With the last setup propulsion speed of the piston pump was further increased by making use of the existing planetary gear parts. Although no measurements took place the flow rate could be increased noticeably. The only problem concerning the setup at hand was that the assembly of the planetary gear was too complicated preventing easy reassembly and quick maintenance.

Despite these drawbacks the hydraulic pump according to setup #V (More Powerful Motor), presented in Figure 5.3, is at use.

5.1.2 Hydraulic Cylinder

The use of a hydraulic cylinder for vertical movement of the mobile robot base was obvious as hydraulic elements were already planned for other robot parts and hydraulics provide a very good power to size ratio. Assuming a total weight of the robot including payload of 60 kg and the worst case scenario that this weight has to be supported by three pistons because one might just be lifted to reach the next floor level, results in 196.2 N per piston. Adding an acceleration

of 1 $\frac{\mathrm{m}}{\mathrm{s}^2}$ for lifting the base increases the necessary lifting force per piston is 216.2 N.

$$F_{l_3} = \frac{F_g + a_v * m}{3} = 216.2\mathrm{N} \tag{5.1}$$

Presuming a hydraulic pressure of 20 bar, 80 % efficiency and a circular piston shape with the surface area (A_p) results in a minimum diameter (D_p) of 13.12 mm.

$$A_p = \frac{F_{l_3}}{p * 0.8} = 135.12\mathrm{mm}^2 \tag{5.2}$$

$$D_p = 2 * \sqrt{\frac{A_p}{\pi}} = 13.12\mathrm{mm} \tag{5.3}$$

As 13.12 mm is an unusual diameter for pipes a diameter of 15 mm, which was the next higher diameter available, was chosen. The piston diameter in combination with a piston rod diameter (D_r) of 5 mm results in a pushing force of 282.7 N and pulling force of 251.3 N.

$$F_{push} = \frac{D_p^2}{4} * \pi * p * 0.8 = \frac{15^2}{4} * \pi * 2 * 0.8 = 282.7\mathrm{N} \tag{5.4}$$

$$F_{pull} = (\frac{D_p^2}{4} - \frac{D_r^2}{4}) * \pi * p * 0.8 = (\frac{15^2}{4} - \frac{5^2}{4}) * \pi * 2 * 0.8 = 251.3\mathrm{N} \tag{5.5}$$

As Figure 5.4 illustrates the difference in pushing and pulling force arises from the piston rod, which reduces the cross section under pressure while pulling.

The general idea for the detailed design was to use as many standard parts as possible while reducing the total number of parts. The basic component for the piston design was a stainless steel pipe with 15 mm inner diameter and 16 mm outer diameter, with a ground inside surface. To provide minimum friction the piston itself is made of PTFE[9]. Guided by the SKF seal catalogue [22] o-ring seals made of FPM75[10] were selected to seal up either pressure chamber from the other. A stainless steel rod of 3mm diameter was chosen to link the piston head with any part attached to the piston. Using standard parts the piston head was fixed to the rod with two washers and a hexagonal nut. To seal up the pipe on either side, an end piece was designed, that holds hose nipples to allow easy and fast connection of hydraulic hoses. The end parts need to be glued onto the steel pipe with a special adhesive which bonds with steel, PC[11]

[9] PTFE - Polytetrafluoroethylene better known as Teflon ™DuPont Co.

[10] FPM - fluorine polymer rubber (exact composition undisclosed) belongs to the fluorelastomers and can also be obtained under the trading name Viton™DuPont Co. The number 75 indicates Shore hardness of the material.

[11] PC - Polycarbonate

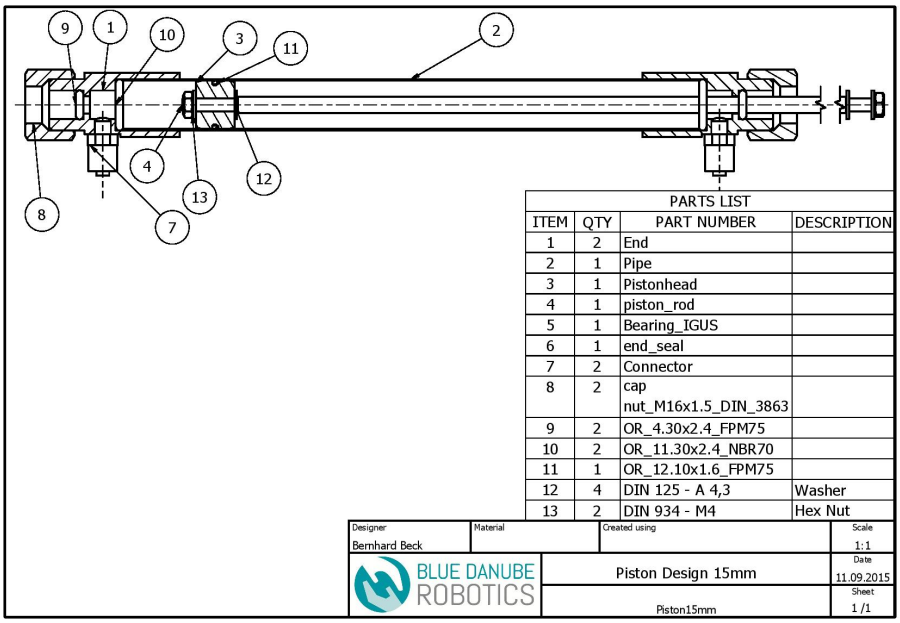


Figure 5.4: Design of a hydraulic piston with 15 mm pressure diameter.

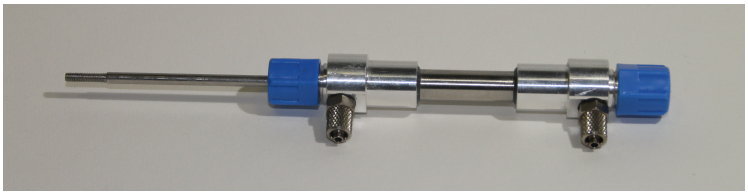


Figure 5.5: Custom hydraulic cylinder manufactured according to the developed design.

and PP[12] and withstands water. To prevent possible leakage due to gluing defects or missing glue an o-ring Seal is added at the end of the pipe, which is placed between the pipe and the end piece before the gluing process. The hose nipples for the hydraulic connection are delivered with a flat sealing and only need to be screwed onto the end pieces. To ensure a watertight connection the end pieces are flattened around the connection hole. Examining the side of the piston where the rod comes through the end piece, a part named slide bearing is inserted into the end piece. This component is designed to minimize the friction between piston rod and the end piece and is made of PTFE due to similar reasons as the piston head. To prevent leakage around the piston rod one more sealing is placed between the end piece and the slide bearing.

At the very end of the piston a nut cap is screwed onto the end piece pushing the slide bearing into the end piece. These three parts (end piece, slide bearing and cap nut) work together to compress the o-ring placed inside the end piece to seal the gap between piston rod and the end cap. On the other side of the piston similar components are used to seal the piston chamber. In this case the task is easier because there is no piston rod, which needs to be sealed on this side.

After designing the piston as presented in Figure 5.4 the total length as well as the stroke length can be measured. Regarding the respective requirements (Requirement 6 and Requirement 3) the stroke should be designed to lift the base 210 mm or more, while allowing the highest area of the mobile base to be below 500 mm when the pistons are retracted. The estimated size of the wheel as well as the hydraulic rotary actuators and the piston design only allow 170 mm stroke or a base height of 540 mm.

After presenting this design decision to my supervisor the focus was set to maintaining the maximum height of 500 mm, resulting in a decrease of the lifting height to 170 mm instead of 210 mm.

