Improving Accuracy and Efficiency in MRI-navigated Breast Biopsy

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MSc Report

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Preamble

This is my thesis for obtaining the degree of Master of Science in Embedded Systems. I have worked on it with much enjoyment for eight months in the Robotics and Mechatronics group.

I would like to thank all people that contributed to this research, in particular prof. dr. ir. Stefano Stramigioli, the laser cutter Alfred de Vries, Jeroen Veltman from ZGT and Abe van der Werf from Machnet. Also, I thank my family and friends for their mental support.

Abstract

One of the breast cancer screening and diagnosis methods is MRI-guided breast biopsy. Current techniques have limitations in accuracy and efficiency, which may cause lesions to be missed. In this research, two seperate innovations are investigated and reported. The first innovation is to improve the breast fixation mechanism by using so-called coffee grippers, which can secure the breast in place. The other innovation is to make use of a robotic biopsy system for needle alignment and insertion, which results in a more accurate biopsy needle insertion and also speeds up the biopsy procedure. Both innovations were investigated with experimental setups. It turns out that the innovative breast fixation mechanism certainly has potential, but that it is difficult to be practically effective considering the large variations in breast size and other factors. On the other hand, the robotic biopsy system proved to be effective and accurate in semi-automatic needle positioning and alignment. This way, more accurate biopsies are possible resulting in better cancer diagnosis.

Contents

Chapter 1

Introduction

Breast cancer is the most occurring invasive cancer among women, accounting for about 29% of all cases in The Netherlands [2]. Early diagnosis is essential for successful treatment [3]. An extensive screening program is available in many countries such as in The Netherlands [1].

When a lesion (a suspicious abnormality) is found in the breast, then it is necessary to perform a biopsy to extract tissue from the lesion for examination. This gives important information about the type of lesion, and whether further treatment (e.g. excision) is needed. Therefore, it is crucial that the biopsy is taken from the right site. In this research, MRI is used to localize the lesion and guide the biopsy needle towards it.

1.1 Problem statement

Most MRI-guided breast biopsies are successful, but in about 10% of the cases the lesion is missed (13.8% according to [6], 5%-10% according to four interviewed experts radiologists). In most cases, a lesion miss can be detected on the scan after which the biopsy is immediately redone, at the cost of extra time and additional tissue damage. But sometimes the lesion miss is unnoticed, potentially resulting in false-negative diagnosis.

Efficiency can also be improved. The entire MRI-guided breast biopsy procedure takes about 45-55 minutes on average. If the procedure could be shortened by 5 minutes, by automatizing certain parts or reducing the number of missed lesions during breast biopsy, then more patients could be helped in the same time.

So the technical problem statement is as follows: how can the efficiency and accuracy of MRI-guided breast biopsy be improved?

1.2 Prior work

Research has been done to better fixate the breast and thus keep the lesion in place [7], but it is difficult to account for the large variety in breast sizes and shapes among women. Also, MRI-compatible robotic devices for biopsy needle positioning have been developed [9, 12, 14]; while these certainly have showed potential, these also have serious drawbacks such as high complexity and slow operation and thus are not yet used in practice.

1.3 Hypothesis

The hypothesis is that two new innovations make MRI-guided breast biopsy more accurate and efficient. These innovations are described in this report. The first innovation is to employ the coffee gripper concept in a novel breast fixation system; the second innovation is to use a robotic system with a new type of actuator to position the biopsy needle with more accuracy and speed than traditional hand-operated systems and prior work.

1.4 Sketch of proposed solution

The novel breast fixation system consists of balloons filled with granular material, supported by a moveable structure and connected to a vacuum pump. Initially the balloons are deformable. When the breast to be fixated is put into place, the moveable structure with the balloons is pushed against the breast and then the vacuum pump sucks all the fluid out of the balloons. Now the balloons become rigid, and secure the breast in place.

The innovative robotic biopsy system consists of a needle hole that is mounted on a pneumatically-actuated MRI-compatible 7 DOF platform. The pneumatic linear actuators are specifically designed for this type of robotic system. After localizing the lesion, a controller aligns the needle guide with that lesion. Then the lesion can be accessed by moving a stylet towards the lesion, either manually or automatically, to the right depth. After this, the radiologist can perform the biopsy procedure manually in the normal way.

1.5 Experiments and evaluations

Experimental setups are created to practically test the innovative ideas. Breast phantoms are fixated with the novel fixation system, and subsequently targeted with the new robotic biopsy system. The speed, accuracy, workspace and other characteristics are measured (quantitatively if possible, qualitatively otherwise), and finally discussed.

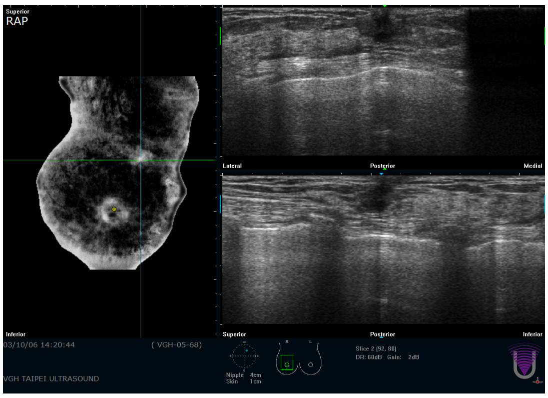
Chapter 2

Background

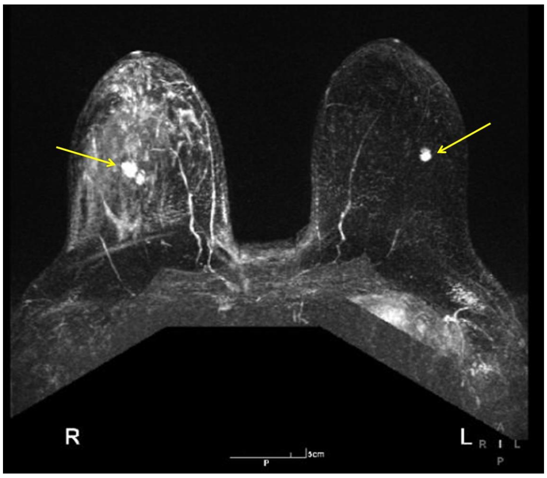
This chapter presents some background information about the research topics. Breast imaging techniques and the MRI-guided breast biopsy procedure are described; also the coffee gripper concept is explained.

2.1 Breast imaging techniques

(a) Mammography



(b) Ultrasonography



(c) MRI

Figure 1: Scans made by three different breast imaging techniques.

Some lesions can be detected by palpation, but not all of them. Imaging techniques are required to detect and localize lesions, and to study the tissue structure inside the breast.

Mammography (Figure 1a) is included in standard breast cancer screening routine. It makes use of X-rays, and produces a flattened, two-dimensional image of the breast. The technique is relatively cheap and simple. Mammography sensitivity ranges from 83% to 95%, and specificity from 94% to 99% for the general population [5].

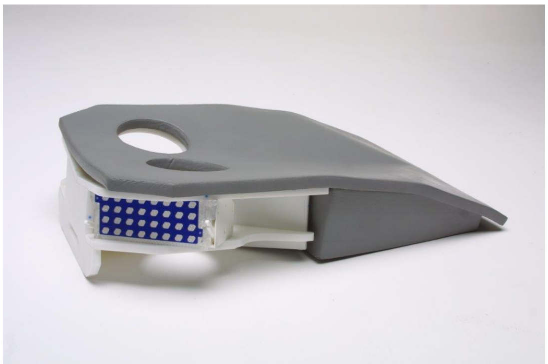
Ultrasonography (Figure 1b) is an ultrasound-based imaging technique, allowing to make two-dimensional sections of the breast. It is for example used to confirm the location of a lesion seen on the mammogram, or to screen high-risk patients in addition to mammography.

MRI imaging (Figure 1c) is the most advanced technique. It makes three-dimensional scans of the breast with high resolution and detail, and uses no harmful radiation (as X-ray does). A MRI scanner is a huge and costly device, compared with mammography and ultrasonography equipment. The sensitivity is very good (90%-99%), but specificity is rather low: values from 37% to 81% are mentioned in literature [4].

2.2 Existing solutions for MRI-guided breast biopsy

In this section, a few existing systems for performing MRI-guided breast biopsy are described.

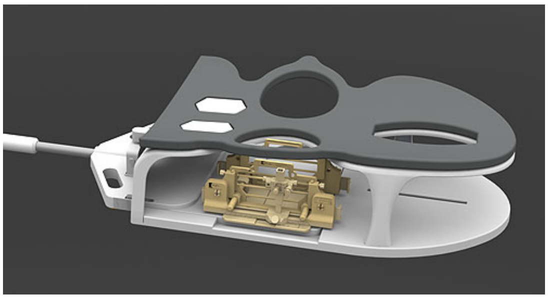
A complete system consists of a patient rest, a breast coil, a breast fixation system, a needle positioning grid (or other needle guidance system), a breast biopsy device (gun) and a software suite. Some parts such as the biopsy needle or gun can be made by different vendors, as long as they are compatible.



