RAM ROBOTICS AND MECHATRONICS

Design & Prototype of McRobot 3.2

D.M.G. (Dinah) Kleiboer

BSc Report

Committee:
Prof.dr.ir. S. Stramigioli
Ir. F.S. Farimani
Dr.ir. D.M. Brouwer

June 2016

010RAM2016
Robotics and Mechatronics
EE-Math-CS
University of Twente
P.O. Box 217
7500 AE Enschede
The Netherlands

UNIVERSITY OF TWENTE.

MIRA BIOMEDICAL TECHNOLOGY AND TECHNICAL MEDICINE

CTIT

UNIVERSITY OF TWENTE.

University of Twente
Advanced Technology

The Design & Prototyping of McRobot 3.2

A patient mounted Parallel Manipulator for surgical tool orientation.

Bachelor Thesis

DINAH KLEIBOER (S1449559)

ROBOTICS AND MECHATRONICS

Chairperson: Prof. Dr. Ir. S. Stramigioli
Supervisor: Ir. F. S. Farimani
External member: Dr. Ir. D.M. Brouwer
Member: Dr. Ir. J. Broenink

June 16, 2016

Abstract

In this thesis the design and prototyping process of McRobot 3.2 is discussed. The McRobot is a Magnetic Resonance Imaging (MRI) compatible robot that assists interventional radiologists in doing biopsies. Version 3.2 is an improvement that only orients the surgical tool using a parallel manipulator and is attached to the patient using velcro straps and adhesives. A parallel manipulator is used as it provides a constant and fixed center of rotation and significantly higher stiffness. For more accuracy, the manipulator its remote center of motion is placed exactly on the skin of the patient where the surgical tool is to be inserted.

Keywords

MRI compatible Robotics, Medical devices, Mechatronics, CAD modeling, Prototyping, Parallel Mechanisms

Acknowledgments

This thesis and the complete prototype of the McRobot version 3.2 have become a reality thanks to the kind support of several individuals.

First, I would like to thank my supervisor, Foad S. Farimani, for giving me the opportunity to work on this project and for his constructive guidance during the design process.

Also to the technicians of the Robotics and Mechatronics (RAM) workgroup who have helped substantially during the design and prototyping process, I would like to express my gratitude.

Radiologist Dr. J. Veltman is also thanked for allowing me to accompany him in the hospital during several breast biopsy procedures.

Last but not least, I thank my colleagues from the RAM Lab for the knowledge they provided me with and their exceptional assistance throughout the entire project.

Dinah Kleiboer (s1449559)

Contents

Abstract 1

Acknowledgments 1

Abbreviations 5

1 Introduction 6
- 1.1 Prior work . . . 6
- 1.2 Problem statement . . . 8
- 1.3 Planning & outline of the thesis . . . 8

2 State of the Art 9
- 2.1 MRI-guided Needle Biopsy Procedure . . . 9
- 2.2 Patient mounted Devices for MIS . . . 9
- 2.3 Parallel manipulators . . . 12

3 Requirements & Specifications 14
- 3.1 MoSCoW Analysis . . . 14
  - 3.1.1 Multi-modality . . . 14
  - 3.1.2 Patient Mounted & Stability . . . 14
  - 3.1.3 Versatility . . . 14
  - 3.1.4 Size . . . 15
  - 3.1.5 Degrees of Freedom . . . 15

4 McRobot 3.2: Design 17
- 4.1 Conceptual Design of the Base . . . 17
- 4.2 The Parallel Manipulator . . . 17
  - 4.2.1 Parallel Manipulator Design . . . 17
  - 4.2.2 Kinematics & Workspace . . . 18
  - 4.2.3 Parallel Manipulator Conceptual Design . . . 20
  - 4.2.4 End-effector . . . 20
- 4.3 McRobot 3.2 conceptual design . . . 21

5 Prototype & Testing 22
- 5.1 Prototype . . . 22
  - 5.1.1 Base . . . 22
  - 5.1.2 Parallel Manipulator prototype . . . 22
- 5.2 Testing . . . 23
  - 5.2.1 Versatility . . . 23
  - 5.2.2 MRI compatibility . . . 23
  - 5.2.3 Actuation & Workspace . . . 24

6 Discussion & Conclusion **25**
6.1 Discussion 25
6.2 Conclusion 26
6.3 Future work 27

Bibliography **29**

Appendices **30**

A Figures **31**
A.1 McRobot 3.1 31
A.2 Gantt Chart 32

B Operating System Setup **33**
B.1 Electrical setup 33
B.2 Arduino code 34

List of Figures

1.1 The initial concept designs of the McRobot by D.H.J.M. van den Hoogen [1]. 7
1.2 The base concept design of the McRobot Version 3.1 by Xiaolong Zhi [2]. 7
1.3 The concept design of the complete McRobot version 3.1 by Xiaolong Zhi [2]. 7

2.1 The fixation process of the spine-puncture robot [3]. 10
2.2 The patient mounted spine puncture robot design by Bekku et al. [3]. 10
2.3 Fixation method using straps and a disposable adaptor for a shoulder-mounted robot [4]. . 10
2.4 The prototype of the CT-Bot by Maurin et al. [5]. 11
2.5 The Light Puncture robot prototype by Bricault et al.[6]. 11
2.6 The Robobsy Beta prototype by Walsh et al. [7]. 12
2.7 Basic structure of the planar four bar parallel mechanism [8]. 13
2.8 The Remote center of motion and workspace of a four bar parallel mechanism. 13
2.9 The Eye-RHAS, a surgical robot with a fixed RCM and its operation based on the parallel structure [9]. 13

3.1 Diagram of the space available inside a 60cm MRI bore for two male subjects. Subject 1: $1,65m$ and $71kg$. Subject 2 (noted in Brackets): $1,85m$ and $99,8kg$ [10]. 15

4.1 Conceptual base design for the McRobot 3.2. 17
4.2 Conceptual design of the strap-holder that may move auround the base or be fixed. 17
4.3 Diagram of the double parallelogram showing the exact location of the RCM. 18
4.4 The workspace obtained from the forward kinematics of the double parallelogram is plotted using Geogebra. 19
4.5 The workspace obtained from the inverse kinematics of the double parallelogram is plotted using Geogebra. 20
4.6 Conceptual design of the double parallelogram mechanism. 20
4.7 The adapted rotor for the actuators used. 20
4.8 The conceptual design of the end-effector. 21
4.9 Conceptual design of the complete McRobot 3.2. 21

5.1 The complete system setup of the first prototype of the McRobot 3.2. 22
5.2 Placement of the prototype on the thoracic region of a volunteer. 23
5.3 The 3D image of a 3D-Hyce MRI scan done with the McRobot on a breast phantom, the objects above the phantom are fish oil markers placed on the robot. 23
5.4 Diagram of the workspace obtained by the first prototype. 24

6.1 CAD model of the recommended configuration of the base joints of the parallel mechanism. 25
6.2 The complete system with the recommended adjustments implemented for an increased workspace. 26

A.1 Exploded view of the actuator designed by X. Zhi for the McRobot 3.1 [2]. 31
A.2 Gantt chart of the project design process. 32

B.1 Electrical circuit setup used to connect the arduino and the pneumatic valves. 33

Abbreviations

McRobot	MRI compatible Robot
DOF	Degrees Of Freedom
MIS	Minimally Invasive Surgery
CT	Computed Tomography
RCM	Remote Center of Motion

Chapter 1

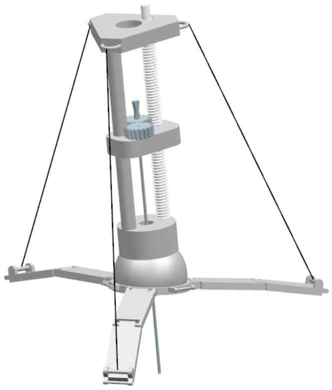
Introduction

Globally the annual number of cancer cases is expected to increase to 22 million by 2032. The cases vary between many different types of cancer with lung cancer being the type causing most deaths, over one million per year [11]. With the help of the right technologies, early detection and immediate treatment is possible, decreasing the number of cancer fatalities. As most medical operations are done manually, giving room for possible human error, the use of special assistive devices is increasing. These assist physicians to achieve higher precision and avoid the possibility for human error. Especially Magnetic Resonance Imaging (MRI) compatible robotics shows to be very promising for robotically assisted invasive surgeries. The **M**RI **c**ompatible **Robot** (**McRobot**) is one of the technological advancements in this field designed to assist in Minimally Invasive Surgeries (MIS) and targeted therapies for cancer. It is a patient mounted design able to orient and insert surgical needles using tele-manipulation and MR-image guidance. The research, design and prototyping of the McRobot started in 2006 in Iran, at the Amirkabir University, Tehran. Since then the model has been under constant improvement with the latest one being version 3.1. The main goal of this bachelor assignment is to further improve the design and create prototype version 3.2, focusing on the base of the robot, how this is to be mounted and attached on the patient during the procedure, and orientation of the surgical tool.

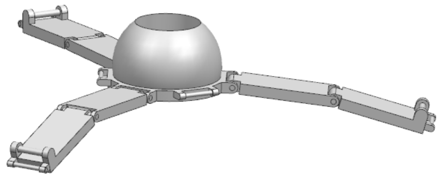
1.1 Prior work

The initial designs of the McRobot focus on creating a universal and versatile device compatible with multiple types of imaging modality and surgical tools for MIS, and appropriate for fixation on a wide variety of patients and body regions. The McRobot is fixed on the patient to passively follow sudden movement and avoid misplacement of the needle. Furthermore, requirements such as telemanipulated insertion of the tool, safety and cost effectiveness of the McRobot create a device with a significant positive impact on MIS for cancer treatment. The patient mounted device has four degrees of freedom (DOF), obtained by a tool insertion mechanism mounted on a ball socket joint allowing it to rotate freely. The ball joint in its turn is mounted on a base that consists of three legs that mimic the shape of an octopus. From each base leg a rope connected to an actuator is attached on the tool insertion mechanism, the ropes get actuated to manipulate the angle of the insertion mechanism [1]. One of the initial concept designs of the McRobot can be seen in Figure 1.1a. The base legs of the McRobot in this design each consist of two passive joints with one degree of freedom. The McRobot is attached on the patient by using straps or velcro straps fixed at the end of the base legs, see Figure 1.1b.

The latest improvement of the McRobot involve pneumatic actuators, called MotoP 1.1, designed and prototyped by Xialong Zhi, in his MSc report for version 3.1 of the McRobot [2]. In this version some adjustments are also made to the base and to the attachment method of the McRobot on the patient. For an increased flexibility and thus also versatility of the McRobot, another joint is added giving the base legs two DOF, see Figure 1.2a. Attachment to the patient occurs via straps, attached to each base leg, in combination with pneumatic suction cups, placed under the base of the ball mechanism and the base legs, as can be seen in Figure 1.2b. The complete design of the latest McRobot version 3.1 can be seen in Figure 1.3.