5.1.3 Slide Vane Actuator

After analysis of the existing hydraulic actuator models the slide vane actuator turned out to be the best fitting solution to actuate the wheels. The most significant properties for its selection as traction engine are the possibility of unlimited rotation angle and the small size compared to a gear motor. As Figure 5.7 shows, a slide vane actuator consists of a stator, a rotor and several slides. The simplest stator has two chambers (labeled A and B) where the hydraulic hoses are connected. These chambers are linked by a circular pocket. The rotor is a disc with rectangular pockets and is placed inside the circular

[12] PP - Polypropylene

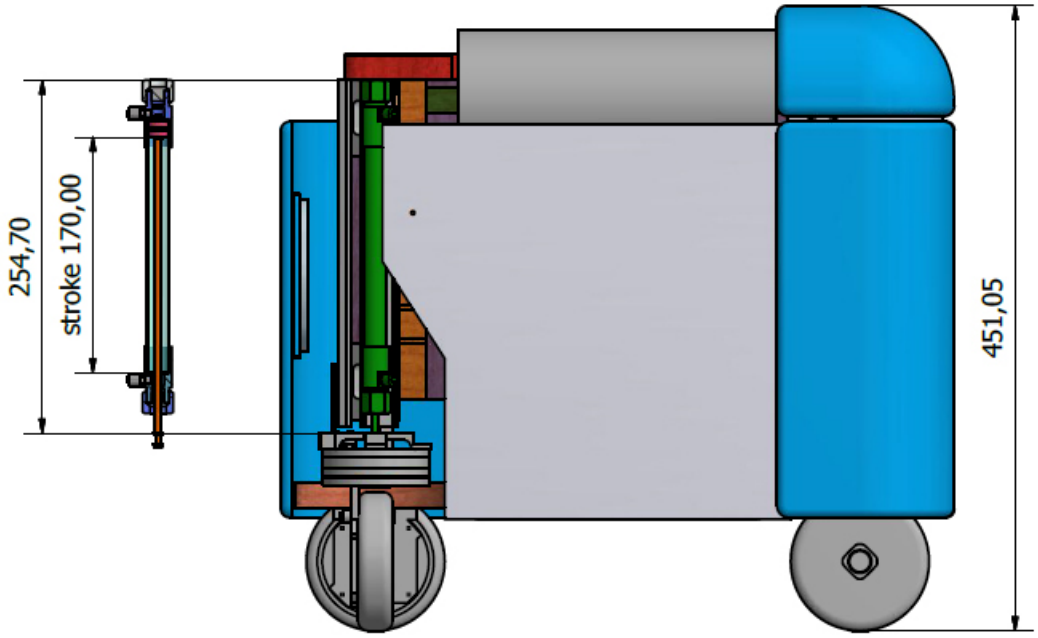


Figure 5.6: Picture showing the possible size of the hydraulic piston based on 500 mm top height and 210 mm stroke.

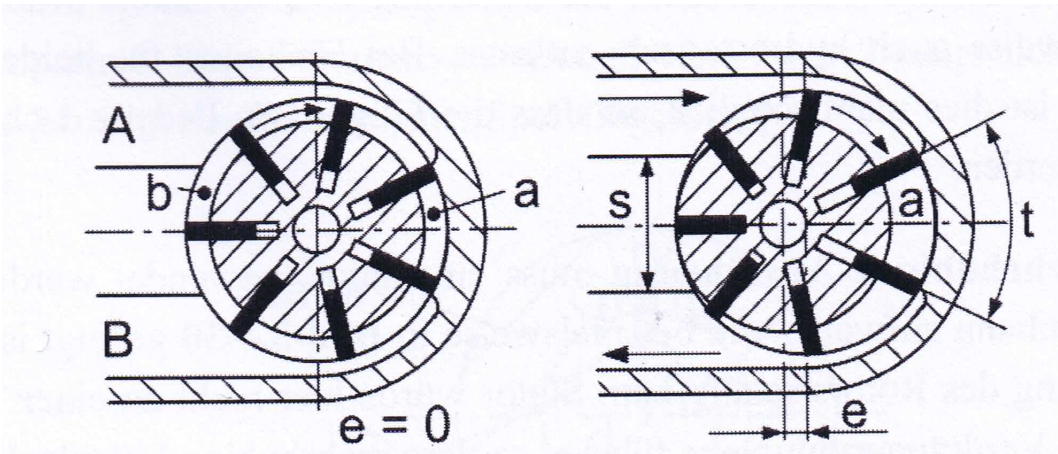


Figure 5.7: The working principle of a slide vane actuator: Pressure difference between chamber A and B push the plates away from the chamber with higher pressure resulting in the rotation of the inner disc. [23, page 189, figure 5.4-29]

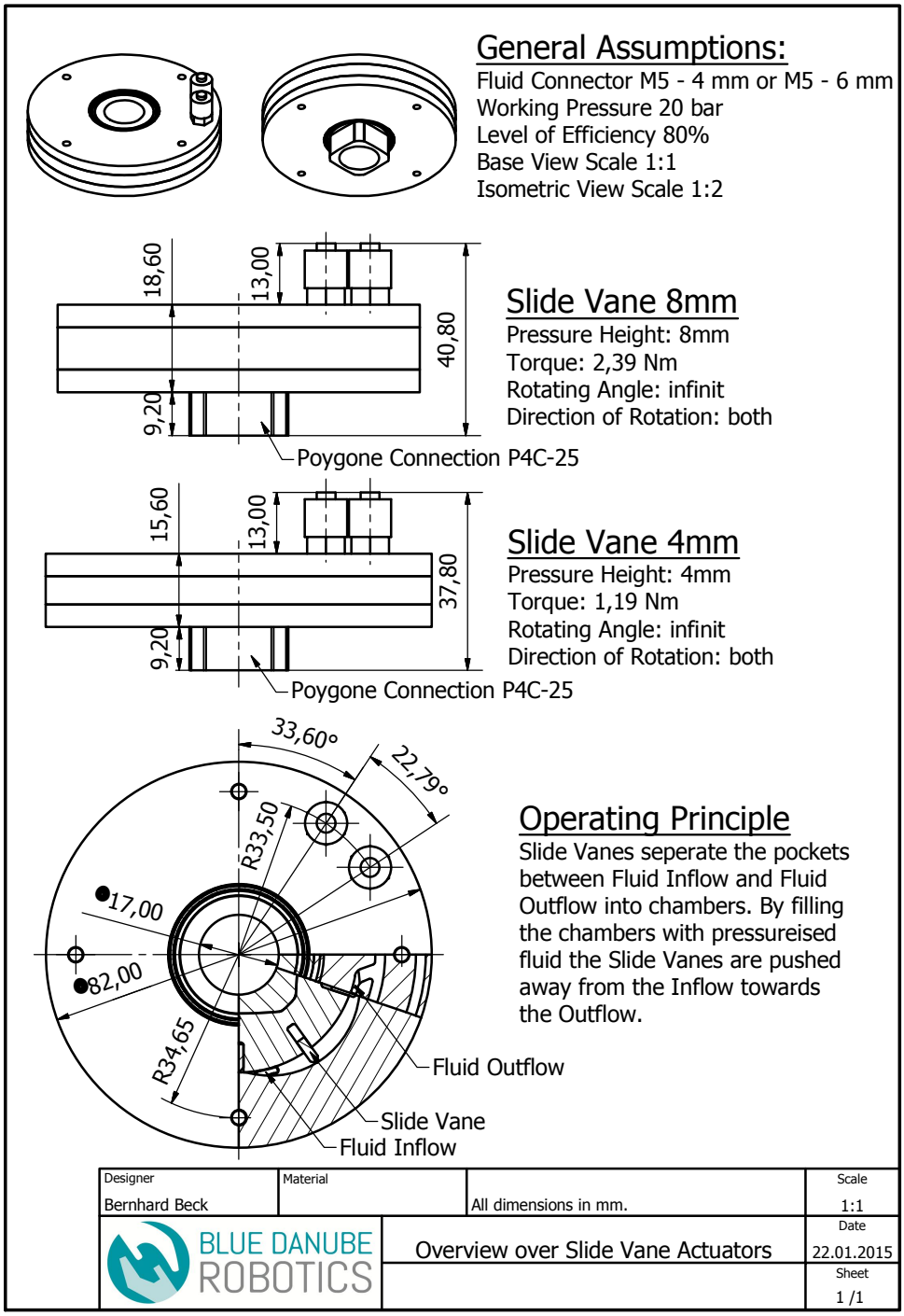


Figure 5.8: Design of two Slide Vane Actuator.