(a) Machet MICS

(b) Invivo Sentinelle

(c) Philips MammoTrak



(d) Noras biopsy unit

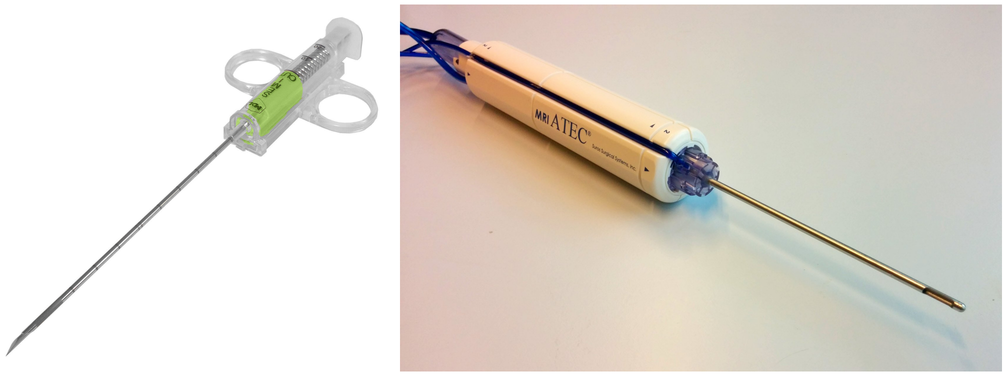
Figure 2: MRI-guided breast biopsy solutions.

The Machnet MICS system (Figure 2a) has a biopsy/fixation unit that can rotate all around the breast, allowing to perform the biopsy from any side. A fine-spaced, rigid grid system allows to insert a biopsy needle (Figure 3a) with minimal error (1-2mm) in the breast. Some regions (close to chest wall or around nipple) are difficult to reach with this system, which is an important disadvantage.

Hologic developed the ATEC vacuum-assisted breast biopsy system (Figure 3b). This device is easy to operate and allows to take multiple biopsies in one run, so it is frequently used by radiologists.

Invivo Corporation, a Philips Healthcare business, developed the Invivo Breast Coil, and acquired the Sentinelle line of breast coils (Figure 2b). Philips itself developed the Mammotrak (Figure 2c).

Noras, a Siemens Healthcare business, developed complete MRI-guided breast biopsy solutions (Figure 2d), but also biopsy units that can be used with Invivo systems.



(a) Core biopsy needle (b) Vacuum-assisted biopsy device

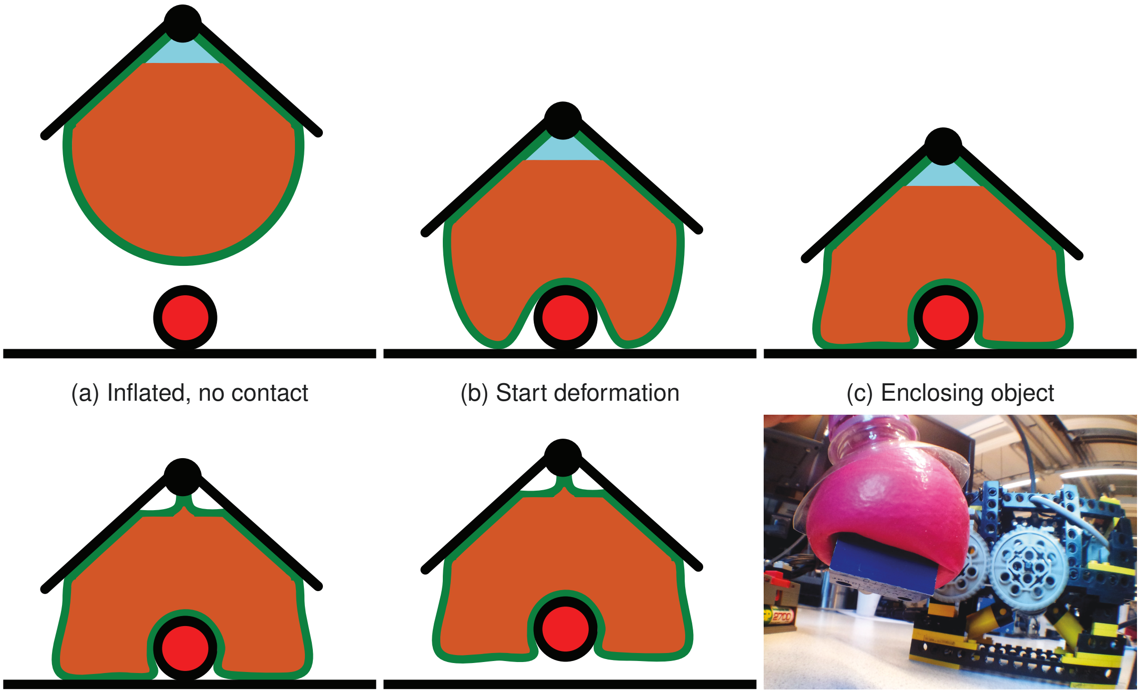
Figure 3: Breast biopsy devices.

From interviews with radiologists, it is learned that MRI-guided solutions from Invivo and Noras are currently most used in hospitals, in combination with the Hologic ATEC vacuum-assisted biopsy device.

2.3 MRI-guided biopsy procedure

The current MRI-guided biopsy procedure is as follows:

1. Patient lies down on table, breast is put through hole in table.
2. Breast is fixated by compressing it between two plates.
3. Table with patient moves into the MRI scanner and a first scan is made.
4. Contrast is applied and a scan is made.
5. Radiologist examines scans and pinpoints the location of the lesion.
6. Computer calculates grid coordinates and depth of the lesion.
7. Table comes back out of the scanner, breast is anaesthetized.
8. Radiologist inserts stylet plus needle guide in correct hole at the right depth.
9. Inner stylet is removed and obturator is inserted inside the needle guide.
10. Table slides back into MRI scanner and a new scan is made.
11. Radiologist validates obtuator position with respect to lesion. If not correct, then repeat from step 5 or 8.
12. Radiologist removes obturator and inserts vacuum-assisted biopsy device.
13. 6-12 tissue samples are extracted with biopsy device.
14. A new scan is made to verify that the lesion has been accurately sampled. If not, then repeat from step 5 or 8.
15. Biopsy device is removed, and a biopsy clip marker is inserted for future reference.
16. A last scan is made to get the location of the clip marker with respect to the lesion.
17. Needle guide and plates are removed, wound is cleansed and patient leaves the table.



(a) Inflated, no contact (b) Start deformation (c) Enclosing object

(d) Vacuum (e) Lifting object (f) Actual photo

Figure 4: Gripping an object in five phases.

2.4 The coffee gripper concept

The process of gripping a small object using the coffee gripper concept is shown schematically in Figure 4a to 4e. A balloon is filled with granular material such as ground coffee, and air is used as the fluid. Initially, the balloon is in inflated state (some air present in upper part of balloon and in the pores), so the gripper can be deformed easily. In phase 4c, the gripper is pressed downwards with some force; this way the gripper material is forced to flow to free areas while keeping membrane area as small as possible. Next, vacuum is applied (< -0.5 bar relative pressure), causing the gripper material to stick together due to the forces on the membrane (equivalent with 0.5 kg/cm^2 gravitational force). Now the object can be lifted. When the vacuum is released and pressure increases back to ambient pressure, then the gripper becomes soft and deformable again, and the object is released.

Chapter 3

Development of novel breast fixation system

In this chapter, the reasoning and development of the breast fixation system is described.

3.1 Analysis and requirements

Current breast fixation systems fixate the breast between two parallel rigid plates. We have seen that after fixating, some breast skin movement is still possible because the breast is only fixated at two sides. Muscle tensioning resulting from uncomfortable compression, and also breathing, may cause displacements of the breast. In order to avoid such movements, a larger portion of the breast skin needs to be immobilized such that the range of possible breast skin movements is significantly reduced.

Breasts can be large and small, be soft or dense, and come in various shapes. This also has to be taken into account.

3.1.1 Requirements

1. The new fixation system shall be able to fixate a breast effectively.
2. The new fixation system shall be more comfortable than existing fixation systems.
3. The new fixation system shall be able to support a large range of breast sizes.
4. The new fixation system shall be as easy to operate as existing fixation systems.
5. The new fixation system shall be MRI-compatible.
6. An access window shall be available, dimensioned such that over 95% of the breast volume can be biopsied.

3.2 The fixation system

Because of the large variety in breast sizes and shapes, it is not possible to use a fixed mould. The fixation system must be deformable in order to adjust to the breast shape, and then be completely rigid in order to immobilize the breast.

A special part which can be in either flexible or rigid state, is needed for the novel breast fixation system. In the flexible (deformable) state, the part shapes itself around the breast, after which it is changed to rigid state, securing the breast into place. Such a concept indeed exist, under the name ”coffee gripper”.