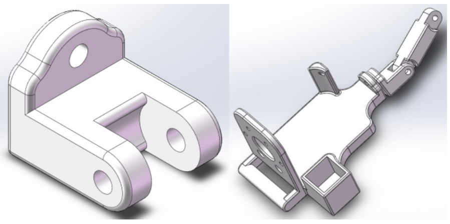


(a)*Initial design of the complete McRobot*

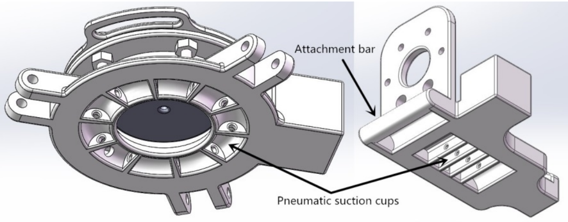


(b)*Design of the base part with attachment bars at the end of the legs.*

Figure 1.1: *The initial concept designs of the McRobot by D.H.J.M. van den Hoogen [1].*



(a)*Left: the extra joint added.*
Right: the base leg containing the extra joint.



(b)*Left: Pneumatic suction cups under the base of the ball mechanism.*
Right: Pneumatic suction cups under a base leg.

Figure 1.2: *The base concept design of the McRobot Version 3.1 by Xiaolong Zhi [2].*

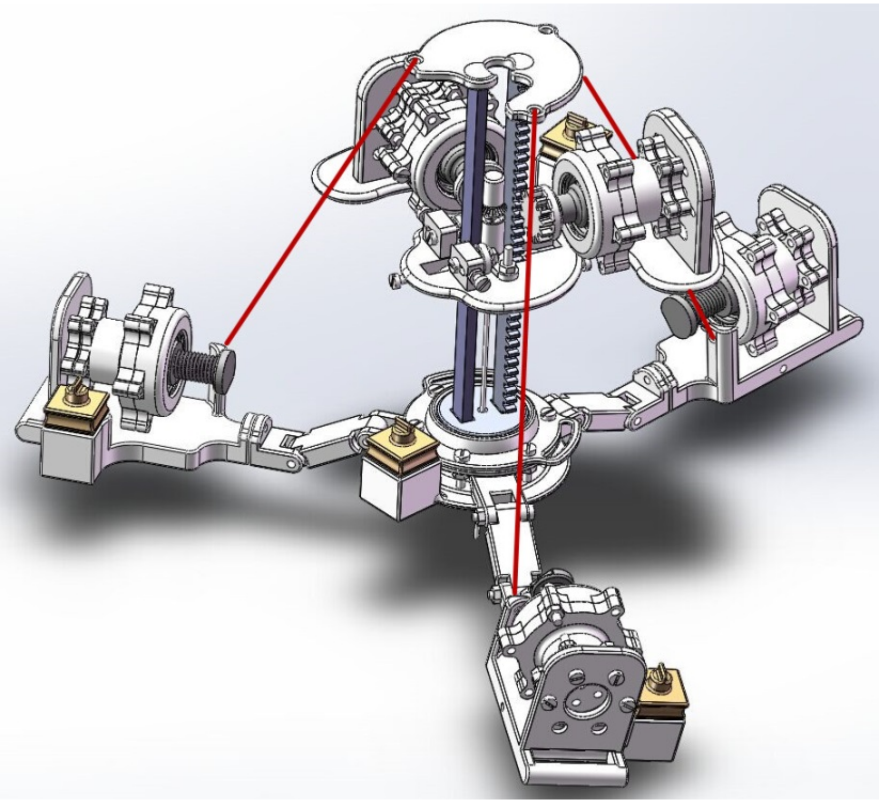


Figure 1.3: *The concept design of the complete McRobot version 3.1 by Xiaolong Zhi [2].*

1.2 Problem statement

The previously designed structures and mounting mechanisms of the McRobot have shown to be inadequate during operation. The main problem lying in the overall stability of the complete system. Due to improper attachment, the base legs move during actuation of the actuators. This also leads to failure in passively following patient motion such as respiratory motion and unexpected movement, due to coughing for example. In previous versions of the McRobot the idea was to insert the needle via telemanipulation, however, consultation with medical specialists proved that this feature is not desired. This is due to the general standards, mainly legality and safety, all devices have to satisfy before being admitted for use in any medical procedure. Therefore, a new mechanism is needed solely for orientation of the needle. Furthermore, there are several requirements set for the McRobot that also have to be met such as multi-imager compatibility, versatility, being safe and cost effective [1]. In this thesis several attachment methods are analysed to solve the instability problem and a needle orientation mechanism is designed.

1.3 Planning & outline of the thesis

The process to create a new and improved prototype of the McRobot requires sufficient planning, therefore, a Gantt Chart (found in section A.2) is used as the basic structure to successfully finish this project. This structure consists of three important phases: the literature study phase, the conceptual design and prototyping phase and the prototype testing phase. Therefore, the thesis is also structured in this manner. First, information is gathered on MRI guided biopsies and a literature study is conducted on existing patient mounted robots and parallel mechanisms for needle orientation. The design phase is started by listing the requirements and specifications of the McRobot 3.2. After which the conceptual design of the first prototype is established and several tests are conducted.

Chapter 2

State of the Art

2.1 MRI-guided Needle Biopsy Procedure

When a patient is diagnosed with the possibility to have cancer, a small tissue sample of the possibly affected area, the lesion, is required for testing to confirm the diagnosis. The procedure of obtaining the tissue sample from the body is called a biopsy. Minimally invasive needle biopsies are generally preferred over open surgery biopsies which require a longer healing time for the patient. For safety and precision the procedure is image-guided by either Magnetic Resonance Imaging (MRI), ultrasound, x-ray or Computed Tomography (CT) imagers. One limitation of needle biopsies, however, is that the tissue sample may be too little for testing and the biopsy procedure has to be repeated [12]. The biopsy may also have to be repeated if the patient accidentally moves during the insertion process causing misplacement of the tool. In general the biopsy procedure goes as follows:

1. A light sedative may be given to the patient before the procedure and the location of needle insertion is anaesthetized. (Depending on the type of biopsy this step may be skipped.)
2. The patient is entered into the MRI-bore and a scan is made to verify the location of the lesion and determine the safest inserting position and needle orientation.
3. The entry point is marked and disinfected, after which a small incision is made for easier insertion.
4. The biopsy tool is inserted by the interventional radiologist until the lesion is reached using the MRI images as a reference.
5. After insertion another MRI scan is done to check if the tool is inserted correctly, if not the tool is removed and the previous step is repeated.
6. The required amount of tissue samples is taken from the lesion and the needle is removed.
7. Possible bleeding is stopped and the incision is covered with a bandage.
8. After observation the patient may go home the same day.

2.2 Patient mounted Devices for MIS

Minimally invasive surgery is a considerably preferred method to perform operation on patients. This method, however, has its drawbacks for the surgeon, as it requires great precision and limits visibility of the operating area substantially. Therefore, the use of assistive devises for these surgeries is desired. These devices are often patient mounted designs, because this provides more savety and has a compact size for use in operating rooms. A few of these already existing devices are analysed below to propose a solution for the stability and attachment issues of the McRobot.

Spine puncture robot

The body mounted robot for assistance in spine surgery was developed by A. Bekku et al [3]. To get proper fixation of the robot on the patient body the suction method was used. Fixation is utilized by a liquid-like device that can take the shape of the body before it turns into a type of solid and fixates itself to the skin by suction. The fixation device consists of a granular substance that acts as the liquid inside a flexible case. The main driving mechanism for this is jamming phase transition, which works by increasing the density of the substance turning it from liquid state into a solid state. Bekku et al.

did this by decreasing the air pressure inside the flexible holder after the required shape is acquired. The fixation process can be seen in Figure 2.1. Their design focused on fixation to the human back by optimizing the thickness of the device between the skin and the robot base. The spine puncture robot and its fixation device designed by Bekku et al. can be seen in Figure 2.2.

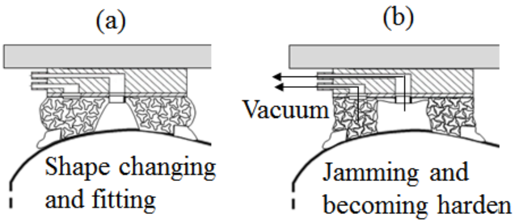
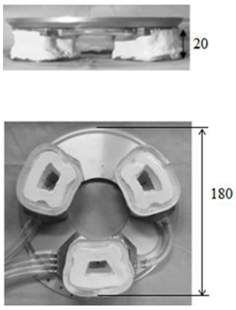
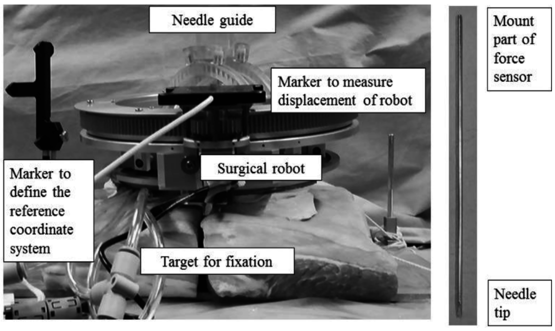


Figure 2.1: *The fixation process of the spine-puncture robot [3].*



(a)*The fixation device of the spine puncture robot with three suction mechanisms.*
Top: Side view.
Bottom: Bottom view.



(b)*The complete spine puncture robot.*

Figure 2.2: *The patient mounted spine puncture robot design by Bekku et al. [3].*

MRI-guided Arthrography robot

A shoulder mounted MRI-compatible robot was developed by Monfaredi et al. [4] to decrease the time of the two-stage arthrography procedure to just one-stage. The robot was designed to determine the precise orientation of insertion and give stability for manual insertion by the physician. For fixation on the shoulder a mounting mechanism consisting of straps and a disposable ring adaptor was used, as can be seen in Figure 2.3. This resulted from the requirements of time efficient attachment, stability during operation and sterility of components in contact with the patient. For versatility of the robot the disposable adaptor could be made in several formations for application on different body parts. To test the stability of the mounting system they did several tests using active markers placed on the base and an optical tracker.

Figure 2.3: *Fixation method using straps and a disposable adaptor for a shoulder-mounted robot [4].*

CT-Bot

The CT-Bot is one of the first needle positioning and orientating robots to be patient mounted. This five DOF robot was designed by Maurin et al. [5] for MIS guided by a Computed Tomography (CT) imaging system. The main requirements they set for the CT-bot were: safety for patients, sterility, light and compact structure and the ability to orient the surgical tool. The prototype was constructed from resin and polymeric powders via 3D-printing methods and can be seen in Figure 2.4. Using straps the circular shaped base of the prototype could be attached to the body of the patient. For extra comfort, rigidity and an increased connection area between the patient and the mechanism, a vacuum mattress was added. The mattress consisting of small polystyrene balls takes the shape of the body curvature and using the jamming transition method it becomes rigid. The operating part of the robot could be fixed and removed again easily without having to detach the base from the patient. This gave several advantages such as choosing the initial position of the robot with ease and the ability to quickly remove it if the physician wishes manual control.