stator pocket. Therefore the diameter of the rotor has to be significantly smaller than the diameter of the stator pocket. Each rectangular pocket of the rotor holds one slide, which is always pushed away from the center of the disc to seal the pressure chambers. The rotor is placed eccentrically inside the stator as presented in Figure 5.7. When chamber A and B are filled with pressurized fluid the pressure pushes on the slides adjacent to the chambers A and B. If the pressure in the two chambers is the same the torques around the rotors center point cancel out, else the rotor starts spinning to transport fluid from the higher pressure to the lower pressure chamber. If the rotor axle sits in the center of the stators circular pocket, as presented on the left side of Figure 5.7, the actuator does not move regardless of the pressure levels in chambers A and B. To understand this fact it is important to keep in mind, that a pressurized fluid puts the same pressure on all surfaces of the chamber, including the slides. In the right hand sub-figure the enclosing slides are stressed with the fluid pressure over different surface areas, resulting in a torque, when the pressure in chamber A and B is different. In the left hand sub-figure the stressed surface area of the enclosing slides of each chamber are equal. This leads to an equilibrium of forces in each chamber regardless of the pressure levels, and therefore no rotation.

For the construction of a slide vane actuator for the propulsion of the mobile base several parameters have been calculated. Based on the total mass (m) of 60 kg of the robot including payload, a maximum acceleration (a_{max}) of 0.1 $\frac{\mathrm{m}}{\mathrm{s}^2}$ and a ramp slope (s) of 10% (or 5.711 rad) the force (F_a) required for acceleration is 64.54 N.

$$F_a = (m*g+m*a_{max})*\sin(s) = (60*9.81+60*0.1)*\sin(5.711) = 64.54\mathrm{N} \quad (5.6)$$

Based on the acceleration force , the wheel diameter (d) of 100 mm and 80 % efficiency the torque for one of four actuators is 1.01 N m.

$$T_{4w} = (\frac{F_a}{4}) * \frac{d}{2} * 0.8 = (\frac{64.54}{4}) * \frac{0.1}{2} * \frac{1}{0.8} = 1.01\mathrm{N\,m} \quad (5.7)$$

Using the dimensions for the drive actuator from Table 5.1 the pressure area (A_p) can be estimated according (5.8)

$$A_p = 0.5 * \frac{d_o - d_i}{2} * b = 0.5 * \frac{57-50}{2} * 3.5 = 14\mathrm{mm}^2 \quad (5.8)$$

The factor of 0.5 takes into account, that the pressure area in each chamber changes with the angle of the rotor from 28 mm^2 to 0 mm^2.

The torque of a slide vane actuator can be calculated according (5.9), with a given number of chambers (n), the given pressure area (A_p) for a single

Table 5.1: Design Parameters for Slide Vane Actuators

Parameter	**Ref.**	**Drive Actuator**	**Steering Actuator**
Inner Diameter	d_i	50 mm	50 mm
Outer Diameter	d_o	57 mm	57 mm
Breadth	b	8 mm	4 mm
Number of Chambers	n	4	4
Pressure Area	a_p	24.5 mm^2	14 mm^2
Torque	T_s	2.39 N m	1.50 N m
Rotations per Minute	r_{pm}	190.99 $\frac{\text{rad}}{\text{min}}$	190.99 $\frac{\text{rad}}{\text{min}}$
Flow	f	0.79 $\frac{\text{L}}{\text{min}}$	0.45 $\frac{\text{L}}{\text{min}}$
Dimensions		60 x 60 x 18.6 mm	60 x 60 x 15.6 mm

chamber, the actuation pressure (p) and the inner and outer diameter (d_i/d_o). Using the values from Table 5.1 and the pressure area form (5.8) results in:

$$T_s = n * A_p * p * \frac{d_i + d_o}{4000} = 2.996\text{N m} \tag{5.9}$$

To estimate the necessary water flow first of all the rotations per minute (r_{pm}) have to be evaluated based on the wheel diameter (d) and the maximum velocity (v_{max}).

$$r_{pm} = \frac{v_{max}}{d * \pi} = \frac{1 * 60}{0.1 * \pi} = 190.99\frac{\text{rad}}{\text{min}} \tag{5.10}$$

The flow is calculated by multiplying the chamber volume with the rounds per minute.

$$f = (\frac{d_o^2}{4} - \frac{d_i^2}{4}) * \pi * b * \frac{1}{100^3} * r_{pm} = 0.79\frac{\text{L}}{\text{min}} \tag{5.11}$$

The parameters of the steering actuator design presented in Table 5.1 only differ from the parameters of the drive actuator design in the breadth of the slides and in the resulting torque and flow. The breadth of the steering actuator was chosen to minimize dimensions while providing a sufficient torque for steering. The necessary estimation of the steering torque is presented in (5.12).

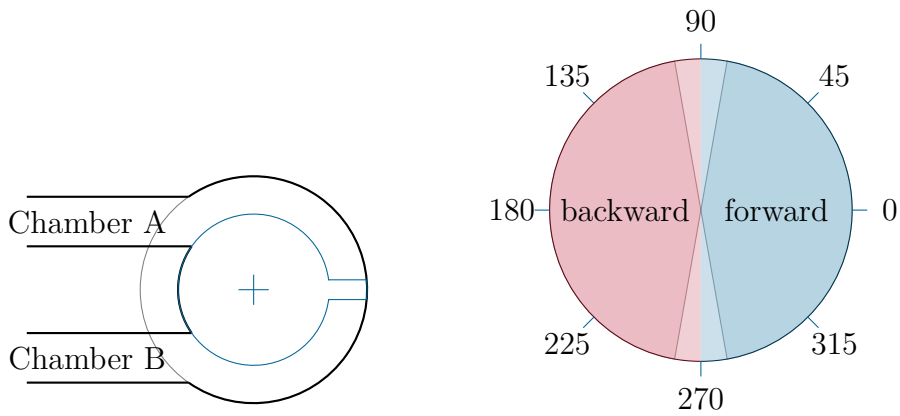
$$T_s = \frac{m * g}{n} * f_{fr} * e = \frac{60 * 9.81}{4} * 1.1 * 0.008 = 1.29\text{N m} \tag{5.12}$$

The parameter m stands for the total mass, n represents the number of wheels, f_{fr} is the anticipated friction coefficient and e is the eccentricity of the friction force.

As Figure 5.8 shows, the slide vane design consists of two similar cover parts, which only differ in two holes where the hydraulic hose nipples will be placed. A ring with six holes and a pocket in form of a four leaf clover is placed between the two covers. The covers are manufactured to partially fit into the pocket to ensure their proper placement and the water tightness of the chamber. The four holes through the mentioned components are designed to use screws to hold the parts together. Both covers feature a cylindrical pocket in the middle which holds the ball bearings. The disc is placed inside of the pocket with a ball bearing on either side. The construction presented in Figure 5.8 did not prove successful. Instead of rotation only leakage could be produced regardless of the input pressure. The attempt sealing all static gaps with silicon glue did not seal the pressure chambers sufficiently to result in a moving actuator. The likeliest reason for this result is that the slides were not produced accurately enough. Due to the small dimensions of the slides mechanical fixation during the CNC milling process was not possible. The parts needed to be glued to a mounting plate. Other possible flaws of the presented slide vane actuator design are presented in Section 5.1.5 and Section 6.2.