The coffee gripper concept consists of a shape filled with some fluid (liquid or gas) plus a granular material (solid), surrounded by a flexible membrane with an opening that lets fluid flow in and out, but is impermeable to the granular material.

The pressure inside the membrane can changed by pumping fluid from/to the membrane volume. There is a certain minimum volume within the membrane's volume because of the granular material, so when all the fluid in the pores between the granules is pumped out, then the pressure drops to vacuum.

At normal pressure, the coffee gripper is flexible, allowing to deform around an object. But when vacuum is applied, the inward forces acting on the membrane push the granules into each other, and the resulting friction turns the matter into a rigid structure.

The choice of the flow material (e.g. air or water) and granular material, has a large impact on the characteristics of the coffee gripper. In order to apply the coffee gripper concept to a practical breast fixation mechanism, the right materials for the fluid, membrane and the granular matter have to be chosen.

Also, a strategy for getting the shape right (around the breast) has to be developed, and the shape itself must be supported by some structure connected to the surrounding frame. The system must be practical to use, which is also a major challenge.

3.2.1 Gripping materials

Different materials have been investigated with air-based grippers:

- **Ground coffee** Good gripping capabilities, but noticeable smell.
- **Gelatine grain** Coarser than coffee ground; good gripping capabilities, especially in large balloons.
- **Portlandcement** Material is very fine; in small balloons it has reasonable gripping capabilities, but in a large balloon the it remains too soft.
- **Wheat flour** Same characteristics as portlandcement; remains too soft under vacuum pressure.

All these materials are non-ferromagnetic and non-conducting, and thus are (theoretically) MRI-compatible.

3.2.2 Gripping phases

We can identify three phases in the fixation process:

1. Gripper flexible, breast outside the fixation system.
2. Gripper flexible, breast in place.
3. Gripper rigid (vacuum applied), breast fixated.

There are many aspects to consider in designing the fixation system. The mechanism must be able to fixate small and large breasts, easy to operate and leave enough room for taking breast biopsies.

3.3 Test setup

A flexible test rig (Figure 5) was set up to accommodate various fixation systems. The top plate has a circular hole to lower the breast in the system. A pair of rail guides allow to slide plates, grids and/or coffee gripper parts from two sides to the breast. The main advantage of this rig is that it is very easy to change one or both fixation parts, allowing to compare different fixation strategies in quick succession.

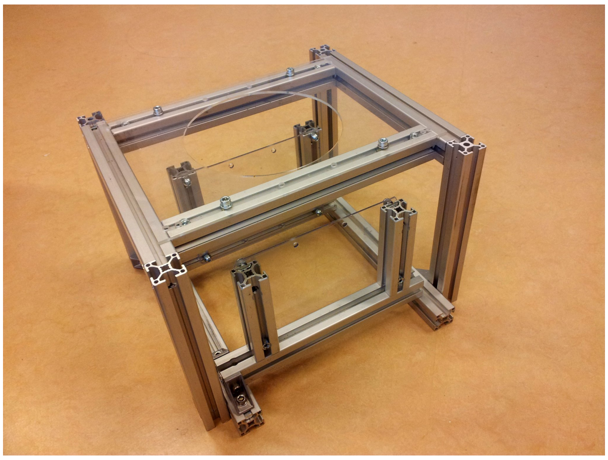


Figure 5: Test setup with traditional fixation plates.

First, a pair of plates was constructed to simulate currently-used fixation systems. This is useful to compare new gripping technologies with traditional fixating methods. Also, a plate with holes is constructed to allow biopsy needle access to the breast.

Next, different frames with coffee gripper technology were constructed and tested. One of the main difficulty is how to design the system such, that the gripper properly folds itself around the breast.

3.4 Difficulties in fixating breasts with air-based grippers

Gripping a small object is not too hard, but fixating a breast is much more difficult. In this section, the difficulties are explained.

3.4.1 Fixating the side of a breast

When fixating a breast with coffee grippers, one gripping strategy is given in Figure 6a. The gripper (left part) immobiles a part of the breast's surface (right part). The gripper's membrane is flexible. When the breast is removed, inflating the gripper causes the gripper material to redistribute according to minimal gravitational energy while maintaining constant membrane area. So the material distribution becomes as in Figure 6c and after applying vacuum again (without breast), it changes shape to that in Figure 6d. This is far from ideal, because when fixating a breast again, it takes effort (by hand) to redistribute the material for a good gripping shape as in Figure 6a. This violates the requirement that the breast fixation procedure should be as simple as possible.

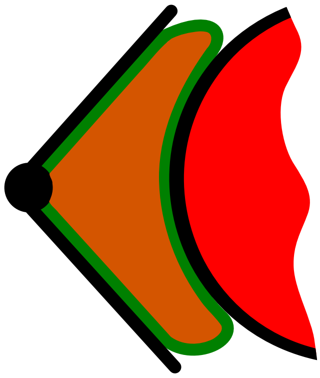
One solution is to pre-form the gripper(s) in a certain shape and keep it vacuum while it is placed against the breast. After making contact, the gripper is partially inflated, allowing to redistribute gripper material for optimal contact, and finally vacuum is applied again.

Another possible solution is to use multiple, smaller grippers to maintain a better material distribution in inflated state. A small gripper can be shaped much easier (i.e. less force needed). See Figure 7a for the schematic fixation method. In Figure 7b the grippers are inflated and the breast removed. Because the gripper material is distributed over multiple grippers, it better remains in place.

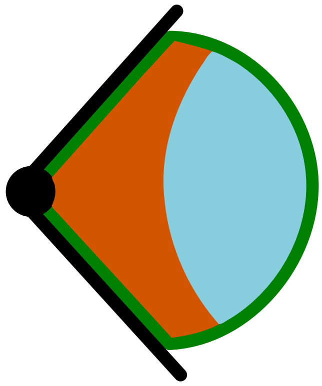
3.4.2 Fixating the bottom of a breast

When fixating the bottom of the breast, one is tempted to use a single, large coffee gripper which is large enough to be shaped around the bottom half of the breast. This desired situation is shown in Figure 8a.

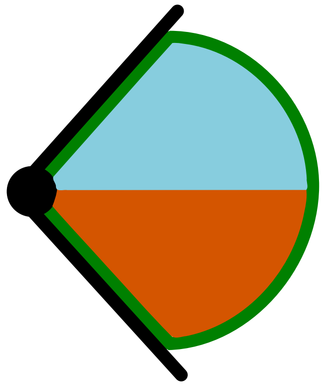
But when testing it into practice, it turns out that it is difficult to distribute the gripper material to get the correct shape. The problem is that when the breast makes contact with the gripper, it applies



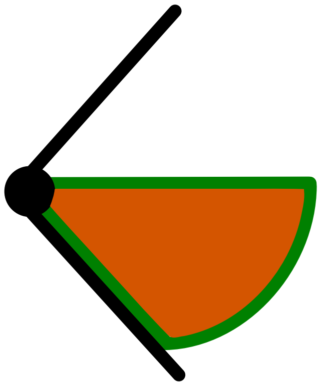
(a) Breast fixed at one side.



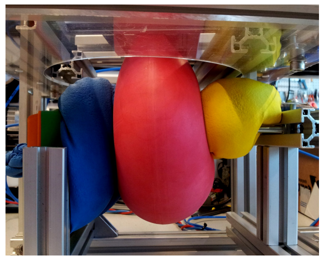
(b) Breast released, gripper inflated.



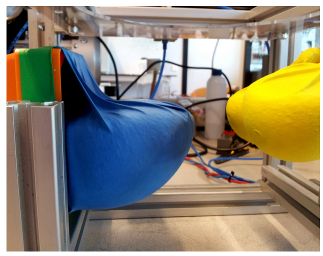
(c) Material energy minimized.



(d) Gripper deflated again.

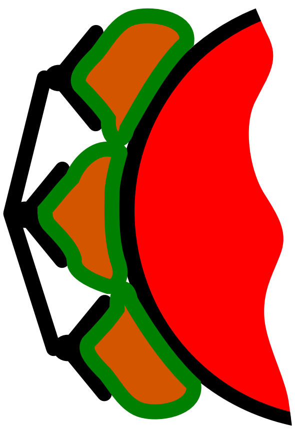


(e) Breast partially fixated by balloons.

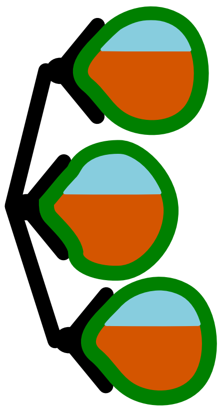


(f) Impractical rest state after inflating.

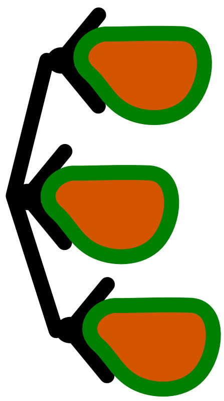
Figure 6: Fixing and releasing a breast by coffee grippers on the sides.



(a) Breast fixed at one side.