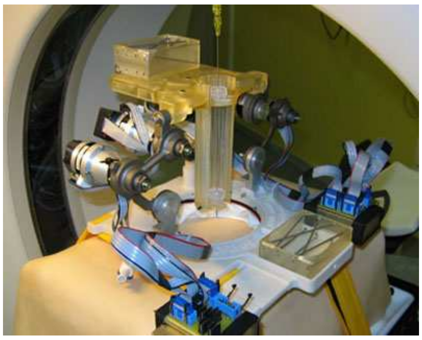
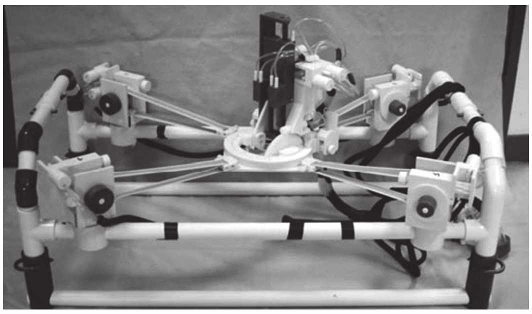


Figure 2.4: *The prototype of the CT-Bot by Maurin et al. [5].*

Light Puncture Robot

A lightweight CT and MRI compatible robot intended for MIS of the thoracic and abdominal area, hence its name Light Puncture Robot (LPR) was designed Bricault et al. [6]. This body-fixed design is fabricated from plastics (nylon, delrin and epoxy) and has a very light and somewhat compact structure, with a mass and volume of $1kg$ and $15by23cm^2$, respectively. The LPR is slightly different from the other robots discussed in this chapter, as it consists of a support frame that initially rests on the patients bed. The part of the robot that orients the needle is connected to the frame via straps and is in direct contact with the patient skin, as can be seen in Figure 2.5. The straps are connected to actuators on the frame that enable the robot to move along the skin with two DOF for more accurate positioning. To fit multiple patient body types and imaging systems the height of the supporting frame is adjustable. To determine the position of the robot via the CT image a square frame, made from epoxy resin, was added to the design of the needle-holding module and could be filled with oil for localization on MR-images.



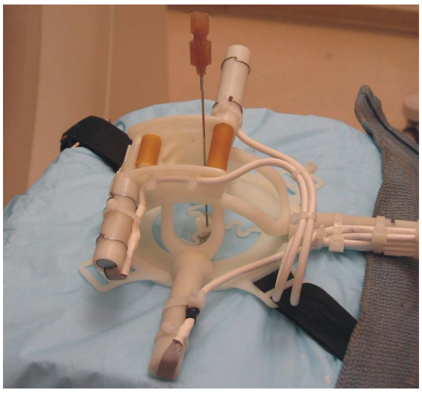
(a)*The complete LPR prototype.*

(b)*The LPR placed on top of a patient in right outside an MRI bore.*

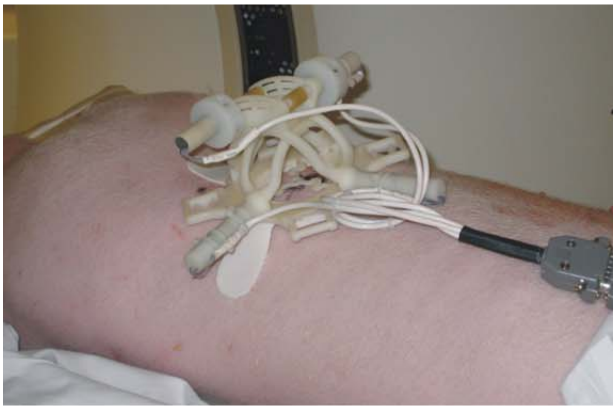
Figure 2.5: *The Light Puncture robot prototype by Bricault et al.[6].*

Robobsy

Robobsy is an economically designed needle guiding and inserting mechanism for CT-compatible MIS by Walsh et al. [7]. Its economical requirement is established from its ease of manufacturability and cost-effectiveness, making the robot disposable apart from its motors and control unit. The robot is made of plastic parts produced from an injection moulding process. The base of the Robobsy has a circular structure, with a diameter of $100mm$, which is fixated on the patient skin by using adhesives. One ring shaped adhesive of the same size as the base is to be placed underneath the robot. The base consists of four attachment bars on the side for tape and (optional) straps for rigid fixation to the skin, see Figure 2.6.



(a)*Robobsy placed on a phantom subject using straps.*



(b)*Robobsy placed on a test subject using adhesives.*

Figure 2.6: *The Robobsy Beta prototype by Walsh et al. [7].*

Overview

The mechanisms discussed above provide inside of the basic requirements for adequate fixation on the patient. It may be deduced that the desired structure of the base should have a circular shape. Most of the mechanisms discussed, comprise a circular base on which the main system is placed. The method used for attachment to the patient is fixed about this base. The attachment method varies for each of the mechanisms. The use of straps, adhesives, jamming transition, suction or a combination of these are proposed attachment methods. However, it can be seen that the use of straps is a widely preferred method for substantial fixation on the patient.

2.3 Parallel manipulators

The parallel manipulator is defined by the 'Handbook of Robotics' [13] as a closed-loop kinematic chain mechanism consisting of an end-effector with n degrees of freedom and a base that is fixed. At least two independent kinematic chains are needed to connect the base and the end-effector. The parallel manipulator has found its use for many applications, with the first design being an amusement device designed by J. E. Gwinnett in 1928 [14].
The use of parallel mechanisms is preferred due to the advantages provided above other structures, mainly having a constant Remote Center of Motion (RCM). The basic structure of the parallelogram mechanism consists of four bars linked by revolute joints, see Figure 2.7. This structure provides stiffness and thus also more stability to the complete system. The end-effector has a rotational output while it maintains a constant orientation with respect to its actuated parallel bar [8]. The fixed center of rotation about which the end-effector moves is the remote center of motion (RCM), see Figure 2.8. Each point of the end-effector that rotates about the RCM makes up the workspace of the parallel mechanism,

being a circular or spherical space depending on the degrees of freedom. The maximum workspace of the parallel mechanism is often limited due to the type of joints used and sometimes even the parallel bars self. Therefore, the design of a parallelogram based parallel manipulator should be done with great care. For the design, complete symmetry is often preferred to avoid differences in forces and moments applied to each bar, this may affect the stiffness of the mechanism but not its operation. The size of the parallel manipulator also does not affect how it operates, the structure may be applied in large scale robotics (monster cranes for example) or micro sized robotics [13].

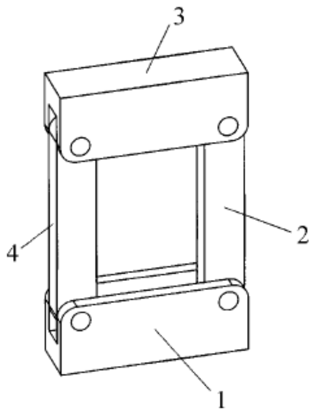


Figure 2.7: *Basic structure of the planar four bar parallel mechanism [8].*

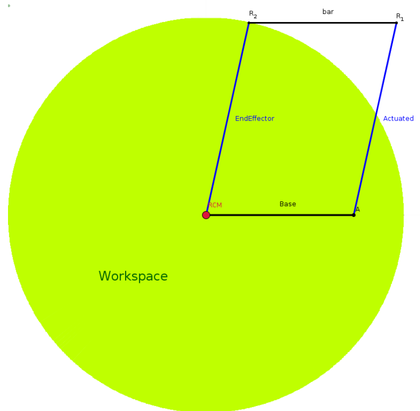


Figure 2.8: *The Remote center of motion and workspace of a four bar parallel mechanism.*

It is not a surprise that the parallel manipulator found its way into the field of medical robotics. One of the recently designed medical robots using parallel manipulators is Eye-RHAS, Figure 2.9, a robot for (vitreoretinal) eye surgery designed by Ebrahim Abedloo et al. at the Eindhoven University of Technology (TU/e). Eye-RHAS consists of two parallelogram structures providing a remote center of motion and four degrees of freedom. It is a table mounted robot able to orient and insert the needle from commands by the surgeon [9].

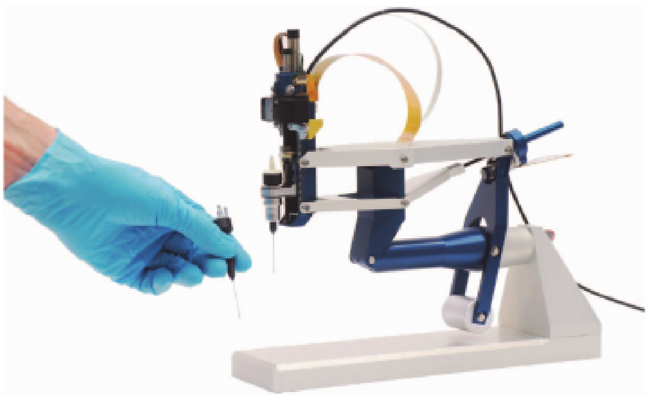


Figure 2.9: *The Eye-RHAS, a surgical robot with a fixed RCM and its operation based on the parallel structure [9].*

Chapter 3

Requirements & Specifications

The main goal of the McRobot is to reduce the procedural time of biopsies by eliminating step five, see section 2.1, and reducing the possible human error. During a biopsy the McRobot will guide the physician to insert the needle with more precision even if the patient accidentally moves, dismissing the need for an extra MRI scan. For such a needle biopsy assisting system there are many regulations and thus requirements that need to be met before it may be used in a hospital. The McRobot 3.2 also has to satisfy these requirements and more to be an improvement of the previous versions. In this chapter the basic requirements of the McRobot 3.2, needed for precise orientation of the biopsy tool, are listed.

3.1 MoSCoW Analysis

The MoSCow method is used to prioritize the requirements of a system and create a time efficient and resource focused design procedure. It is used during the design process to determine the **M**ust have, **S**hould have, **C**ould have and **W**ont have, hence **M**o**SC**o**W**. [15]
The requirements of the McRobot 3.2 and its specifications are listed in Table 3.1 following the MoSCoW method and are briefly elaborated.

3.1.1 Multi-modality

The McRobot 3.2 must be compatible with multiple types of medical imaging devices, such as Computed Tomography (CT), Positron Emission Tomography (PET) and Magnetic Resonance Imaging (MRI). The high regulations for MRI compatibility provide that the device is also CT and PET compatible. Therefore the McRobot 3.2 design should at least meet the MRI regulations. Devices to be used in the MR environment must be labelled according to the correct terms following the ASTM standards. The McRobot 3.2 must be MR Safe which holds that the device should not pose any hazards in all MR environments. To be MR Safe the device must consist of only non-magnetic and non-conducting materials, such as plastics [16]. The robot should also not have any influence on the quality of the MR-image.

3.1.2 Patient Mounted & Stability

The limited accessibility of the patient inside a closed bore MRI requires the need of a device that can enter the bore together with the patient. The patient mounted design of the McRobot meets this requirement. Fixated placement of the robot on the patient ensures that body motion is compensated. This gives stability to the system as the Remote Center of Motion (RCM) maintains a constant position that passively follows patient motion. For precise insertion of the surgical tool the RCM must also be exactly on the skin of the patient where the incision is made.

3.1.3 Versatility

Minimally invasive interventions are performed on a wide variety of patients and body regions, as the occurrence of cancer for example is not limited to one specific region. For an increased customer value of the McRobot it is essential to extend its operating area. The ability of the McRobot to adapt to each body shape is, therefore, a key requirement. The attachment method and size of the McRobot are important aspects for this adaptability.

3.1.4 Size

The maximum size and operating space of the robot is also limited due to the size of a MRI bore. The most used 3Tesla MRI scanner has a bore diameter of 60cm which, according to a study done by Eftychios G. Christoforou et al. [10], gives an average clearance of just 14cm between the patient and the bore wall. In Figure 3.1 the clearance is shown for two male subjects, one with a height and weight of $1,65m$ and $71kg$ and the other (denoted in brackets) with a height and weight of $1,85m$ and $99,8kg$ respectively. The space needed by the robot to operate freely is thus limited to a half-spherical shape with a maximum radius of 14cm. For optimized versatility and closed bore MRI compatibility a compact design of the McRobot is desired.