5.1.4 Rotary Vane Actuator

For the steering actuator a limited rotation angel of minimum 180 ° is necessary to enable movement in any direction as long as the drive motor can rotate clockwise as well as counter clockwise. (See Figure 5.9b for better understanding) The initial idea was to use the slide vane actuator designed as drive engine for the steering actuation, which would have allowed an infinite number of rotations for the steering actuator. A basic physical limitation of the maximum angle of rotation would have come from the maximum torsion of the cabling and piping of the actuators and sensors mounted next to the wheel. After failing with producing a working slide vane motor to actuate driving as well as steering motions, the task was to create a less complex actuator.



(a) Design of a Rotary Vane Actuator (b) Minumum steering angle for omnidirectional motion.

Figure 5.9: Working principle and minimum angle of rotation of a rotary vane actuator for omnidirectional movement.

As Figure 5.9a shows the rotary vane actuator requires fewer flexible parts at a similar basic design and therefore represents a concept with less complexity. The operating principle is based on the same principle as a hydraulic cylinder. Two pressure chambers are separated by one rigid sheet, which changes its position based on the pressure difference between the two chambers and transmits its motion to a connected object. While the piston of hydraulic cylinders moves linearly the rotor of a rotary vane actuator rotates. As Figure 5.9a illustrates, the two pressure chambers are separated by a the rotor and a static barrier. The maximum rotation angle of the actuator depends on the position of the two supply holes because the rotor must always stay between the pressure chambers.

Figure 5.10 illustrates the design of a rotary vane actuator consisting of two covers, two ball bearings, one rotor with a sealing, one sealing plate, one o-ring sealing, two hose nipples and eight screws. The two cover parts only differ by two holes for the hose nipples and the circular groove for the o-ring sealing. In contrast to the illustration showing the operating principle of the rotary vane actuator, the hydraulic connectors are placed on top of the actuator to better suite the design to the mounting position. The shape of the barrier is adapted in the presented design to guarantee that the rotor always stays in a position between the two hydraulic supply lines. Both of the covers have eight holes for the screws which hold the covers together, one pocket where the rotor is placed and a deeper cylindrical pocket for the ball bearing. The o-ring which is placed in the grove of the cover prevents leakage at the contact surface of the covers. The o-ring which is placed in the grove of the rotor fulfills two

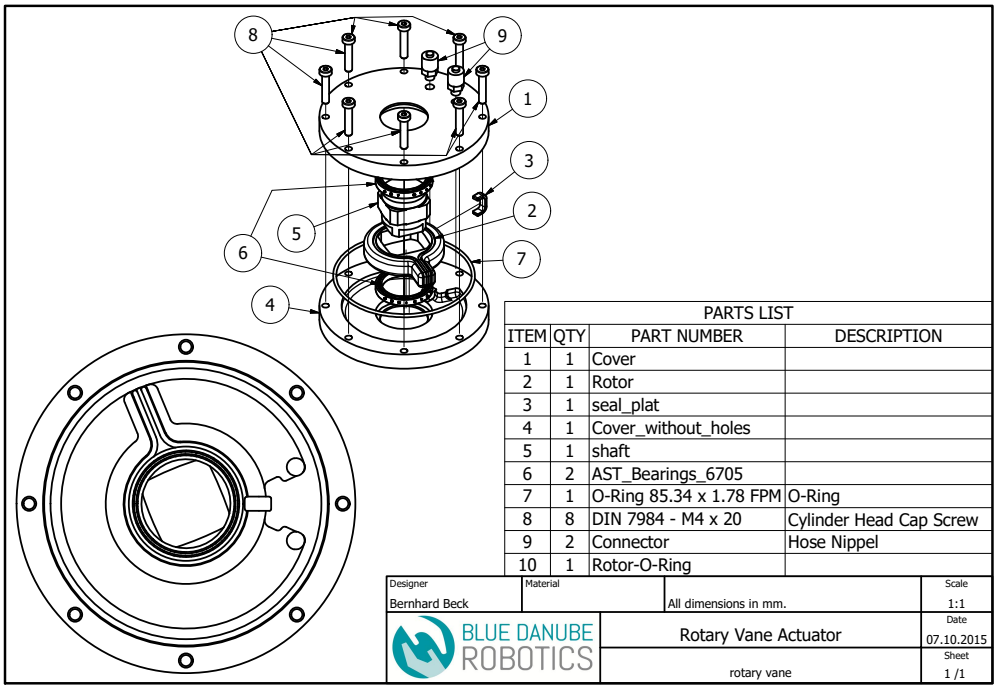


Figure 5.10: Design of a Rotary Vane Actuator.

Table 5.2: Design Parameters for Rotary Vane Actuator

Parameter	**Ref.**	**Steering Actuator**
Inner Diameter	d_i	45 mm
Outer Diameter	d_o	70 mm
Breadth	b	9.5 mm
Number of Chambers	n	1
Pressure Area	a_p	76 mm^2
Torque	T_s	2.185 N m
Dimensions		95 x 95 x 20 mm

important tasks. It seals one pressure chamber from the other at the tip of the rotor and additionally prevents leakage next to the shaft. The sealing plate seals the two pressure chambers at the gap between barrier wall and rotor.

As the rotary vane actuator does not suit the requirements of a drive engine, the following calculations have only been made for the use as a steering motor. According to (5.12) the necessary torque is estimated to be 1.29 N m. The selected dimensions as well as the resulting torque of the rotary vane actuator are presented in Table 5.2

Using the dimensions for the steering actuator from Table 5.2 the pressure area (A_p) can be estimated according (5.13)

$$A_p = \frac{d_o - d_i}{2} * b = \frac{70 - 45}{2} * 9.5 = 76\text{mm}^2 \tag{5.13}$$

The torque of a rotary vane actuator can be calculated according (5.14), with the calculated pressure area (A_p) for one chamber, the given actuation pressure (p) and the inner and outer diameter (d_i/d_o). As a reaction on the failing of the slide vane actuator design the efficiency coefficient for this design is set to 50%.

$$T_r = 0.5 * A_p * p * \frac{d_i + d_o}{4000} = 2.185\text{N m} \tag{5.14}$$

According to (5.14) the presented rotary vane actuator design provides a torque of 2.185 N m, sufficient for steering a wheel of the mobile base.

5.1.5 Alternative to Hydraulic Rotary Actuators

Due to time limitations it was not possible to resolve the production problems which occurred concerning the hydraulic rotary actuators. All prototypes of

the slide vane actuators and the rotary vane actuators showed leakage during tests with 2 to 20 bar. In most cases the leaking could be reduced using silicon glue and an increased contact pressure by tightening the screwing connections. No prototype showed movement in any of the tests. This result might be based on the inaccurate production machines and the high number of self produced components of the rotary actuators. The design of the rotary actuators did not allow to increase the surface pressure of the sealing contact surfaces without increasing the contact pressure between rotor and stator. This characteristic is problematic because tightening the screws enables the actuator to withstand higher pressure before leaking, but it also increases the fluid pressure needed to overcome friction and to move the rotor.

The focus of prototyping was placed on a functioning omnidirectional robot base, rather than a working hydraulic rotary actuator. To enable the robot base to move, the hydraulic actuators were replaced by electric stepper motors. The implementation of the stepper motors[13] proved to be difficult due to the dimensions of the engines. The drive motor, which replaces the slide vane actuator was fit into the wheel to minimize space. The axial length of the steering motor left not enough space to include a hydraulic cylinder in the drive unit because of the limitation of the base height.

5.2 Structural Sub Assemblies

5.2.1 Bearing Structure

For the bearing structure two prototypes were fabricated. The first prototype was made of a wood press board according to the design presented in Section 3.2.2. Figure 5.11 shows all components as well as the assembly of the first prototype in one drawing. All parts were cut from 10 mm sheets using a CNC milling machine. The form-fit plug-in connections were varied in shape and pattern to limit the possible positioning to only one way for each piece. The first prototype had too little stability to be used. To improve this critical characteristic several actions were taken. The use of press board was abandoned as the material crumbled and broke when it was hit. A test object cut from glued laminated timber proved not to be better. It showed acceptable results when bent along the fibers, but cracked and burst when forces where applied bending it across the grain direction. Finally a three-layer plywood with total thickness of 14 mm was chosen. This material proved to be

[13] The stepper motors used for driving and steering are Nanotec ST6018M2008, see specifications at `http://de.nanotec.com/fileadmin/files/Baureihenuebersichten/Schrittmotoren/Baureihenuebersicht_ST6018.pdf`.