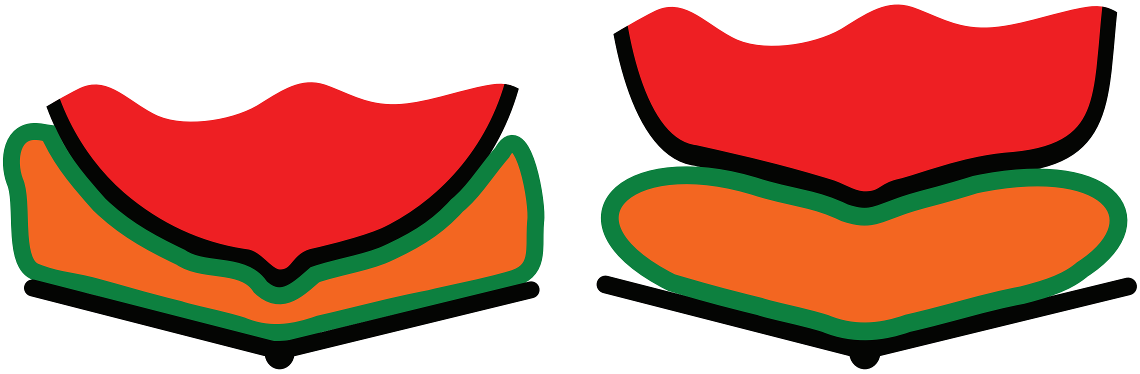
(b) Inflated state.



(c) Vacuum from rest state.

Figure 7: One way to use multiple small grippers.

pressure onto the membrane, making the gripper material more sticky, increasing resistance. Gravity and membrane tension also work against the desired material flow. What then happens is that the breast itself is deformed, resulting in a more flat surface on the bottom, further increasing pressure on the membrane. Eventually you get the situation in Figure 8b, which is no longer an effective fixation anymore.



(a) Ideal situation. (b) Experiment result situation.

Figure 8: Fixating the bottom of the breast.

3.5 Water-based grippers

The use of liquid, such as water, as the fluid (instead of air) opens new possibilities. Many granules are lighter than water and thus float, and water itself has a very low viscosity (even under high pressure), so using water-based grippers theoretically makes it easier to distribute granular material around the breast.

3.5.1 New water pump

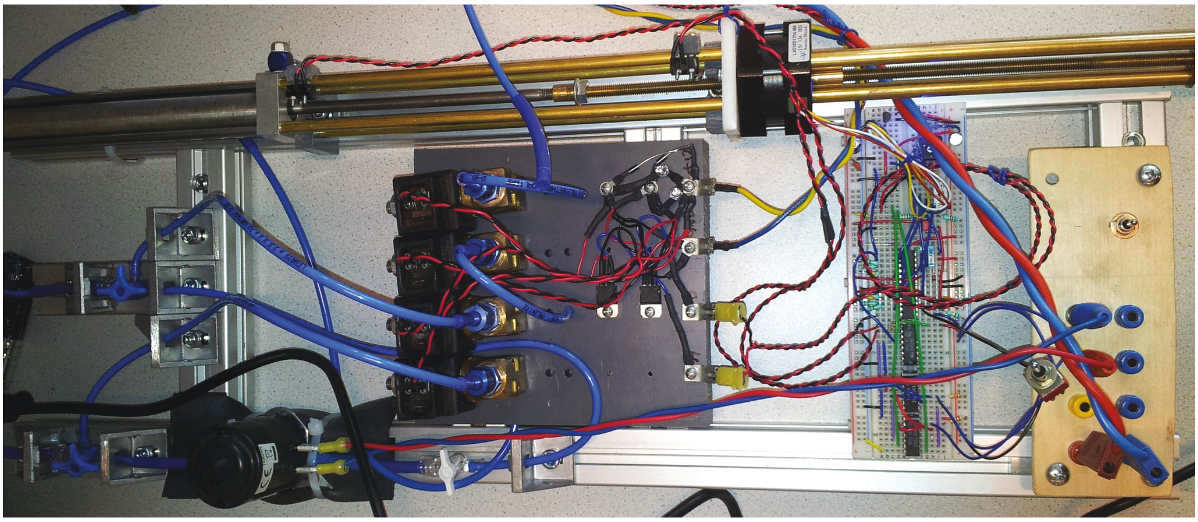


Figure 9: Piston water pump (top) with control electronics (right) and valve aquaduct (center). Another water pump can be seen at bottom left.

A custom-made water pump was constructed to enable suction of water from the coffee grippers. An electric stepper motor moves a piston up and down in the cylinder, and valves are opened and closed in such a way that the desired water flow results from resizing the cylinder chambers. It is a particular implementation of the positive displacement pump type.

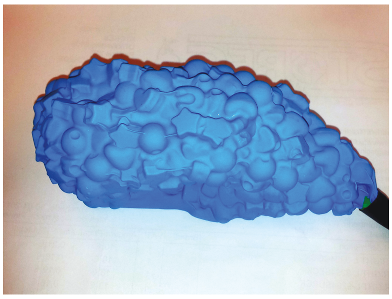
The L6228N IC, a stepper motor controller, drives the motor. A 555 timer IC generates the clock pulses, a set/reset latch maintains the current piston direction, and a simple logic circuit control the states of the valves according to piston direction and desired flow direction.

The volumetric flow rate is rather low, in the order of $1\,\mathrm{cm}^3$/sec. So it is placed parallel to a commercial water pump, which displaces up to $30\,\mathrm{cm}^3$/sec, but unlike the custom-made water pump it cannot pump water at low pressures.

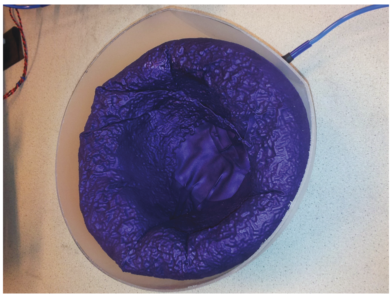
3.5.2 Gripping quality

This section describes experimental results with medium-sized water-based grippers. Relative vacuum pressure is about -0.6 to -0.8 bar, unless stated otherwise

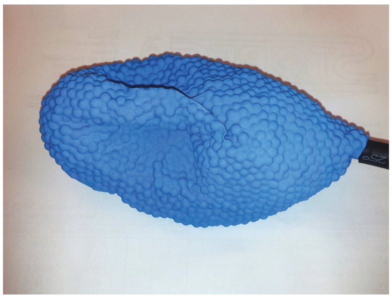
Figure 10: Five waterproof granular materials. Top row: 6-8mm hard beads, 2.5mm soft beads, 3mm glass spheres. Bottom row: 3-4mm hard granules, 3-6mm soft styrofoam.



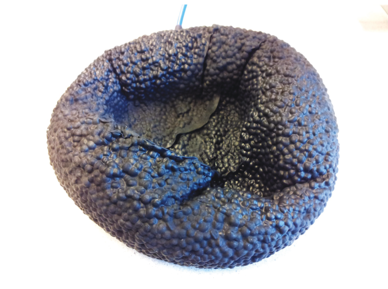
(a) 6-8mm hard plastic beads.



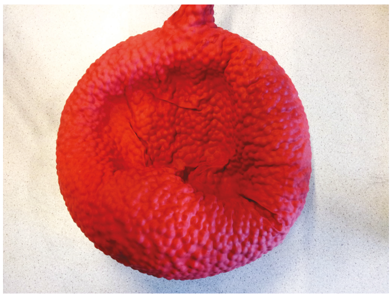
(b) 2.5mm soft plastic beads.



(c) 3mm glass spheres.



(d) 3-4mm hard plastic granules.



(e) 3-6mm soft styrofoam spheres.

Figure 11: Balloons filled with the five materials from Figure 10.

- **6-8mm hard beads** Hard plastic beads. Structure under vacuum is very strong, but the surface is also quite rough due to the large granule size and so it would be not so comfortable.
- **2.5mm soft beads** Mini ”iron beads”, made out of soft plastic which can be molten together with an iron. Vacuum structure is a bit flexible, like rubber, but looks good enough for breast fixation. Vacuum pressure does not go more negative than -0.4 bar, reason not immediately clear. Maybe because of the spring energy in the beads, possibly combined with the large amount of air trapped within the holes, or because the balloon is quite large.