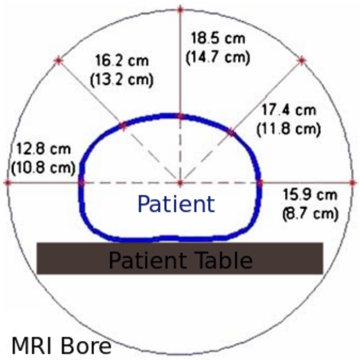


Figure 3.1: *Diagram of the space available inside a 60cm MRI bore for two male subjects. Subject 1:* $1,65m$ *and* $71kg$*. Subject 2 (noted in Brackets):* $1,85m$ *and* $99,8kg$ *[10].*

3.1.5 Degrees of Freedom

Due to medical regulations the needle inserting feature of the McRobot 3.1 is omitted as a requirement for the McRobot 3.2. The robot only has to place the surgical tool in the correct orientation after which it is manually inserted in the patient. For this process the robot requires only two degrees of freedom, which can be realized by using a parallel mechanism. The actuators and other tools required during its operation may limit its workspace, therefore, an extra rotational degree of freedom about the vertical axis of the robot could be added.

Table 3.1: *Requirements and Specifications of the McRobot 3.2, MoSCoW analysis.*

	Requirements	Specifications
Must	Multimodality	MR Safe (MRI, CT and PET compatible) Maximum height of 14cm.
	Patient Mounted	Rigidly attached on the patient during operation.
	Stability	Constant RCM within the workspace (on the incision). Passively follows patient motion.
	Versatility	Operates on different body types and regions.
	User Friendly	Easy to operate. Time efficient attachment, operation and detachment.
	2 DOF	Orient the surgical tool. (using a parallel mechanism)
	Pre-designed Actuators	Uses actuators design for McRobot 3.1.
	Sterile	Sterilizable and disposable parts.
	Safe	Easy to remove in case of emergency. Safe for patient. Backdrivable.
	Compact size	Fit in MRI for different size patients. Easy to store.
Should	Patient comfort	No sharp edges.
	Cost effective	Easy to manufacture. Affordable for end user.
	Multi-tool compatible	Needle gauge sizes: $10 - 25$ [17]. (Tool outer diameter of: $3,4 - 0,51mm$)
Could	Pose determination	Determine pose of the robot with respect to the fixed world during operation.
	Extra Rotational DOF	Rotate the robot during operation for increased workspace.
Wont	Needle Insertion	Needle inserted by the physician

Chapter 4

McRobot 3.2: Design

The MoSCoW analysis provides a general foundation upon which the design choices are based. In this chapter the design choices are elucidated and a conceptual design is established with the use of 'FreeCAD', an open-source parametric 3D CAD modelling software. Furthermore, the basic dimensional and kinematic analysis of the tool orientation mechanism are explained.

4.1 Conceptual Design of the Base

The base of the McRobot holds the parallel mechanism and the actuators, and is to be mounted right above the incision. It is, therefore, the most important part of the system responsible for stability. From the MoSCoW analysis follows that the location of the base must not move with respect to the RCM during operation. Therefore, the base is attached to the patient by using a combination of two methods, velcro straps and adhesion, inspired by Robobsy and the MRI-guided Arthrography robot discussed previously. Both of these methods are MRI compatible, safe and provide versatility. The straps provide a more rigid and stable attachment to the patient, whereas the adhesives function as an extra grip. As a result from the state of the art literature study, section 2.2, the circular shaped structure is also chosen for the base of the McRobot 3.2. Because this structure and a uniform surface provide more stability. The base, Figure 4.1, is chosen to have a uniform surface unlike that of the McRobot 3.1. This surface consists of a circular part with an opening that is to be placed exactly on the location of tool insertion. The remaining part of the base is required to hold the orientation mechanism and its actuators.

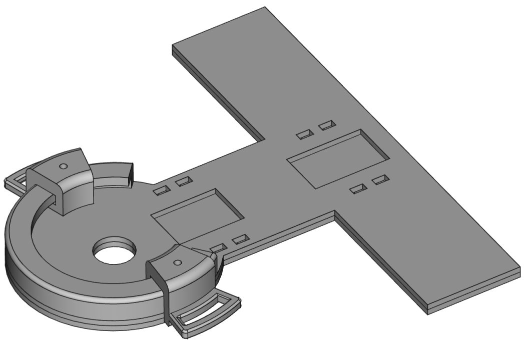


Figure 4.1: *Conceptual base design for the McRobot 3.2.*

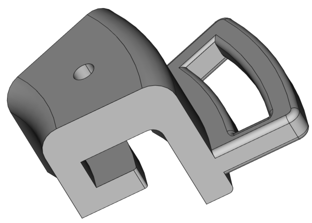


Figure 4.2: *Conceptual design of the strap-holder that may move auround the base or be fixed.*

The straps are attached around the circular part and the adhesives are used under the rest of the base. The straps are attached to the strap-holders which can rotate around the incision for secure attachment that is comfortable for the patient. A minimum of two straps is required, however, depending on the location more may be used. The additional straps can be attached by adding more strapholders (Figure 4.2) to the robot.

4.2 The Parallel Manipulator

4.2.1 Parallel Manipulator Design

Based on the requirements for a constant remote center of motion and two degrees of freedom, a parallel manipulator is used to orient the surgical tool. The parallel manipulator is based on the use of two parallelogram structures somewhat like the Eye-RHAS. The parallel manipulator consists of five bars that are connected by revolute joints and a base connected by universal joints. The double parallelogram structure is used to place the RCM at a fixed distance from the first base joint. Here the RCM is the intersecting point of two imaginary lines drawn through the end-effector and the base, as can be seen in Figure 4.3. The dimensions of the bars are determined from the requirement that the system must fit inside the MRI-bore together with the patient. Due to the average clearance of 14*cm* and the clearance with the bigger patient inside the MRI-bore, the maximum height of the parallel mechanism is chosen to be of length of 9*cm*. For safety and sterility purposes, the distance between the incision and the parallel mechanism base and end-effector is chosen to be 5*cm*, the length of bars L_2 and L_4. The length of the end-effector (L_5) then has to be 4*cm*. With these design choices, however, complete symmetry of the system is difficult to obtain for an optimal workspace. Due to the thickness of the bars, the limited swing of the universal joints and placement of the actuators it is decided to place the base joints of the parallel mechanism at an 8*cm* distance from each other. As mentioned before it is required for the RCM to be right on the incision, however, due to the thickness of the base of the McRobot this is not the case when the parallel mechanism base is horizontal. For this reason the base of the parallel mechanism is tilted a certain angle with respect to the base of the McRobot self. Using trigonometry rules the position of the base joints on the base plate is determined for the RCM at the origin.

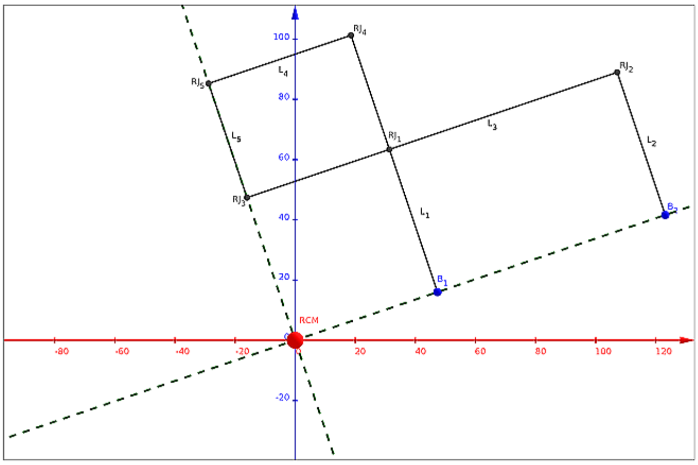


Figure 4.3: *Diagram of the double parallelogram showing the exact location of the RCM.*

Table 4.1: *The length of each bar of the double parallelogram.*

Link	Dimension (cm)
L_1	9
L_2	5
L_3	$8 + 5 = 13$
L_4	5
L_5	4

4.2.2 Kinematics & Workspace

The kinematics of the parallel mechanism give the ability to analyse its exact motion and determine the maximum workspace that can be obtained. In this chapter the forward and inverse kinematics of the double parallelogram are determined. These are very useful in order to control the mechanism and precisely place the surgical tool. Especially since each orientation of the end-effector follows from a specific input angle of the actuators.

Forward Kinematics

The forward kinematics of the double parallelogram describe the motion of the system and the position the end-effector can obtain around the constant RCM with a specified input angle of the actuators. This is useful to know how the system behaves with different inputs. The two rotational degrees of freedom of the system result from the angles a_1 and a_2. Here a_1 is rotation in the plane of the mechanism about the RCM, also referred to as the forward-backward motion, and a_2 is rotation of the mechanism self about the RCM, the sideways motion. The tool used for the biopsy goes through the end-effector and enters the patient exactly on the RCM. The vector position of the tip of the tool is expressed as a function of both a_1 and a_2.

$$Tooltip = -L_I\left(sin(a_1) * \overrightarrow{Xb}_u + cos(a_1)sin(a_2) * \overrightarrow{Yb}_u + cos(a_1)cos(a_2) * \overrightarrow{Zb}_u\right) \tag{4.1}$$

Here Xb_u, Yb_u and Zb_u are the unit vectors of a new rotated coordinate frame with its origin in B_1. L_I is the length of the inserted part of the tool, the distance from the RCM to the tooltip, and it is taken between 0 and 15cm. Altering the angles a_1 and a_2 changes the position of each revolute joint and the end-effector with respect to the base. Each position the tool tip can acquire then determines the workspace of the McRobot below the RCM. This workspace is shown in Figure 4.4 for all values of L_I and a maximum a_1 and a_2 of 60° in the positive and negative direction, estimated from the limited rotation of the parallel mechanism joints. This limitation results in a semi-circular shaped gap in the workspace below the base joints.

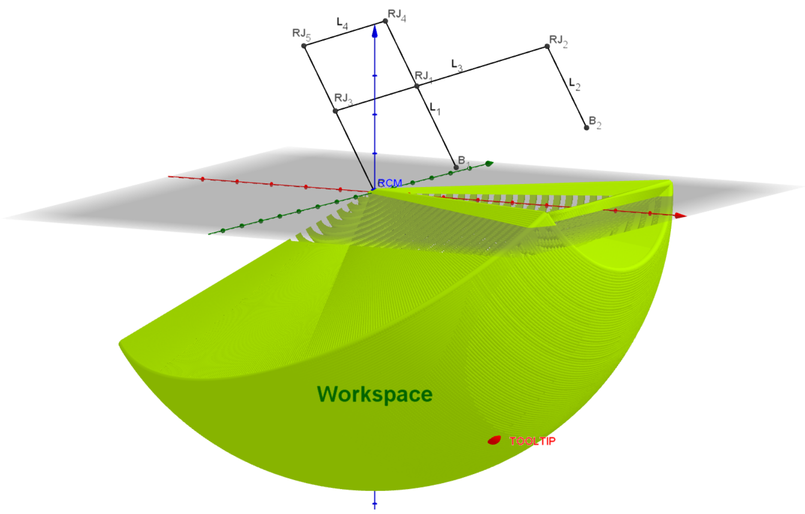


Figure 4.4: *The workspace obtained from the forward kinematics of the double parallelogram is plotted using Geogebra.*

Inverse Kinematics

The inverse kinematics of the parallel mechanism give the ability to specify the final position of the tool tip and determine the angle of each joint and the input angle of the actuators needed. The inverse kinematics are useful for motion planning of the McRobot, as the exact position of the lesion is determined by the MR-Image before insertion. First the vector position of the tip of the tool is specified in spherical coordinates with respect to the normal xyz-coordinate system. Since the system is completely parallel, the orientation of the revolute joints (RJ) is expressed as a function of the tool-tip its unit vector. The angles a_1 and a_2 are then calculated using simple trigonometry rules.