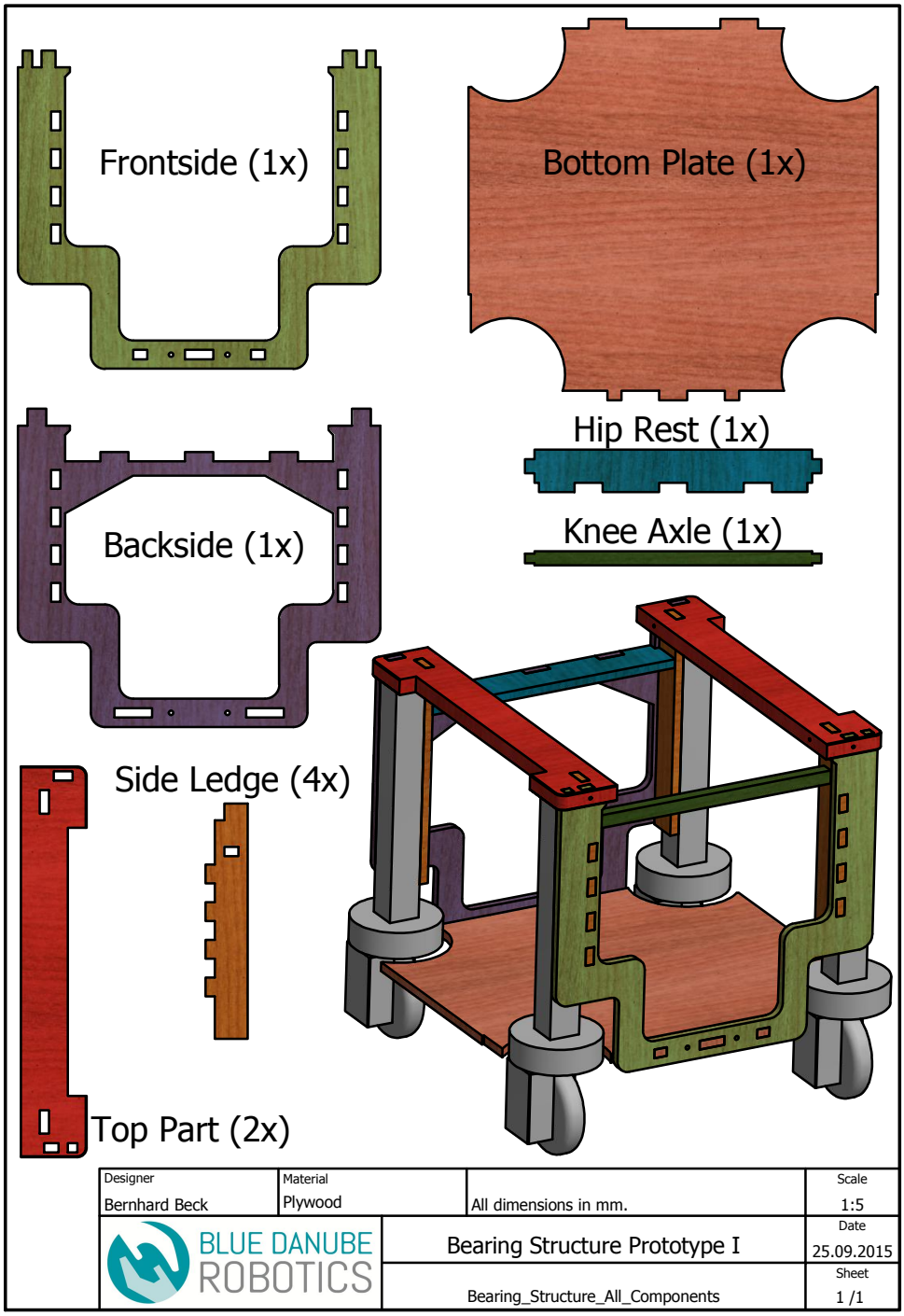
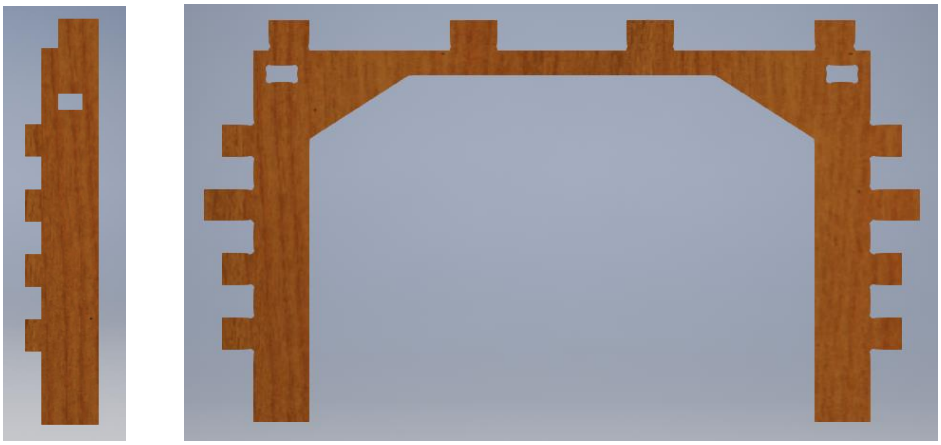


Figure 5.11: Components and assembly of the first prototype of the bearing structure.



(a) Side ledge v1

(b) Side ledge v2

Figure 5.12: Two side ledge parts were merged to one, linking them at the top while using this link to further connect the top component with the lower parts.

a standard product available in any do-it-yourself store as well as capable of withstanding forces and bending moments. It is furthermore easy to cut with the available milling machine. Design alterations were made to prohibit the top components from shaking. Following the idea of using minimum material, the first prototype featured two top parts of similar shape, each linking one front drive unit with one rear drive unit. To increase the sidewards stability the two top parts from the first prototype design were replaced by one wooden top sheet linking all four drive units. Cuttings were only made for plug-in connections and to allow the motion of the upper leg. Although this component will only be implemented as a dummy part the idea was to save space at the most likely areas of rotation and actuation of the upper leg. With the redesign of the top part, the part named hip rest (in Figure 5.11) was integrated in the new top component. Besides the top parts the side ledges were also redesigned to improve the stability of the bearing structure. In the first prototype two side ledges have been implemented on each side. To improve the stability of the robot base the second prototype has only two side ledges, one per side. The new parts were derived from the old geometry by linking two side ledges with a bar. The design changes of the side ledge are illustrated in Figure 5.12.

Figure 5.13 presents the components of the second and last prototype of the bearing structure. The adapted design proved stable enough to hold the weight and to withstand the loads arising from acceleration.