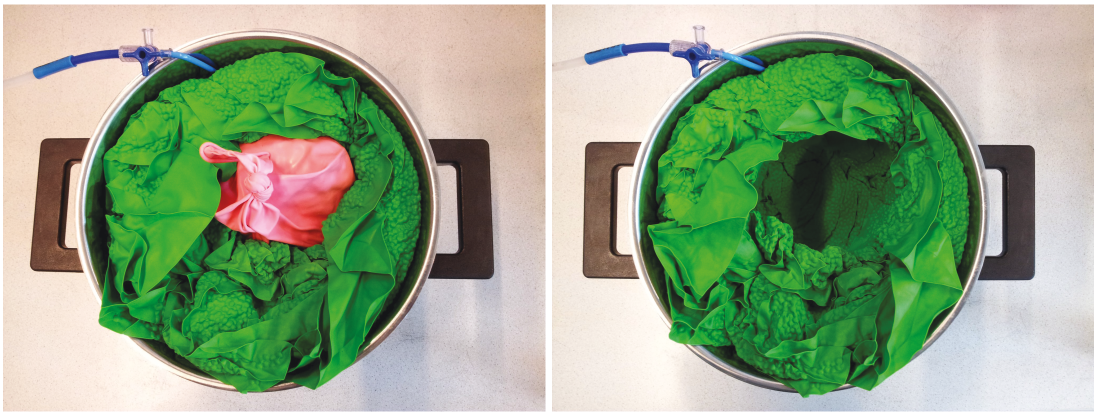
- **1.5/3.0mm glass spheres** Tested with 3mm and 1.5mm glass spheres, results are comparable. Strong vacuum structure, but because of the high weight it does not easily move sideways or upwards. Especially when a large object is lowerd into a water/glass sphere mixture, there is quite strong resistance.
- **3-4mm plastic granules** PET or similar. Good gripping quality. Material is hard, somewhat irregular shaped, and sufficiently small to get a good distribution with little effort.
- **3-6mm soft styrofoam spheres** Material is very lightweight and flexible. In air-filled balloon, when vacuum is applied, the balloon shrinks; this may be not ideal because it changes the breast fixation grip. In water-filled balloon, it takes forever to extract enough water from the balloon to get a moderately rigid structure. And even then, the structure is still deformable because of the soft material.

These materials are also non-ferromagnetic and non-conducting, and thus are (theoretically) MRI-compatible.

3.5.3 Conclusion on the material choice

Currently, the best fill granular materials are the 3-4mm plastic granules. These are hard, have good buoyancy and are sufficiently small for our purpose.

3.5.4 Adjusted breast fixation assembly



(a) Breast (pink) immobilized

(b) Cavity after removing breast

Figure 12: Pan with gripper balloon fixating a breast

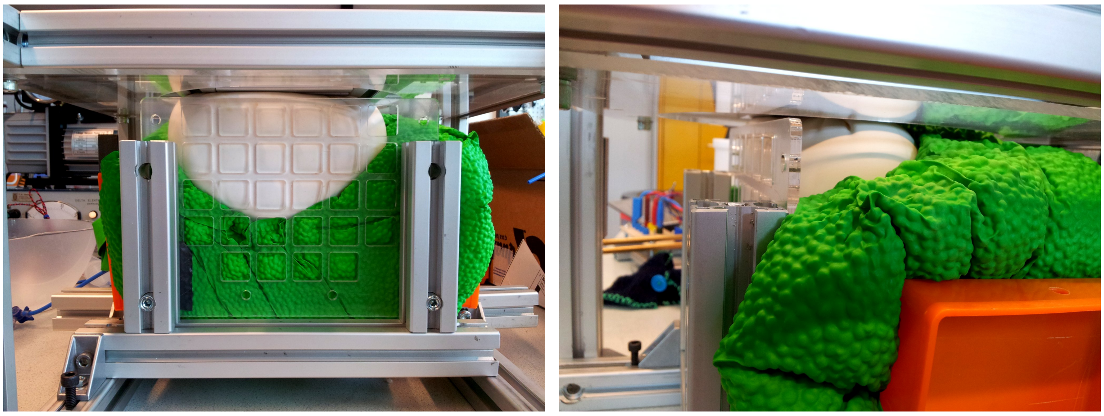
To immobilize a large breast at all sides with a single gripper, a very large balloon with a lot of granular material is needed. The gripper itself also needs to be supported at all sides with rigid walls/plates.

3.5.5 Experiments with large water-based gripper

In Figure 12a, a large pan with gripper balloon, fixating a smaller breast phantom is shown.

The buoyancy effect of the water-based gripper can be experienced, but because of the friction between breast and balloon, some hand work is still necessary to shape the gripper effectively around the entire breast. The fixation seems to be fine, one problem is that there is no access window yet for the biopsy instrument.

The balloon gripper has a quite large surface, this is why the surface folds and forms loose flaps under vacuum. This is more or less unavoidable, because the balloon gripper must be deformable in all directions and thus may need more balloon surface. It is no option to stretch the balloon membrane instead, because the associated surface tension forces are quite high.



(a) Front view

(b) Side view

Figure 13: Breast fixation assembly with breast phantom and balloon gripper.

When the original setup (with access grid) is used again (Figure 13a and 13b), then one experiences problems with holding the heavy gripper balloon in place because the setup is not closed at all sides. It is very difficult to construct a starting state in which the breast can be easily inserted and then fixated. A lot of hand work is always needed to distribute the granular material around the breast as desired. But when everything is in place and the gripper is rigidified, then the breast is fixated really well and virtually all sideways movements are effectively eliminated.

3.6 Conclusion

It can now be checked which requirements are fulfilled:

1. The new fixation system shall be able to fixate a breast effectively. **This requirement is fulfilled.**
2. The new fixation system shall be more comfortable than existing fixation systems. **This requirement was not tested.**
3. The new fixation system shall be able to support a large range of breast sizes. **Not enough test data available to make a judgement.**
4. The new fixation system shall be as easy to operate as existing fixation systems. **This requirement is violated.**
5. The new fixation system shall be MRI-compatible. **This requirement was not tested.** Only MRI-compatible materials were used for the gripping system, but no actual MRI testing was performed so that it remains unknown whether this requirement has been met.
6. An access window shall be available, dimensioned such that over 95% of the breast volume can be biopsied. **This requirement is fulfilled.** The condition is that the biopsy needle can be angled. In this case, the openings in 13a are sufficient to access all regions in the breast.

Chapter 4

Robotic biopsy system

This chapter describes the development and construction of the robotic biopsy system. First, the requirements are stated and consequences discussed. Next, the chosen actuation type is investigated and a suitable actuator is developed. The full manpiulator is designed, constructed and tested. Finally, experiments are performed.

4.1 Requirements of the biopsy robot system

The requirements are stated as follows:

1. The system shall be able to access all regions within the breast, and allow to approach locations from different angles.
2. The system shall be MRI compatible.
3. The tooltip accuracy shall be in the order of one millimeter. This includes backlash and deflections by gravitational and interaction forces. The maximum interaction forces are 10N.
4. The system shall reduce the total time of the MRI-guided breast biopsy procedure time by at least one minute.

4.1.1 Consequences of requirements

The requirements of the robotic system to allow accessing locations from different angles, implies that at least five degrees of freedom are necessary: three for accessing the location, and two for setting the angles from which the location is accessed. Another way to view this is that any asymmetrically object has six DOFs, but an axisymmetric object such as a needle has one less.

The requirement that the system shall be MRI-compatible, severily limits the choice of materials and actuators: metallic and other conductive materials distort the MRI imaging process and are thus excluded in the vicinity of the MRI scanner.

Plastic components can be fabricated easily, thanks to rapid prototyping machines like the laser cutter and 3D printer. But a drawback is that plastics are not as strong and rigid as metals like aluminium and steel. This has major implications on the possible configurations of the robotic system driving the biopsy needle, also taking the accuracy requirement into account.

4.2 Serial vs. parallel manipulator

A serial kinematic chain consisting of six links connected by five joints has serious challenges to make each joint strong enough and achieve the required accuracy when made all out of plastic materials.

The first few joints (near the base) have carry all the weight of the remaining joints plus its actuators, resulting in excessively high torques, in the order of several Newton meters (a $1\,\mathrm{kg}$ load at $0.2\,\mathrm{m}$ distance generates a $2\,\mathrm{N{\cdot}m}$ torque). It is already difficult to construct a plastic joint that can be loaded with such forces and actuated with an actuator, and achieving the desired accuracy is then too difficult.

Table 1: Material properties of common plastics and metals.

Material	Density [g/cm^3]	Young's modulus [GPa]
Aluminium	2.7	69
Steel	8.0	180
ABS	1.1	3.1
Acrylic	1.2	3.2
Acetal	1.4	2.8

Another way to understand the difficulties in designing a MRI-comaptible serial manipulator, is to compare the elasticity and density of the materials (Table 1). We observe that the Young's modulus of aluminium and steel are much higher than that of ABS, acrylic and acetal, and that the lower density of plastics cannot compensate for the strength of the metals. So, a parallel manipulator is required.

4.2.1 Choice of actuation type

Actuation of the robotic biopsy system is another challenge. As electric signals interfere with the MRI scanner, it is very difficult to use electromagnetic actuators inside the MRI bore. Fortunately, there also exist actuation systems that do not use electricity, but use different way to transfer power to drive the system. Examples are air pressure (pneumatics), liquid pressure (hydraulics) and mechanical transfer by wires (Bowden cables and torsion cables). These methods allow to place the supplier of mechanical work sufficiently far away from the MRI scanner, so that the robotic system itself remains MRI-compatible.

Pneumatics is chosen as the power transfer medium, because pressurized air is readily available in hospitals and in the lab, so that only a set of valves and tubes are needed to operate a set of pneumatic actuators.