The workspace of the McRobot remains the same as determined previously using forward kinematics, except for the fact that limitations of the parallel mechanism joints are not accounted for. In Figure 4.5 the workspace of the inverse kinematics can be seen without the gap and the angles are also shown for the orientation of the mechanism.

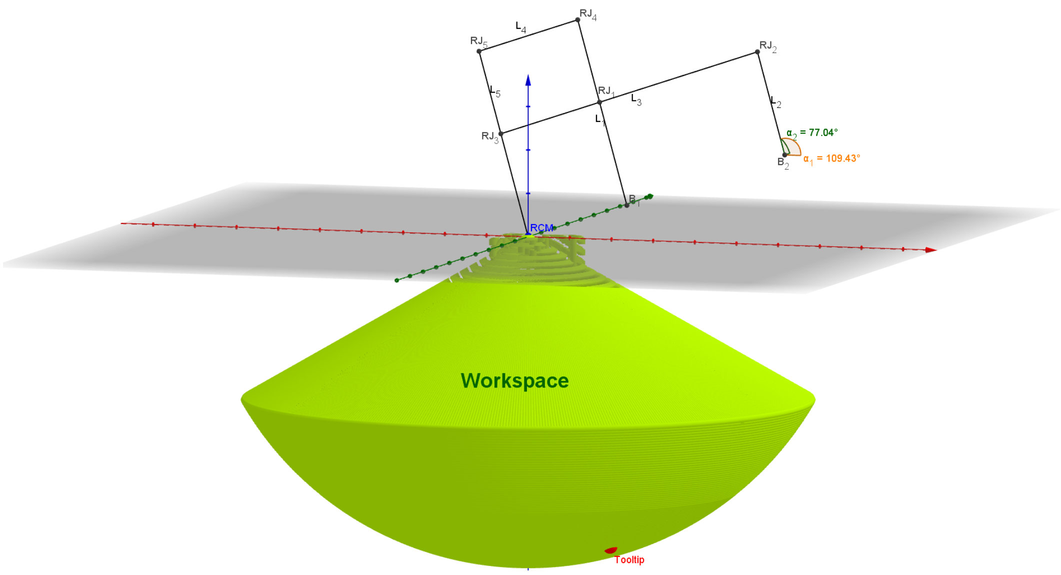


Figure 4.5: *The workspace obtained from the inverse kinematics of the double parallelogram is plotted using Geogebra.*

4.2.3 Parallel Manipulator Conceptual Design

From the design choices and the kinematic and workspace analysis a conceptual design of the parallel manipulator is established, as can be seen in Figure 4.6. The parallel mechanism consists of two horizontal bars that are attached to the vertical bars by adjustable ball bearings that act as revolute joints. The end-effector is multi-tool compatible and consists of two parts to hold the tool (the needle). The two vertical bars, to be attached to the base, consist of two flat bars each. These flat bars are held together by clips through which the ball bearings are also assembled.

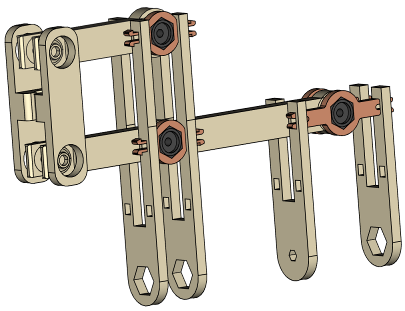


Figure 4.6: *Conceptual design of the double parallelogram mechanism.*

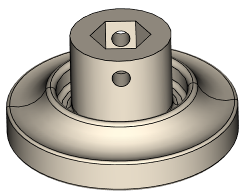


Figure 4.7: *The adapted rotor for the actuators used.*

4.2.4 End-effector

The end-effector must also satisfy the requirements of the McRobot such as stable and sterile. Depending on the material used to manufacture the end-effector it may be a part that can be sterilized or disposed of. Using a ceramic type of material provides the customer with the ability to sterilise the component using chemicals or heat. By using an inexpensive material like plastics, on the other hand, makes the end-effector disposable, which requires the customer to purchase a supply of these components. The most important requirement of the end-effector, however, is that it should be multi-tool compatible, meaning that it should hold a variety of biopsy needle sizes. Its conceptual design consists of two parts that create a cylindrical shaped opening through which the needle can be placed. The two parts are held together by the ball-bearings, see Figure 4.8. The cylindrical space has a diameter of $6mm$ for which special fillers may be used to fit different sized needles ranging from $0,51mm$ to $3,40mm$ in diameter.

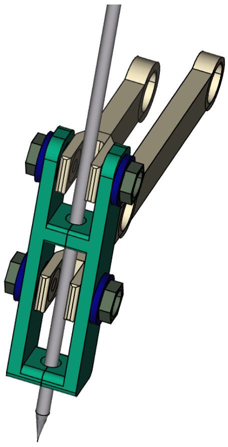


Figure 4.8: *The conceptual design of the end-effector.*

4.3 McRobot 3.2 conceptual design

The parallel mechanism is actuated by the actuators designed for McRobot 3.1 with adjustments made to the rotor for attachment of a differential joint, see Figure 4.7. In Appendix A the complete actuator designed and used for McRobot 3.1 can be seen in Figure A.1. These actuators are placed at the second base joint (B_2) of the parallel mechanism. A differential joint at B_2 provides the ability to rotate the parallel mechanism and maintain the two DOFs. At the first base joint (B_1) a universal joint is used for rotation of the mechanism. In Figure 4.9 the conceptual design of the complete assembled McRobot 3.2 can be seen.

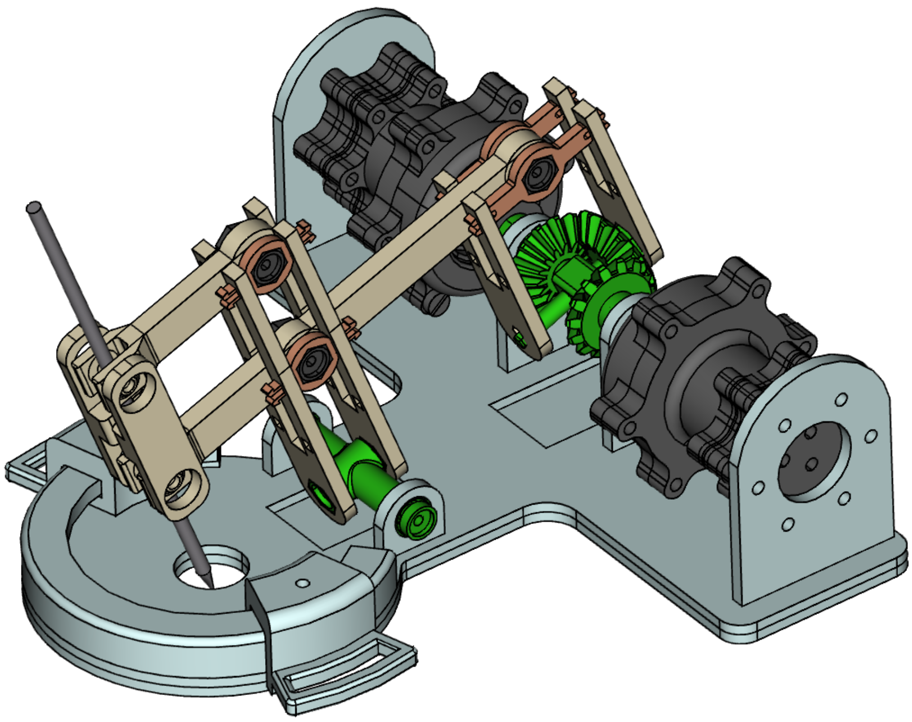


Figure 4.9: *Conceptual design of the complete McRobot 3.2.*

Chapter 5

Prototype & Testing

5.1 Prototype

The prototype of the McRobot 3.2, Figure 5.1, is completely made from materials that do not cause danger inside the medical- and MRI-environment. The methods used to manufacture the individual parts of the prototype are shortly described in the following sections. The prototype is actuated using the same pneumatic and electrical setup as the McRobot 3.1. The control setup and code used to operate the system are added in Appendix B.

5.1.1 Base

The baseplate on which the components are assembled should be strong enough yet light weight for stable and comfortable fixation on the patient. The baseplate and the holders for the parallel mechanism and actuators are, therefore, manufactured using Delrin that is laser cut. The circular shaped part of the base and the strap-holders on which the attachment straps are fixed are 3D printed from the ABSplus plastic material. The individual parts are then assembled and fixed by sliding them into the holes of the baseplate.

5.1.2 Parallel Manipulator prototype

Bars

Due to the slightly different functions of the bars, each one is prototyped using a different method. The upright standing bars need to be rigid and wide enough for attachment to the base without limiting the rotation, therefore, these are laser cut from Delrin as well and assembled using laser-cut clips. The bars parallel with the base are 3D printed because of the odd shape needed to hold the surgical tool at the end of the bars. The end-effector is 3D printed as well from ABSplus to hold different size surgical tools by adding fillers.

Joints

The universal joint, differential joint and the ball bearings used as revolute joints are all 3D printed of the 'FullCure 720' material using a high precision Objet printer. This is highly needed for smooth rotation at all joints and higher strength to keep the mechanism together.

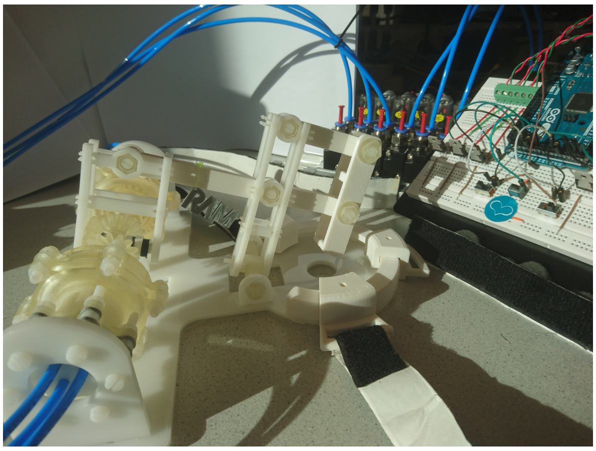


Figure 5.1: *The complete system setup of the first prototype of the McRobot 3.2.*

5.2 Testing

To establish if the must have requirements of the McRobot 3.2 are met several tests are conducted. The first prototype of the McRobot 3.2 is tested on its patient mounting ability, versatility, MRI compatibility and the workspace obtained.