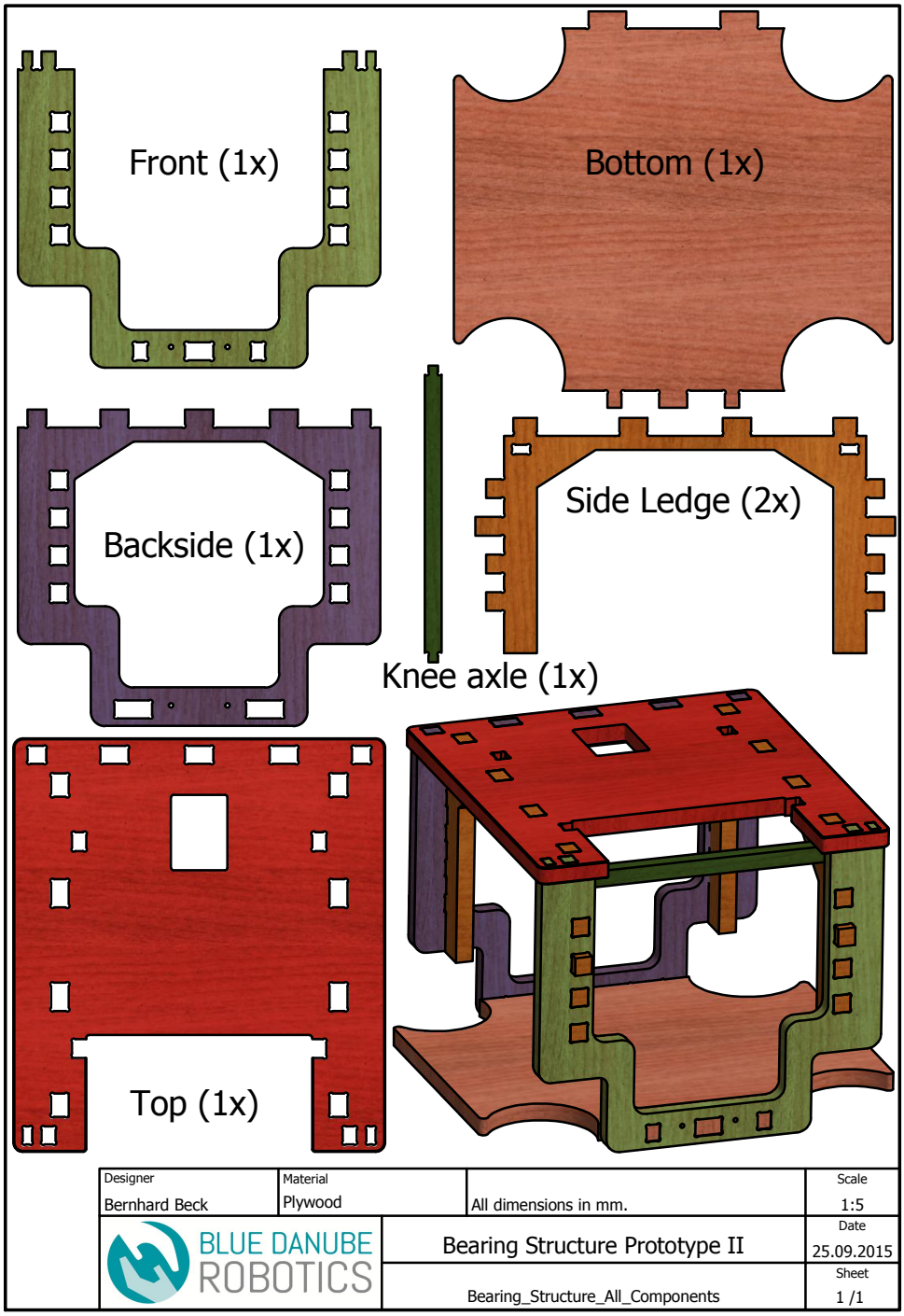


Figure 5.13: Components and Assembly of the second prototype of the bearing structure.

5.2.2 Base Hull

To realize the base hull design presented in Figure 5.14 this assembly has to consist of four AirSkin pads and one supporting framework holding the tactile bodies in place and attaching them to the bearing structure. This combination allows a variety of shapes and forms for the structural component. Three different approaches were used each tailored to the properties and production limitations of three different materials.

PVC - Polyvinyl-Chloride

The first approach was to cut a form from a polystyrene foam [14] block via CNC cutter and use this form to thermo-form the PVC. Creating the necessary form did not pose a problem. The form was manufactured in four pieces due to the height limitation of the available milling machine and glued together afterward. After creating a sheet-metal design of the part, the contour was cut and positioned on the largest plane surface of the form. A heat gun was used to heat the 4 mm PVC sheet at each surface, that needed bending. The surfaces were bent one at a time and fastened to the form while cooling down. Several problems occurred during this step. The first problem was to maintain a continuous temperature in the surface, which needed bending, resulting in inhomogeneous bending radii despite the use of the supporting form underneath the PVC sheet. The second problem showed when the polystyrene material was exposed to the air flow from the heat gun. At areas, which were heated, the form slowly collapsed before the PVC reached the temperature required for bending. Although the technique could be used to create a supporting framework for the tactile pads the result was not precise enough and the production process damaged the bending form.

Glass Fiber Reinforced Polyester

The second production idea followed a similar idea. The plan was to use the same form as for the PVC framework to create a glass fiber reinforced polyester cover. The same material is used in small lightweight boats like canoes and kayaks. A test sample showed that the polyester resin corrodes the polystyrene foam material. To solve this problem the form was covered with a layer of hair wax to separate the form and the resin. As the wax layer was applied manually the layer thickness varies and the shape of the cover was no longer as accurate as the CNC form before. Finding the right ratio of resin and curing agent is an

[14] The used product was an *Austrotherm XPS - extruded polystyrene foam* for further information see: `http://en.austrotherm.com`

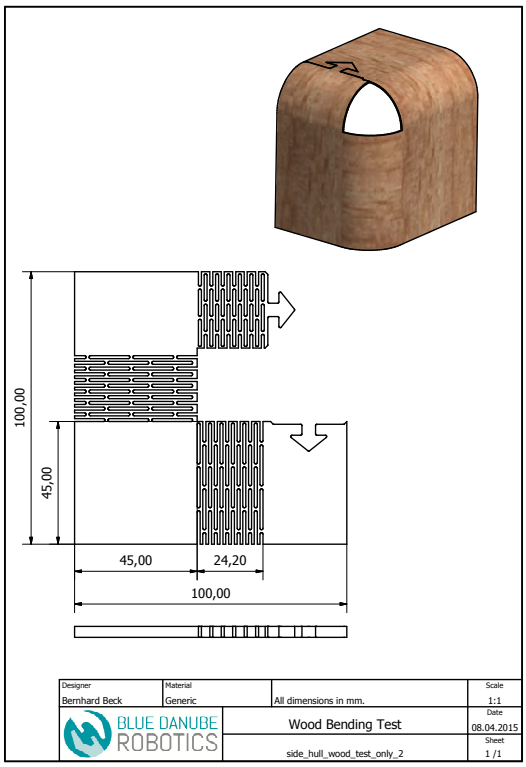
Figure 5.14: Base Hull Prototype for one Side Cover

essential task as well because the hardening time has to be long enough so the whole surface is netted with polyester, but not too long else the resin starts flowing down the vertical surfaces of the form. The first test with glass fiber reinforced polyester did not harden within three days (72 h) and damaged the form further more. Due to effort necessary for a second try of this production technique, a third production idea was tested.

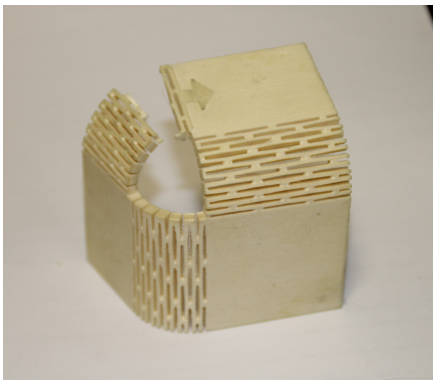
Plywood

Motivated by the good result using wood as a material for the bearing structure the idea was born to use a 5 mm plywood sheet and bend it. There basically are two methods for bending wood. Either by gradually deforming a wooden sheet in steam atmosphere or by cutting slots cross to the bending direction. As the frame structure will be made from a 650 mm x 450 mm wood sheet, bending under steam would require an even bigger box to hold the steam as well as the material. To test the feasibility of bending wood without the use of steam a sketch containing the flat pattern of a three sided corner with rounded edges was created. The chosen material was a three layered plywood, as bending the wood 90° to the fiber direction would cause it to break. The arrow shape in the flat pattern of the test object is used to create a plug connection holding the wood in folded position. The shape of an arrow was chosen to emphasize a intuitive folding instruction. The size of this test object as well as the sheet metal representation are shown in Figure 5.15. The test was conducted successfully but cutting the wood with the CNC milling machine took about 30 min. As Figure 5.15b illustrates the test body broke into pieces due to frequent folding and unfolding by curious colleagues.