4.3 Pneumatics

MRI-compatible pneumatic cylinders are not yet available commercially, so a custom design is needed. Convential cylinders have a circular bore and piston, and is sealed with O-rings. The process of producing such a cylinder involves many labour-intensive production steps, such as drilling and cutting various parts.

So it would be useful to design a new type of pneumatic cylinder which is produced more easily, employing automatic tooling/prototyping machines like laser cutters and 3D printers as much as possible. One way to do this is by designing a cylinder which solely consists of laser-cut parts from commonly available plastic sheets.

4.3.1 Laser-cutting pneumatics

A laser cutter makes two-dimensional cuts in sheets of plastic, wood, rubber and other materials. Cut-out part have the same thickness as the original material sheet,

Materials

Acrylic (Plexiglas) and Delrin (polyoxymethylene, POM, acetal) are good materials for laser-cutting. Acrylic is transparant, hard and strong, but also brittle. Delrin is stronger and more elastic than acrylic, and is self-lubricant. Both acrylic and Delrin have smooth surfaces and are airtight. So these materials are primarily chosen for the cylinder housing and piston. One problem is that these materials are not as strong as metals such as aluminium, titanium and steel: the elasticity modulus is 2-3 GPa for plastics, and 70-180 GPa for the mentioned metallic materials.

4.4 Design of a pneumatic cylinder

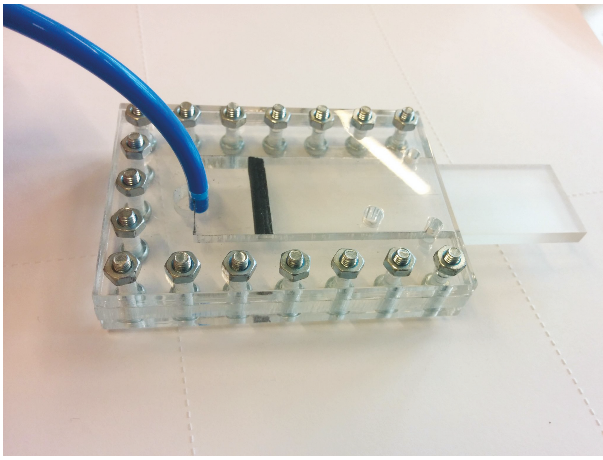


Figure 14: Single-acting cylinder

The use of laser-cut parts poses a number of constraints to the design. Cross-sections are rectangular [1], so no O-rings can be used to seal parts off. A single-acting cylinder (Figure 14) was produced to test different construction and sealing methods.

The housing consists of three layers: a bottom layer, a middle layer with space for the piston, and a top layer with holes for pneumatic tubing. The layers are fixed together with screws. No sealing material was used between the layers, but the brims resulting from laser-cutting were removed with a sharp knife. Thanks to the smoothness of the acrylic and Delrin surfaces and the pressure from the screws, the housing can be made airtight this way.

Silicone rubber seals, either hand-cut or laser-cut, are used to cover the entire cross-section of the cylinder bore, making the chambers air-tight.

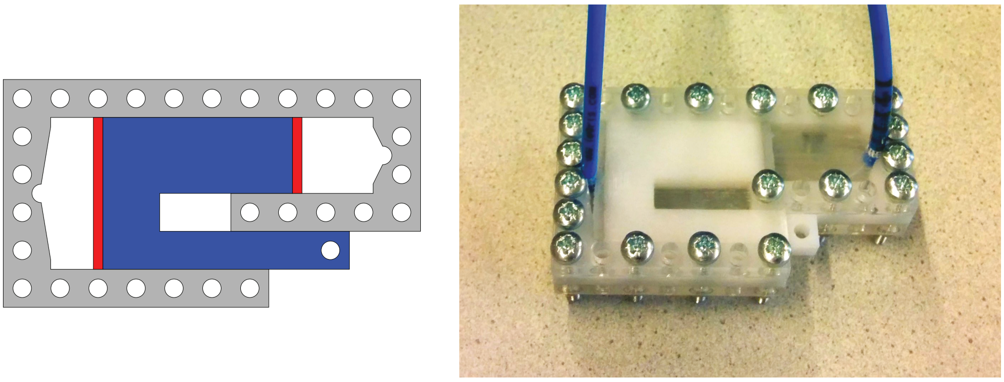
The piston needs a small clearance in order to move freely. A spacing of 0.05mm to 0.1mm all around the piston is fine; too small clearance results in excessive friction while too large spacing gives problems with the sealing.

There are different ways to match the piston height to the cylinder bore. The most useful ones are as follows:

- **Tooling** Sliding parts can be made thinner by milling or sanding them. This does work, but it is against the principles of laser-cutting pneumatics which is to avoid traditional tooling machines as much as possible.
- **Spacer** The middle housing layer can be made thicker with some material or spacer, such as a layer of laser-cut 0.1-0.2mm thick polyester. A clearance of 0.2mm is a bit on the high side, the resulting play in the piston causes backlash in the mechanical system. So 0.1mm thick spacing is about ideal.

[1] Actually, the cross-sections are slightly trapezoid because the conical shape of the laser beam results in tapered edges.

- **Thickness variations** Typical acrylic sheet have variations in thickness. A 4mm thick, 600x300mm size acrylic sheet was measured around the edges and the actual thickness was found to be between 3.58 en 3.86mm. This thickness variation can be exploited by cutting the housing from a relatively thick part of the sheet, and the piston from a thin part. This strategy works usually fine, but local gradients (at most 0.16mm thickness change per 100mm planar distance) may cause too much variations in large parts.



(a) CAD design

(b) Implementation

Figure 15: Design and implementation of a laser-cut double-acting pneumatic cylinder.

A double-acting cylinder can be designed by connecting two single-acting cylinders at opposite ends. See Figure 15a and 15b for the design and realization of one particular configuration. Notice that the piston rod lies outside both piston chambers, so that the rod does not infere with chamber sealing.

4.5 Pneumatic stepper motor

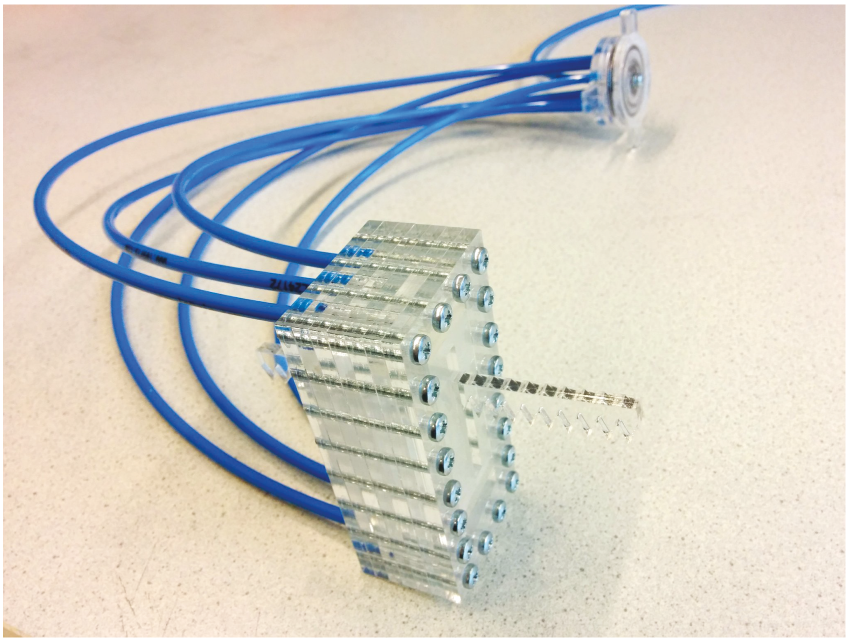
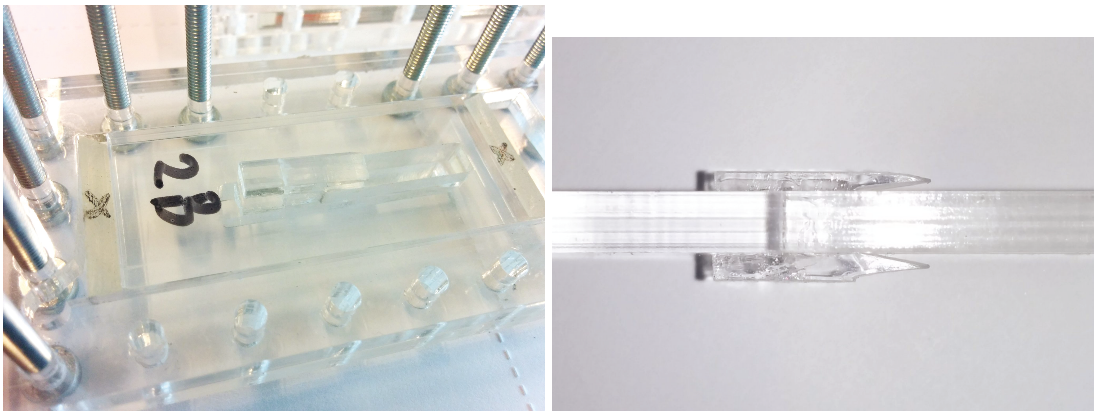


Figure 16: New actuator.