5.2.1 Versatility

Versatility of the McRobot is tested by mounting it on various body parts of a volunteer. The robot is initially placed around the thoracic region because here the lung cancer biopsies are performed. In Figure 5.2 the placement of the prototype on the side and the front of the volunteer is shown. Here comfort for the volunteer and stability of the system are taken as the most important factors.

(a) *The prototype mounted on the chest.*

(b) *The prototype mounted on the side.*

Figure 5.2: *Placement of the prototype on the thoracic region of a volunteer.*

5.2.2 MRI compatibility

The first prototype of the McRobot 3.2 is tested on its MRI compatibility: whether it is MR safe and how it affects the MR-image. The tests are conducted inside a 0.25Tesla G-scan Brio MRI system available at the University of Twente. Several MRI scans are made with a breast shaped phantom and the McRobot. During these tests it is observed that the robot does not cause any hazard inside the MRI environment. The images of the scans are analysed using the '3D-Slicer' software and show that the robot does not have any influence on the MR-images. This can be seen in the 3D image, Figure 5.3, obtained from the 3D Hyce scan where the McRobot is placed on top of the phantom. As a reference two markers containing fish oil, which is visible in MR-images, are placed on the base of the McRobot and one on the long horizontal bar, showing that the robot itself is completely invisible. The scans confirm that the McRobot 3.2 is MR Safe and theoretically thus also multi-modal compatible.

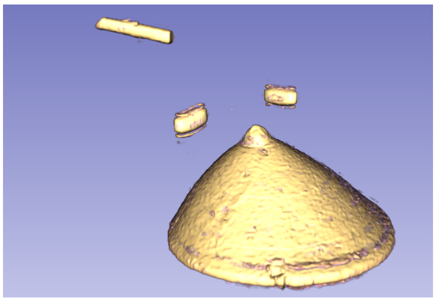


Figure 5.3: *The 3D image of a 3D-Hyce MRI scan done with the McRobot on a breast phantom, the objects above the phantom are fish oil markers placed on the robot.*

5.2.3 Actuation & Workspace

The parallel mechanism is tested on its rotational abilities and the maximum workspace obtained by this. These tests are first conducted manually with the actuators in static position by moving the mechanism around its joints. With the mechanism in upward position ($\alpha_2 = 90°$) the forward and backward motion, rotation angle α_1, make a minimum and maximum angle with the base of approximately 35° and 115°, respectively. It is seen that this motion is constrained by the base and the bars of the parallel mechanism self.

The sideways motion of the parallel mechanism on the other hand, which constitutes the angle α_2 with the base, shows limited rotation for most values of α_1. For $\alpha_1 \approx 72°$ and small deviations from this the parallel mechanism reaches a minimum and maximum angle of approximately 46° and 134°. The limiting factor for this rotation is mainly caused by the base and placement of the actuators. For the other values of α_1 the sideways rotation of the parallel mechanism drastically decreases and even reaches 0° for $\alpha_1 > 90°$. The unexpected limitation is caused by an error made during the design of the parallel mechanism. The most important requirement of parallel mechanisms is that all bars always remain parallel with those opposite to them. Due to an error in placement of the base joints the virtual bar through these joints is not parallel to its opposites for values of $\alpha_1 \neq 72°$. For visualisation the workspace obtained with the current configuration of the joints is plotted in Figure 5.4.

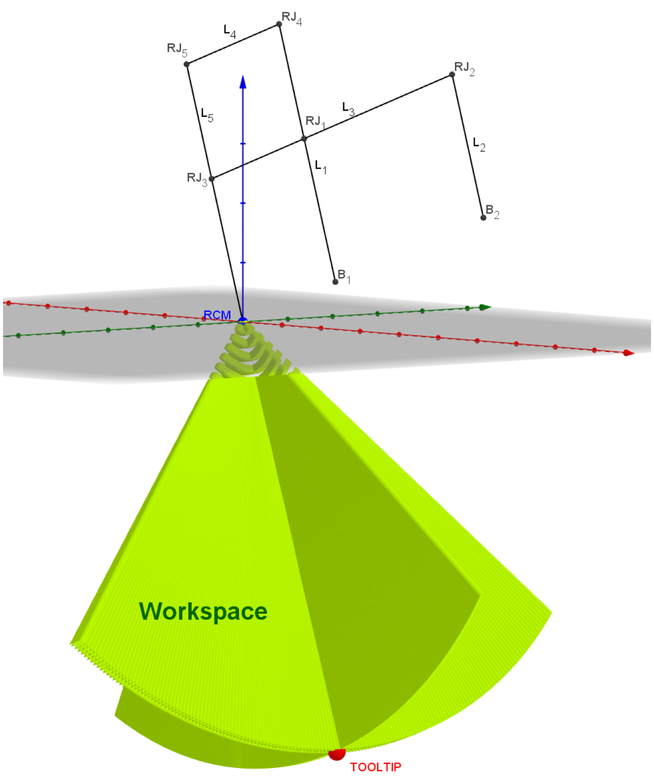


Figure 5.4: *Diagram of the workspace obtained by the first prototype.*

Chapter 6

Discussion & Conclusion

6.1 Discussion

The the first prototype of the McRobot 3.2 showed some inconsistencies of the design choices. The most important problem realised after this prototype is that configuration of the base joints is wrong, having an abundantly decreased workspace as consequence. This problem can be solved by simply changing the configuration of the universal and differential joint, by rotating them 90°. However, this is easier said than done, as rotating the differential joint also changes the position of the actuators. Therefore, a new base has to be designed as well as vertical bars. In Figure 6.1 and Figure 6.2 the recommended configuration of the base joints and the other adjustments are shown in a CAD model.

Apart from this, it can be said that the design of the McRobot 3.2 suffices most of the Must and Should have requirements of the MoSCoW analysis. Complete stability and a sterile mechanism are not yet optimized for this design due to the materials used to manufacture the prototype. 3D printing of the used materials is not accurate enough causing some flaws in the assembly of the prototype, which results in some instability. Due to the use of plastic materials sterilizing the McRobot is limited to the use of chemicals instead of heat, which is a more preferred method for medical tools. The FullCure material used for the joints and actuators also shows to deteriorate overtime due to friction between the parts. For long term use of the McRobot 3.2 the currently used prototyping materials are not sufficient.

Furthermore, to be admitted for medical use the experiments done are not sufficient enough. The versatility and stability tests are to be conducted on a wider range of test subjects during operation of the device, as they are currently only done in static mode. The MRI-test is not likely to show different results when done in a MRI scanner with a higher magnetic field strength, however, to confirm complete multi-modality more tests may conducted.

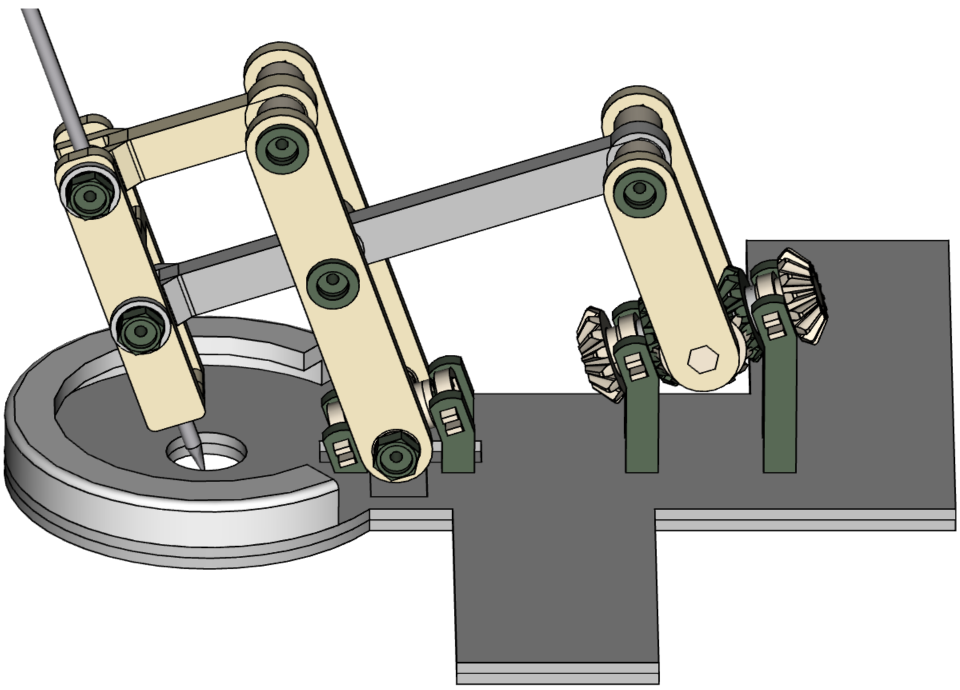


Figure 6.1: *CAD model of the recommended configuration of the base joints of the parallel mechanism.*

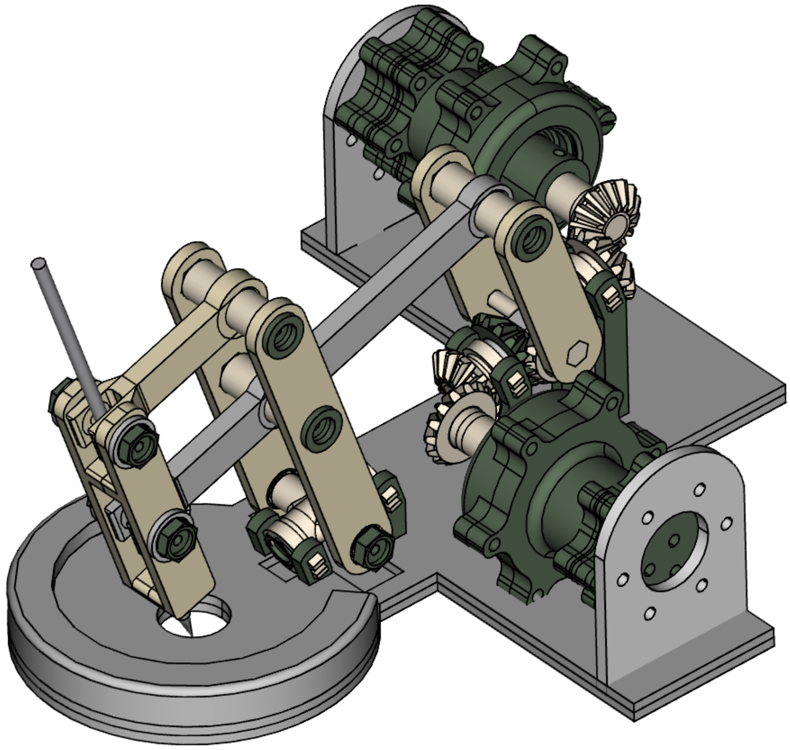


Figure 6.2: *The complete system with the recommended adjustments implemented for an increased workspace.*

6.2 Conclusion

The main objective of this bachelor assignment was to improve the base of the McRobot 3.1 and design a needle orienting mechanism for minimal invasive MRI-guided surgeries. The McRobot 3.2 is a completely redesigned mechanism that satisfies the initial requirements of the McRobot series. Its base is designed to be patient mounted on various body types and regions using velcro and adhesives. The needle orienting mechanism is based on a double parallelogram structure that has two degrees of freedom, which are driven by the actuators designed for the McRobot 3.1. The double parallelogram structure is used due to its constant remote center of motion placed exactly on the skin of the patient. The fixed RCM and proper attachment to the patient provide stability and safety of the system because it passively follows movements of the patient, such as those caused by respiration or coughing. The motion and workspace of the parallel mechanism are analysed with inverse and forward kinematics, both useful for control of the robot and motion planning for precise insertion of the surgical tool by the physician. The first prototype of the McRobot 3.2 is established by 3D printing and laser cutting. Despite a design error in the base joints, the prototype can currently obtain a maximum workspace of $35^\circ \leq a_1 \leq 115^\circ$, when the mechanism is in upright position ($a_2 = 90^\circ$), and $46^\circ \leq a_2 \leq 134^\circ$, when the base joints are aligned for $a_1 \approx 72^\circ$. Several tests show that the McRobot 3.2 is MRI-compatible and versatile. It may also be concluded that the requirements for a user and patient friendly, safe, cost effective and compact device are satisfied. The McRobot 3.2 is indeed an improvement from the McRobot 3.1 since it has a stable structure to hold the surgical tool and is a more compact design that can be rigidly attached on the patient.