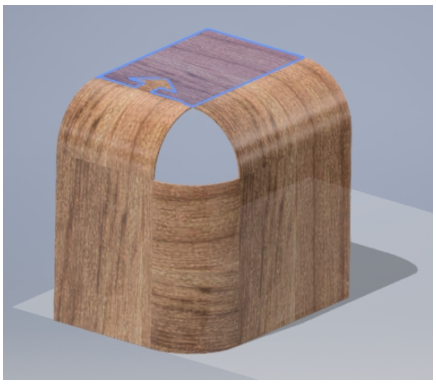
After finishing the bending test, some small adjustments of the base hulls structural component were necessary to create a promising prototype. First of all the shape was simplified by eliminating one of the edges to reduce the number of bends. Furthermore the rounded corners are left out because they can not be brought to a flat pattern without creating polygons instead of a steady curved surface. This fact is based on the problem that there is no coherent flat pattern which can be folded to create a sphere. Furthermore two rectangular slots and two rectangular pockets were implemented to hold the folded part in place when it is mounted to the bearing structure. The remaining holes of the structure are designed to hold the sensor surfaces in place. The first step was to create a sheet metal model to cut the contour from a sheet of plywood. As the cutting of the side part for the prototype of the base hull would have taken very long with the available CNC-mill, this component was laser cut by an external company. The extensive cutting time is strongly based on the number of slots needed to give the wood enough flexibility to



(a) Flat pattern of the corner



(b) Picture of the bending test object



(c) Folded corner

Figure 5.15: Bending wood

bend. While the milling process required a small tool and more than one step down of the machine head, the laser cutting machine was capable of cutting the material in one step with a much higher cutting speed. After creating the flat pattern, the wood was moistened and bent in steps, to minimize the risk of over-straining the material. The plug-in connections were fastened with wood glue to increase the stability of the connection.

Selected Technique

From the above presented production possibilities for the structural component of the base hull, the last one was chosen. The latest prototype is equipped with a laser cut and bent sheet of 5 mm plywood, which can be furnished with a soft and tactile cover.

6 Conclusion

6.1 Final Setup

The design of the bearing structure could be implemented without alterations. The functional unit named base hull could be implemented with one exception, which is the realization of the soft and tactile cover. The implementation of ©AirSkin technology could not yet be realized, because of the high workload of Blue Danube Robotics. The AirSkin sensors can be mounted whenever the production process is finished.

As no working hydraulic rotary actuators could be manufactured, a different actuator for driving and steering needed to be found. As mentioned in Section 5.1.5, electric stepper motors from Nanotec[1] were selected. It was possible to mount the drive motor inside of the wheel, similar to the hydraulic actuator. The replacement of the steering actuator was more problematic because the design of the mobile base restricts the installation space. To avoid drastic design changes and additional components for torque transmission, the stepper motors were placed at the same position as the hydraulic steering actuators were planned to be. Due to the dimensions of the stepper motor a drive module consisting of two stepper motors and one hydraulic cylinder would be much bigger than the originally planned drive module. This fact left the choice to either ignore the height limitation of the mobile base presented in Requirement 6 or to exclude its ability to climb thresholds ($\geq$ 20mm) and single steps (requested in Requirement 3). The conservation of the outside dimensions was decided to be more important because they have extensive consequences on the other parts of the robot. The base height determines the mounting height of the arms and the head, influencing the reach and the field of view of the robot. Figure 6.1 presents one of the currently mounted drive modules of the mobile robot base. The prototype of the mobile base is only capable of overcoming obstacles and thresholds by rolling over them, which limits object height to 20 mm and smaller.

The first prototype of the omnidirectional robot base does not contain all items presented in Section 4.4 (Designing Internal Components). At the moment the mobile base only contains components, which are necessary for the mobile

[1]The selected stepper motors are Nanotec ST6018M2008

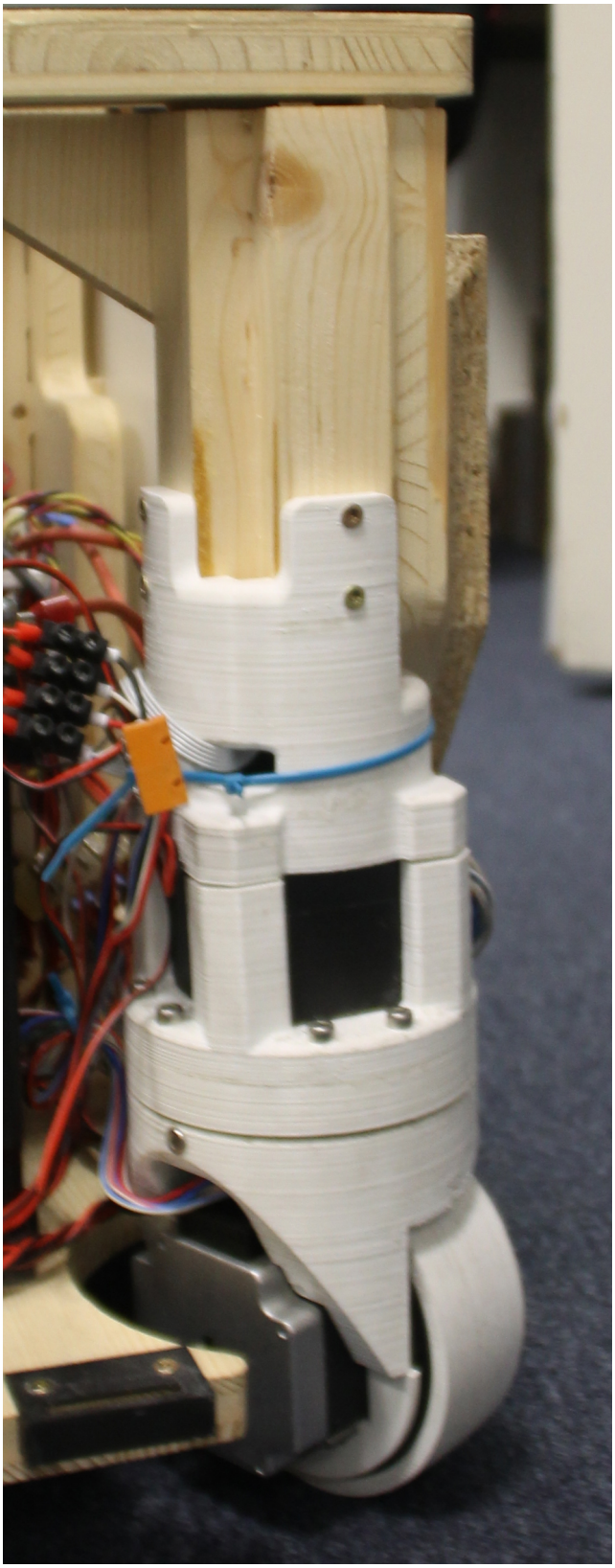


Figure 6.1: The prototype of the drive module consists of two stepper motors. The implementation of the hydraulic cylinder was resigned to retain the height of the base despite the use of stepper motors.

(a) Front view of the mobile base prototype

(b) Side view of the mobile base prototype

Figure 6.2: The prototype of the omnidirectional mobile robot base.

base to move. As the implemented actuators do not require the mounting of a hydraulic circuit, the pump and fluid container are not installed at the moment. Any of the items listed in Table 2.1 (Contained Components) can be installed inside the mobile base any time, as there is space reserved for them. Figure 6.2 illustrates the first prototype as described in this section.