The piston of a pneumatic cylinder can slide up and down. The extreme positions are well-defined, but it is very difficult to control the piston in the intermediate positions. A position feedback system would be necessary, the air pressure in both chambers must be controllable, and the system dynamics including the compressibility of air and the nonlinear friction of the seals have to be taken into account. Considering that the system also has to be MRI-compatible which implies that electronic sensors cannot



(a) Close-up (b) Side view of piston

Figure 17: Close-ups of new actuator.

be placed in the vicinity of the cylinder, means that the resulting system would be very complex. So it would be useful to have an alternative pneumatic system with position control without the associated complexity. This is achieved with the design of the linear pneumatic stepper motor.

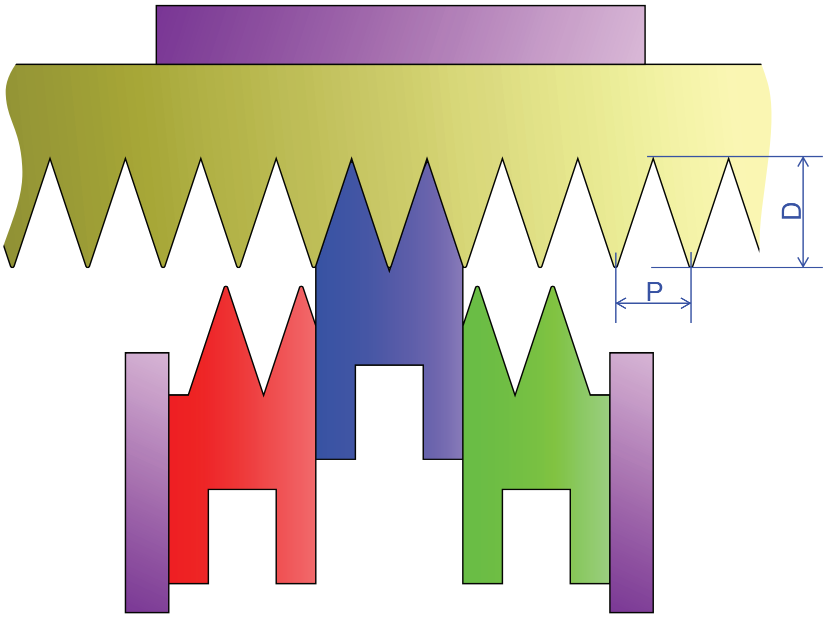


Figure 18: Schematic drawing of rack-and-piston actuator mechanism. P = pitch, D = teeth depth.

The housing is 80mm x 40mm x 28mm, each cylinder has a cross-sectional area of 20.1mm x 3.9mm = 78.4mm^2. The effective stroke (teeth depth) is 6mm. Figure 17a shows a close-up of the motor internals. Note that the seals are not affixed to the piston, this is not needed because the seal is always pressed to the piston in all motions.

The side view of one piston (Figure 17b) just shows two of the four 2mm-pitch teeth used to move the rack. The teeth part is a seperate laser-cut piece, glued to the piston.

Figure 18 shows a schematic drawing, with 4mm-pitch teeth. The middle piston's teeth are pressed against the rack here. When the right piston moves up and the middle one is retracted, then the rack will move to the left over a distance $\frac{P}{3}$, and pushing the left piston after this further moves the rack to the left. Pushing the pistons in reverse order moves the rack to the right. So it has three phases, similar to a three phase motor.

Four different sizes of the teeth pitch have been tested: 2mm, 2.5mm, 3mm and 4mm. The racks are laser-cut out of Delrin, this material is stronger and slides better than acrylic.

4.5.1 Actuator measurements

Measurements were performed on the actuator, to test the maximum force it could exert at different pressures and pitch sizes.

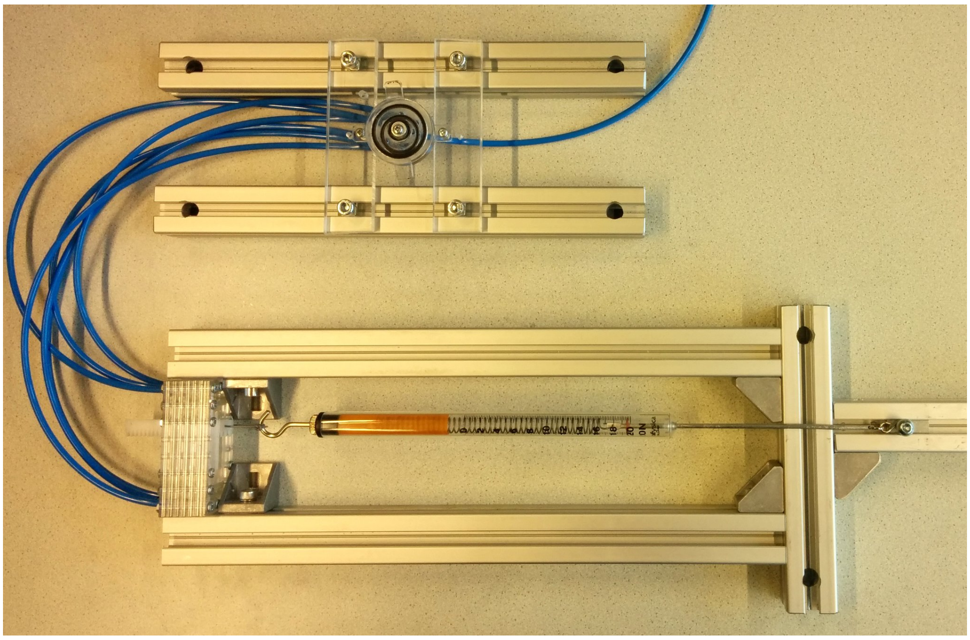


Figure 19: Test rig for measuring force.

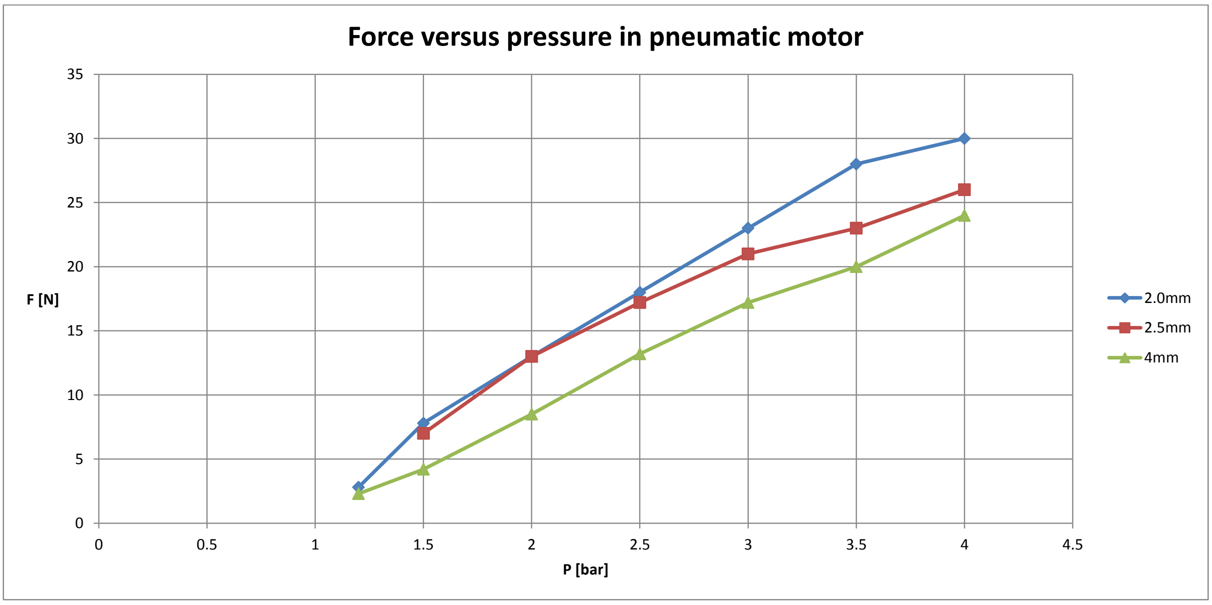


Figure 20: Force measurement results.

Test rig

The test rig is shown in Figure 19. A spring scale applies force to the rack, its magnitude can be read on the scale. The one shown measures force up to 20N; a difference scale measures up to 100N. The scales turned out to be not very accurate; the average error was found to be approximately 10%.

Experiment procedure

Pressure was increased from 1.2 to 4.0 bar, and the actuator was operated until the motor failed, i.e. steps were skipped by slipping teeth. The results were repeated with 2.0mm, 2.5mm and 4.0mm pitches, and graphed in Figure 20. The 3.0mm pitched rack showed signs of damage and was not included in the testing..