6.3 Future work

Being the first prototype of a completely new design of the McRobot series the McRobot 3.2 is susceptible to change. First, the could have requirements listed in the MoSCoW analysis, Table 3.1, can be implemented in future designs. For more certainty of the insertion angle required to reach a specific lesion, the exact orientation of the end-effector should be determined. This can be done by using optical position sensors, MRI-Markers or a hybrid tracking method which is a combination of both.

For an increased workspace of the system, an extra degree of freedom can be implemented into the design. The extra DOF allows rotation of the parallel manipulator around the vertical axis through the RCM. This will also make the workspace a symmetric cone shape.

The motion of the parallel mechanism may also be improved by a moment analysis to determine the minimum torque required for rotation of the system. By doing this the actuators used can be optimized and likely decreased in size, as they take up a considerable amount of space currently.

To make the McRobot 3.2 more durable and customer friendly it is advised to research which materials are the best for this device. Especially keeping in mind that the device should be completely sterile for each medical operation. Degradation of the material should be avoided and the requirement for a cost-effective and light weight device should be kept in mind.

Bibliography

[1] D. van den Hoogen, "Conceptual mechanism design and kinematic analysis of an mri compatible surgery robot," *Confidential*, 2013, mSc Thesis.

[2] X. Zhi, "Design and prototyping of mcrobot version 3.1: Multi-modality compatible robot for image guided minimally invasive intervention and therapy," *Confidential*, 2015, mSc Thesis.

[3] A. Bekku, Y. Nakajima, J. Kim, and K. Yonenobu, "Improvement of fixing method for the surgical assistance robot and optimization of body-mounted robotic system," *J Osteopor Phys Act*, vol. 3, no. 137, 2015.

[4] R. Monfaredi, E. Wilson, R. Sze, K. Sharma, B. Azizi, I. Iordachita, and K. Cleary, "Shoulder-mounted robot for mri-guided arthrography: Accuracy and mounting study," in *Engineering in Medicine and Biology Society (EMBC), 2015 37th Annual International Conference of the IEEE*. IEEE, 2015, pp. 3643–3646.

[5] B. Maurin, B. Bayle, O. Piccin, J. Gangloff, M. de Mathelin, C. Doignon, P. Zanne, and A. Gangi, "A patient-mounted robotic platform for ct-scan guided procedures," *Biomedical Engineering, IEEE Transactions on*, vol. 55, no. 10, pp. 2417–2425, 2008.

[6] I. Bricault, N. Zemiti, E. Jouniaux, C. Fouard, E. Taillant, F. Dorandeu, and P. Cinquin, "Light puncture robot for ct and mri interventions," *Engineering in Medicine and Biology Magazine, IEEE*, vol. 27, no. 3, pp. 42–50, 2008.

[7] C. J. Walsh, N. C. Hanumara, A. H. Slocum, J.-A. Shepard, and R. Gupta, "A patient-mounted, telerobotic tool for ct-guided percutaneous interventions," *Journal of Medical Devices*, vol. 2, no. 1, p. 011007, 2008.

[8] X.-J. Liu and J. Wang, "Some new parallel mechanisms containing the planar four-bar parallelogram," *The International Journal of Robotics Research*, vol. 22, no. 9, pp. 717–732, 2003.

[9] E. Abedloo, S. Gholami, and H. D. Taghirad, "Eye-rhas manipulator: From kinematics to trajectory control," in *Robotics and Mechatronics (ICROM), 2015 3rd RSI International Conference on*. IEEE, 2015, pp. 061–066.

[10] E. G. Christoforou, N. V. Tsekos, and A. Özcan, "Design and testing of a robotic system for mr image-guided interventions," *Intelligent and Robotic Systems*, vol. 47, no. 2, pp. 175–196, 2006.

[11] B. W. Stewart and C. P. Wild, "World cancer report 2014," *http://www.who.int/mediacentre/factsheets/fs297/en/*, 2014.

[12] RadiologyInfo.org, "Biopsies-overview," *http://www.radiologyinfo.org/en/pdf/biopgen.pdf*, 2015.

[13] J.-P. Merlet and C. Gosselin, "Parallel mechanisms and robots," in *Springer Handbook of Robotics*. Springer, 2008, pp. 269–285.

[14] I. Bonev, "The true origins of parallel robots," *ParalleMIC: the Parallel Mechanisms Information Center*, 2003.

[15] D. Clegg and R. Barker, *Case Method Fast-Track: A Rad Approach.* Boston, MA, USA: Addison-Wesley Longman Publishing Co., Inc., 1994.

[16] ASTM-F2503-13, "Standard practice for marking medical devices and other items for safety in the magnetic resonance environment," *ASTM International, West Conshohocken, PA, www.astm.org*, 2005.

[17] C. Medical, "Needles for biopsy and special purpose," *IR-BM-BSPN-EN-201102-M3*, 2011.

Appendices

Appendix A

Figures

A.1 McRobot 3.1

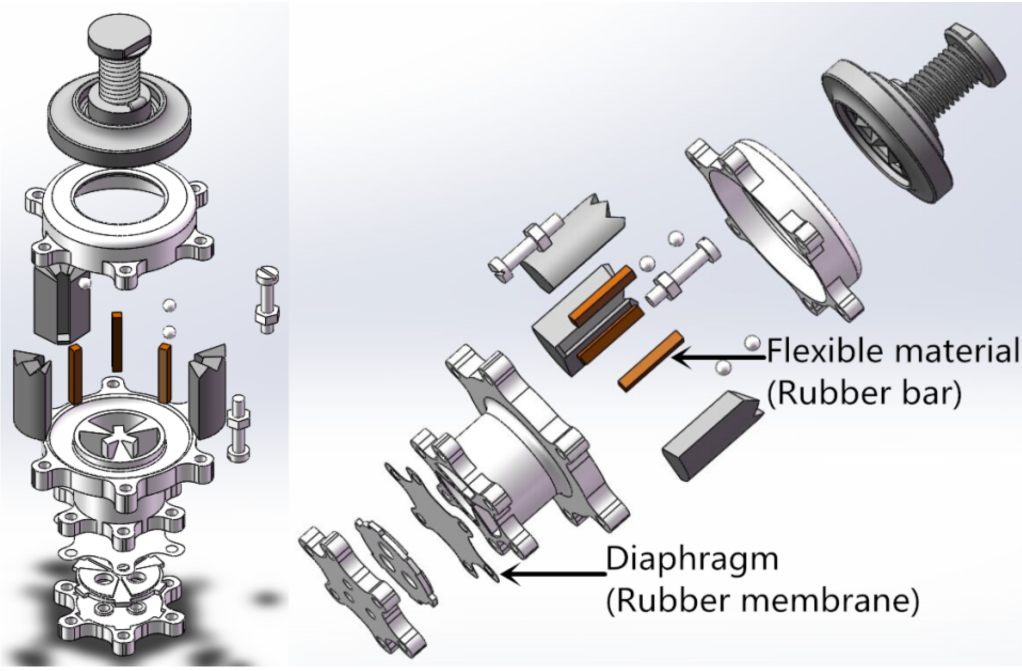


Figure A.1: *Exploded view of the actuator designed by X. Zhi for the McRobot 3.1 [2].*

A.2 Gantt Chart

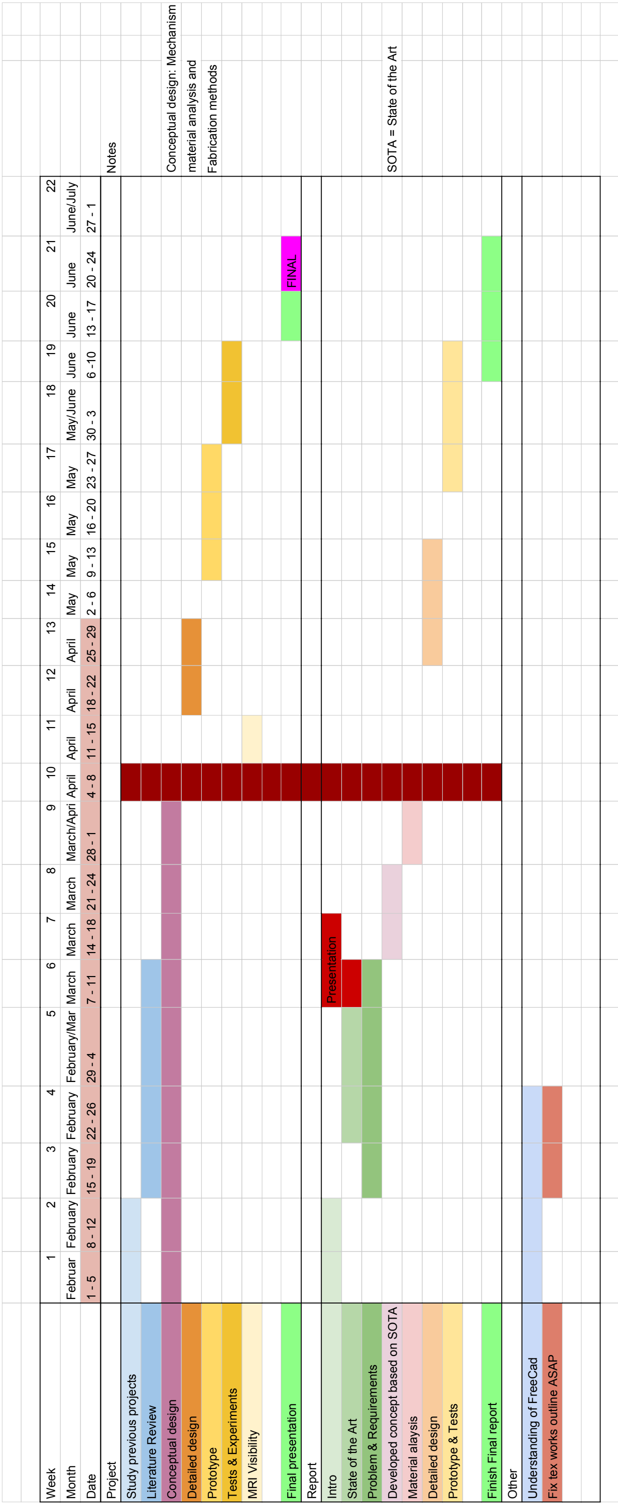


Figure A.2: *Gantt chart of the project design process.*

Appendix B

Operating System Setup

B.1 Electrical setup

The system used to operate the McRobot 3.2 is an adapted version of that of the McRobot 3.1. For each actuator three pneumatic valves are required, so the McRobot 3.2 uses six valves in total. In Figure B.1 below the electrical setup to actuate the valves is shown. The circuit consists of a 4.7$k\Omega$ resistor and a NPN transistor for each valve, a 24V power source, an Arduino and three switches to control the output of the valves (the rotation of the actuators). The code for the arduino that is used to operate the system is added below, see section B.2.