6.2 Lessons Learned

Prototyping From the prototype and the tests several understandings were gained. The most important lesson learned is that although it is tempting to include as many features and abilities in a first prototype to prevent too many changes, a large number of prototypes, or a total redesign of the system, this approach is risky. This strategy holds the danger that any result can only be seen at the end of the total project. Furthermore one inoperable component like the rotary hydraulic actuators, stops the progress of the total project and thereby prevents testing the operable components as parts of the system. The referring example in this thesis are the hydraulic actuators. Although the hydraulic piston was a successful design, the first prototype combined a lot of very specific ideas. The best description might be, that the first prototype built, was the third prototype designed. The design loop of this sub-assembly provided a very simple, but sophisticated design, in which every component was optimized with regard to functionality, easy and cheap production as well as with regard to a minimum number of different components. In this special case the elaborate design of the first prototype resulted in a sub-assembly without

the need for further improvements. In case of the hydraulic rotary actuators, a similar complex design process was performed. In contrast to the hydraulic cylinder the designs presented in Section 5.1.4 and did not function from the start. Due to the complexity of the first prototype a simple error analysis was not possible, resulting in a long but fruitless search for the problem. A different approach following a larger number of simple steps, might have resulted in a less elaborate, but working prototype, preventing the necessary step to incorporate the electric motors in the drive system.

Despite the impression, that a step-by-step development strategy is preferable to a all-in-one approach, the development of hydraulic actuators is more challenging than expected even when the goal is to manufacture an actuator using a common mechanism. Although the design and manufacturing of the hydraulic piston worked right from the start, leakage is a problem, which is still present with the last prototype. This indicates that the selection of proper seals and manufacturing tolerances experience in the field of application or even better with the specific working principle of the actuator is inevitable. During this thesis the SKF - Design Catalog[2] was used as guideline for seal selection and tolerance definition of the contact surfaces. Although no single factor could be found, which prevents the slide vane actuator and the rotary vane actuator design from working, the number of in-house manufactured components is higher than with the piston design. Furthermore the piston design allows to adjust the pressure on each sealing independently, whereas the design of the rotary actuators does not. This may result in leakage or higher friction than necessary when manufacturing is not precise enough. Another difference between the operable and the inoperable actuator is the material combination at the moving surfaces. In case of the hydraulic cylinder a PTFE[3] piston slides on a stainless steel surface. In case of the rotary actuators several different material combinations were tested. The slide vane actuator featured PTFE on PP[4]. The rotor of the rotary vane actuator is made of UHMWPE[5] with the stator made of ™Necuron[6]. Any of these material combinations is expected to have low friction, but as with most material combinations tribological characteristic values are untested.

3d Printer 3d printing is a remarkable technology, regardless of the specific physical mechanisms used. Although this technology improved and still im-

[2]SKF - Design Catalog was used as a guideline for the selection of seals. [22]
[3]PTFE - Polytetrafluoroethylene better known as ™Teflon DuPont Co.
[4]PP - Polypropylene
[5]UHMWPE - Ultra-high-molecular-weight polyethylene
[6]™Necuron - material composition undisclosed, ™Necuron is a material for modelling and prototyping produced by NECUMER GmbH

proves the rapid prototyping process, the printing quality and precision of the printers available in the low and medium price section as well as the material properties of the printable materials hardly fitted for a physical demonstrator or physical prototype. While the printed parts suite as representatives of their digital models, they seldom work as physical models. Often the dimensions and surface qualities do not comply with the digital model. For example the printing of tooth connections, as necessary in Section 5.1.1 for pump assembly components, is a difficult task requiring precise tools. The use of the available 3d printer (Ultimaker Original and Profi3DMaker) at the current level of development produced components which required a lot of rework. Nonetheless the process was not much more extensive than CNC-milling the same object.

6.3 Improvements

6.3.1 Functional Improvements

Motion Capabilities

Although a variable footprint was decided to be too expensive and complicated for this master thesis, the idea of adapting the supporting polygon depending on the task at hand and the available space is very appealing. The master thesis presented with Rollin' Justin [7] illustrates the feasibility as well as one elegant design to implement a variable foot print for a service robot. A combination of the variable footprint and the ability to climb single steps might be interesting.

Another improvement on the motion capabilities of BLUE, would be to extend the ability of climbing single steps to climbing stairways. Although single step climbing is a significant step in pushing the robots boundaries, the step towards surmounting straight stairways would enable BLUE to operate on multiple floors of a house. Although the development from single step to stairways might be trickier than expected, a flexible footprint could help with this task.

Actuator Prototype

Solving the problems which occurred with in-house production of the slide vane actuator would open up more exciting possibilities for the omnidirectional robot base. First of all it would be possible for the robot to use a steering angle of more than 360° because with the presented design all cables and pipes could go through the hole in the center of the actuator, resulting in cable torsion

[7] see Section 1.3.2 and further [24]

being the angular limitation. Furthermore the reduction in height will allow the implementation of hydraulic pistons for overcoming high obstacles as well as single steps.

Hydraulic Circuit

The optimization of the hydraulic circuit and especially the hydraulic pump seems very promising, as the current pump generates a noise level similar to drilling machines. The selection of a different motor and a more precisely manufactured transmission could reduce the noise pollution, as most of the noise is produced by the motor and the gear transmission. In the long run only a specially designed hydraulic pump will reduce the noise generation to an acceptable level. Furthermore general optimizations can reduce the time the pump has to work, reducing the duration of noise generation.

6.3.2 Improvements for Serial Production

The shift from prototyping to serial production influences which production techniques have most advantages. While CNC-laser cutting is a quick and cheap way to produce the wooden frame structure for the base hull prototype, a punching tool with the same contour can be used to cut the wooden sheets faster. Another technology, which might be even more efficient is an injection molding process using wood-plastic-composites. With the last technology mentioned the sheet of wood must not be bent, but comes out of the injection mold in the needed 3d shape.

The 2d contours of the components used in the bearing structure can further be improved to fit as many parts to an as small sheet of wood as possible. This way the scrap wood can be minimized. The biggest optimization potential lies in the static connection parts used in the drive units. They have been designed with focus on mechanical strength and geometrical simplicity. The components have not yet been optimized concerning production processes.

Although changed production processes require the redesign of many components, it opens up new possibilities, which can help reduce the product price in the long run.

6.4 Prospects

With the presented prototype, the mobile service robot BLUE is one step closer to its implementation. As mobility is an important aspect of a personal assistant, the omnidirectional mobile base provides an essential ability for

BLUE. Nevertheless the most exciting developments are yet to come. The implementation and testing of the single step climbing strategy is one of the highlights concerning BLUEs mobility in close future. As mentioned in Section 6.3.1 the combination of the presented design and Rollin' Justins variable footprint would open up totally new possibilities. Although the implementation of the hydraulic rotary actuators failed in this master thesis, mobile hydraulics could show the way to more powerful but still compliant and user friendly actuators for mobile robots.

A Standing up from the ground

For most people getting up from the ground is a common task that poses no problem. But there are several persons in our social environment who have difficulties with this movement. In some cases getting up grows harder due to aging of the musculoskeletal system, in other cases disabilities occur as a result of accidents. Most affected persons know one or another simple strategy which helps them getting up more easily. The standard technique makes use of a chair, or a similar furniture, as Figure A.1 illustrates. For further information on how to get up from the floor refere to the following sources.

Figure A.1: Standard Technique for getting up from the ground. Screenshot of the video on fall-recovery techniques ©homeability.com

- The Berkshire NHS Falls Prevention Services[1] provides general information on what to do after a fall on a A4 format pamphlet[2].
- homeablity.com, a platform providing many information on aging or living with disability at the own home. Especially interesting are the article on "How to get off the floor"[3] and the video titled "How to get up MacGuyver style"[4] where Figure A.1 is taken from.

[1]Berkshire NHS Falls Prevention Services, UK - www.bhps.org.uk/falls

[2]The pamphlet on "I have had a fall!" can be found at `http://bhps.org.uk/falls/hadafall.htm`

[3]The article "How to get off the floor" accessible at: `http://homeability.com/falls-how-to-get-off-the-floor/`

[4]A video on how to get up using unconventional methods. `https://youtu.be/4ETgQD8QhZs`

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