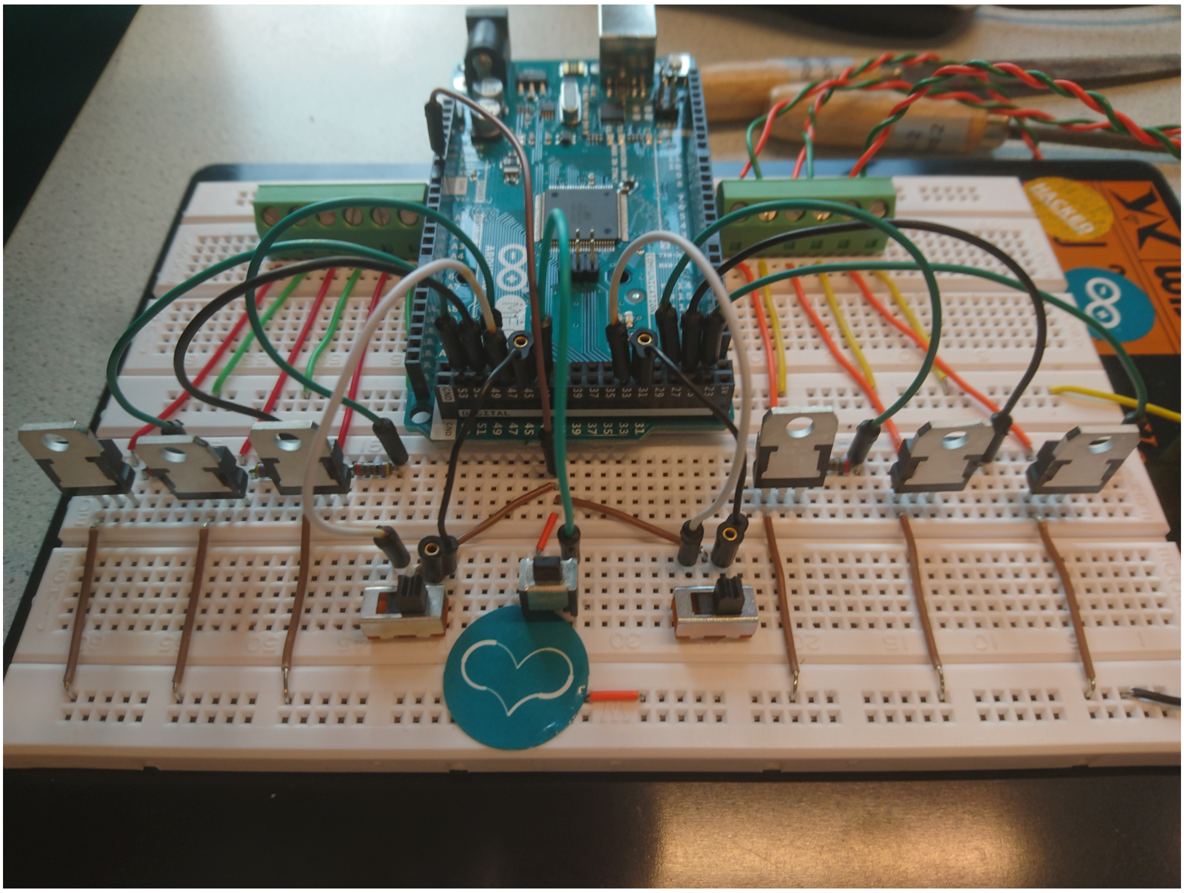


Figure B.1: *Electrical circuit setup used to connect the arduino and the pneumatic valves.*

B.2 Arduino code

The code below is implemented on the Arduino to operate the two actuators by using three switches. One main switch to turn the system on or off and two slide switches to change the rotational direction of the actuators.

```
//Define valve frequency (also alters speed)
const int freq= 300;

//Define switch pins
//MainSwitch to turn system on and off
const int Main_Switch= 42;

//Define switch for Actuator 1
const int Switch_A1_1= 31;
const int Switch_A1_2= 33;

//Define switch for Actuator 2
const int Switch_A2_1= 45;
const int Switch_A2_2= 47;


//Define Actuator 1 Valve pins
const int Valve_A1_1= 22;
const int Valve_A1_2= 24;
const int Valve_A1_3= 26;

//Define Actuator 2 Valve pins
const int Valve_A2_1 = 48;
const int Valve_A2_2 = 50;
const int Valve_A2_3 = 52;


void setup() {
 //Define switches
  pinMode(Main_Switch, INPUT_PULLUP);

  pinMode(Switch_A1_1, INPUT_PULLUP);
  pinMode(Switch_A1_2, INPUT_PULLUP);

  pinMode(Switch_A2_1, INPUT_PULLUP);
  pinMode(Switch_A2_2, INPUT_PULLUP);

 //Define Original state of switches
  digitalWrite(Main_Switch, HIGH);


 //Define Actuator pin modes
  pinMode(Valve_A1_1,OUTPUT);
  pinMode(Valve_A1_2,OUTPUT);
  pinMode(Valve_A1_3,OUTPUT);
```

```
  pinMode(Valve_A2_1,OUTPUT);
  pinMode(Valve_A2_2,OUTPUT);
  pinMode(Valve_A2_3,OUTPUT);

 //Define Original State of Valves
  digitalWrite(Valve_A1_1,LOW);
  digitalWrite(Valve_A1_2,LOW);
  digitalWrite(Valve_A1_3,LOW);

  digitalWrite(Valve_A2_1,LOW);
  digitalWrite(Valve_A2_2,LOW);
  digitalWrite(Valve_A2_3,LOW);
}

void loop() {
if(digitalRead(Main_Switch)==LOW)
//If the Main switch is pressed the actuators will rotate
{
 //Switch for Actuator 1
 if(digitalRead(Switch_A1_1)== LOW && digitalRead(Switch_A2_1)==LOW)
 //When Switch A_1 is slided left Actuator 1 Rotates "Clockwise"
   {
  digitalWrite(Valve_A1_1,HIGH);
  digitalWrite(Valve_A1_2,LOW);
  digitalWrite(Valve_A1_3,LOW);
  digitalWrite(Valve_A2_1,HIGH);
  digitalWrite(Valve_A2_2,LOW);
  digitalWrite(Valve_A2_3,LOW);
  delay(freq);

  digitalWrite(Valve_A1_1,LOW);
  digitalWrite(Valve_A1_2,HIGH);
  digitalWrite(Valve_A1_3,LOW);
  digitalWrite(Valve_A2_1,LOW);
  digitalWrite(Valve_A2_2,HIGH);
  digitalWrite(Valve_A2_3,LOW);
  delay(freq);

  digitalWrite(Valve_A1_1,LOW);
  digitalWrite(Valve_A1_2,LOW);
  digitalWrite(Valve_A1_3,HIGH);
  digitalWrite(Valve_A2_1,LOW);
  digitalWrite(Valve_A2_2,LOW);
  digitalWrite(Valve_A2_3,HIGH);
  delay(freq);
  }

 if(digitalRead(Switch_A1_2)== LOW && digitalRead(Switch_A2_2)==LOW)
 //When switch A1 is slided right Actuator 1 rotates "Anti-Clockwise"
```

```
 {
 digitalWrite(Valve_A1_1,LOW);
 digitalWrite(Valve_A1_2,LOW);
 digitalWrite(Valve_A1_3,HIGH);
 digitalWrite(Valve_A2_1,LOW);
 digitalWrite(Valve_A2_2,LOW);
 digitalWrite(Valve_A2_3,HIGH);
 delay(freq);

 digitalWrite(Valve_A1_1,LOW);
 digitalWrite(Valve_A1_2,HIGH);
 digitalWrite(Valve_A1_3,LOW);
 digitalWrite(Valve_A2_1,LOW);
 digitalWrite(Valve_A2_2,HIGH);
 digitalWrite(Valve_A2_3,LOW);
 delay(freq);

 digitalWrite(Valve_A1_1,HIGH);
 digitalWrite(Valve_A1_2,LOW);
 digitalWrite(Valve_A1_3,LOW);
 digitalWrite(Valve_A2_1,HIGH);
 digitalWrite(Valve_A2_2,LOW);
 digitalWrite(Valve_A2_3,LOW);
 delay(freq);
 }

if(digitalRead(Switch_A1_1)== LOW && digitalRead(Switch_A2_2)==LOW)
//Both rotate opposite direction
{
 digitalWrite(Valve_A1_1,HIGH);
 digitalWrite(Valve_A1_2,LOW);
 digitalWrite(Valve_A1_3,LOW);

 digitalWrite(Valve_A2_1,LOW);
 digitalWrite(Valve_A2_2,LOW);
 digitalWrite(Valve_A2_3,HIGH);
 delay(freq);

 digitalWrite(Valve_A1_1,LOW);
 digitalWrite(Valve_A1_2,HIGH);
 digitalWrite(Valve_A1_3,LOW);

 digitalWrite(Valve_A2_1,LOW);
 digitalWrite(Valve_A2_2,HIGH);
 digitalWrite(Valve_A2_3,LOW);
 delay(freq);

 digitalWrite(Valve_A1_1,LOW);
 digitalWrite(Valve_A1_2,LOW);
 digitalWrite(Valve_A1_3,HIGH);
```

```
  digitalWrite(Valve_A2_1,HIGH);
  digitalWrite(Valve_A2_2,LOW);
  digitalWrite(Valve_A2_3,LOW);
  delay(freq);
 }

 if(digitalRead(Switch_A1_2)== LOW && digitalRead(Switch_A2_1)==LOW)
 //Both rotate in opposite direction
 {
  digitalWrite(Valve_A1_1,LOW);
  digitalWrite(Valve_A1_2,LOW);
  digitalWrite(Valve_A1_3,HIGH);

  digitalWrite(Valve_A2_1,HIGH);
  digitalWrite(Valve_A2_2,LOW);
  digitalWrite(Valve_A2_3,LOW);
  delay(freq);

  digitalWrite(Valve_A1_1,LOW);
  digitalWrite(Valve_A1_2,HIGH);
  digitalWrite(Valve_A1_3,LOW);

  digitalWrite(Valve_A2_1,LOW);
  digitalWrite(Valve_A2_2,HIGH);
  digitalWrite(Valve_A2_3,LOW);
  delay(freq);

  digitalWrite(Valve_A1_1,HIGH);
  digitalWrite(Valve_A1_2,LOW);
  digitalWrite(Valve_A1_3,LOW);

  digitalWrite(Valve_A2_1,LOW);
  digitalWrite(Valve_A2_2,LOW);
  digitalWrite(Valve_A2_3,HIGH);
  delay(freq);
 }}
else
  {
  digitalWrite(Valve_A1_1,LOW);
  digitalWrite(Valve_A1_2,LOW);
  digitalWrite(Valve_A1_3,LOW);
  digitalWrite(Valve_A2_1,LOW);
  digitalWrite(Valve_A2_2,LOW);
  digitalWrite(Valve_A2_3,LOW);
  }}
```