Analysis and calculations

The graph shows a lot of useful information. Pistons with smaller pitches exert higher maximum forces at equal pressure. There is a good linear relationship between applied pressure and exerted force. The dynamic friction of the seals can now be estimated by extrapolating the graphs and finding the intersection with the horizontal axis, which happens to be around 0.90 bar.

The cylinder cross-section area is $78.4 \cdot 10^{-6}$m^2, so the friction force of the seals is $78.4 \cdot 10^{-6} \cdot 0.90 \cdot 10^5 = 7.1$ N. It is unclear whether this friction force can be considered constant, or pressure-dependent. From experience, most friction is due to the seal on the opposite side of the piston, which is not pressurized at all. This is because of the trapezoid shape of the seal. It could be measured with a specialized test piston, but for now we assume this friction is approximately constant.

Increasing the pressure above 0.90 bar, increases the theoretical piston force by $78.4 \cdot 10^{-6} \cdot 10^5 = 7.8$ N bar^{-1}.

There is a mechanical advantage in converting the piston movement to the rack movement, because the angle of the teeth is not 45°. The advantage ratio is equal to the teeth depth divided by half the teeth pitch. In case of 4mm pitch, the advantage ratio is $\frac{6.0mm}{0.5 \cdot 4.0mm} = 3.0$. So a piston displacement of 6.0 mm results in a rack displacement of $\frac{6.0}{3.0} = 2.0$ mm, and a force of 7.8 N in the piston translates to a force of $3.0 \cdot 7.8 = 23$ N in the rack (when ignoring friction losses).

The slope of the graph with 4mm pitch, is $\frac{25\,\text{N}}{3.1\,\text{bar}} = 8.1$ N bar^{-1}. The efficiency of the piston-to-rack transfer can now be calculated as $\frac{8.1}{23} = 35\%$. This would mean that 65% of the mechanical force is lost due to friction in the sliding parts, excluding the seals.

The fine-pitched 2.0mm and 2.5mm mechanisms show better results, with forces up to 30N at 4 bar for the 2.0mm case. The 2.0mm pitch pistons each have four teeth, so the average load per tooth is $\frac{30}{4} = 7.5$ N at most. This is quite high for thin acrylic teeth; one could increase the pressure further to find the point where the teeth breaks apart, but this has not been done yet. If more strength is required, the teeth faces can simply be made wider (without changing the pitch or depth). In the current design, the teeth width is 4mm, but it could be increased to up to 10mm without changing the actuator's outer dimensions.

The stepper motor can also be made out of Delrin instead of acrylic. The advantage of Delrin is the lower friction and higher strength, possibly resulting in lower wear and higher force outputs.

4.6 Manipulator design

The task of the manipulator is to bring the needle to the correct position and orientation, aligned with the suspicious lesion. Then, the manipulator must insert the needle towards the lesion so that a biopsy can be performed.

Serial configurations have already been ruled out, but there are many parallel configurations possible. These differ in dexterity, stability, joint types, degrees of freedom, actuation requirements etcetera. We consider the most important requirements and then choose between different configuration alternatives.

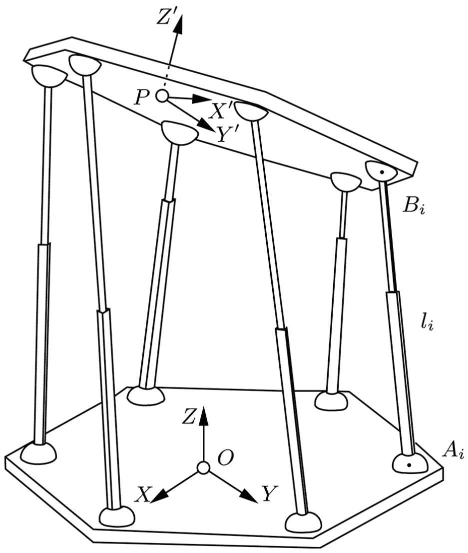
4.6.1 Degrees of freedom

A lesion is located at a (X, Y, Z) point in space. Bringing the needle tip to that point requires three degrees of freedom (DOFs). The lesion can be accessed from different directions. Controlling the azimuth and polar angles require two additional DOFs.

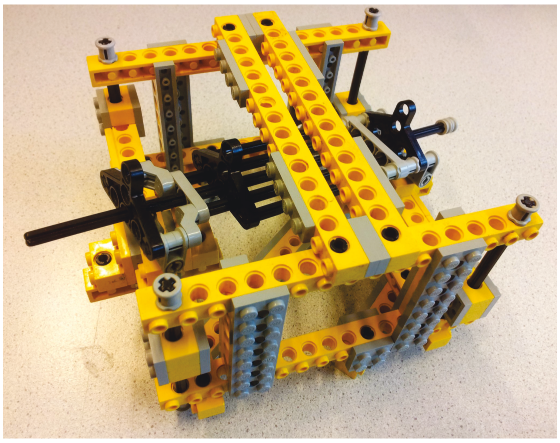
So the system needs at least five DOFs in total. One of them must be dedicated to needle insertion in axial direction, so that sideways movements can be prevented by locking all other DOFs. The system can now be split in a needle insertion mechanism (1 DOF), mounted on a 4 DOF platform.

4.6.2 Platform configuration

Four degrees of freedom are needed to move the platform part of the manipulator. Parallel manipulators use two or more serial chains to support a single platform. Examples are the Delta platform (3 DOF) and the Stewart platform (6 DOF). The main advantage is the rigidity: small tolerances in one link are not amplified, but reduced by the other links.



(a) Stewart platform



(b) Lego model

Figure 21: Two parallel manipulator designs.

The Stewart platform hexapod (Figure 21a) allows for simple construction: each link is a prismatic actuator with ball joints on either end. The links only feel tension or compression, without any bending or torque. One possible drawback is that the hexapod is a 6 DOF platform, so it has two redundant degrees of freedom. Another drawback of the hexapod is the more complicated control; while the inverse kinematics are straightforward, forward kinematics are very complicated. Singularities must be avoided at all cost, or the stiffness is lost [15] and the manipulator orientation may change unexpectedly. So the joint dimensions and workspace area must be well chosen.

The Lego model (Figure 21b) is also a parallel manipulator, consisting of two serial chains. Each chain consists of two prismatic joints. The two parallel chains are connected together by a couple of passive joints. The Lego design has four degrees of freedom, which is just enough. The forward and inverse kinematics are simple, and no singularities exist in the system. One drawback is the complexity involved in making the platform stiff enough to obtain the required accuracy for the needle biopsy procedure.

The Stewart platform was favoured over the Lego model, because this one is easier to develop due to the six links being exactly equal.

4.7 Construction of the biopsy robot

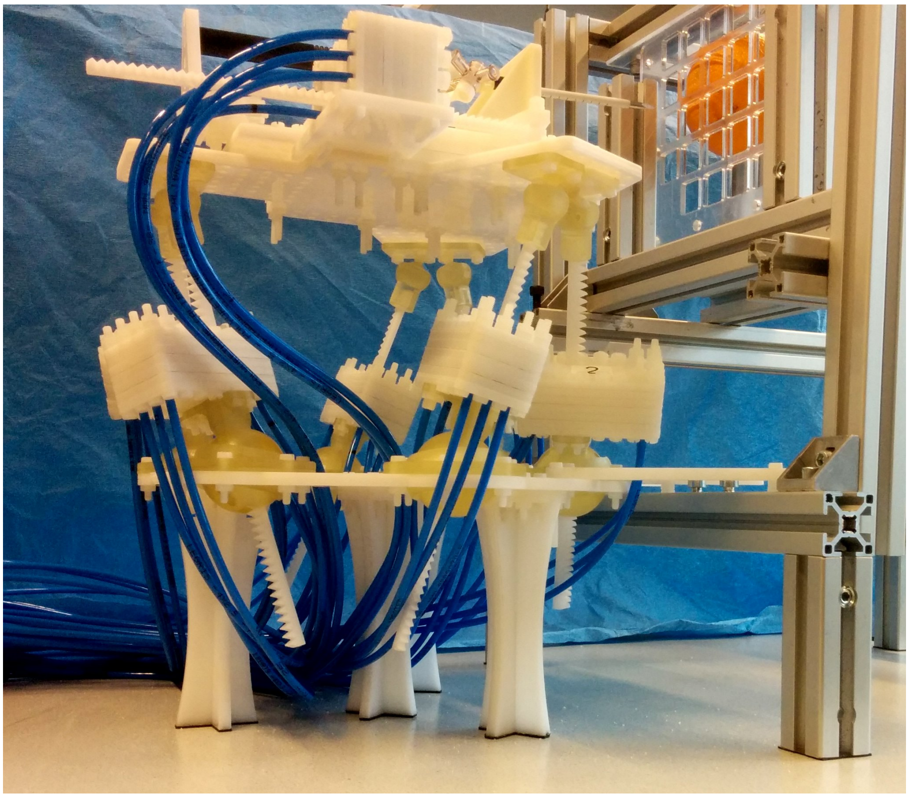
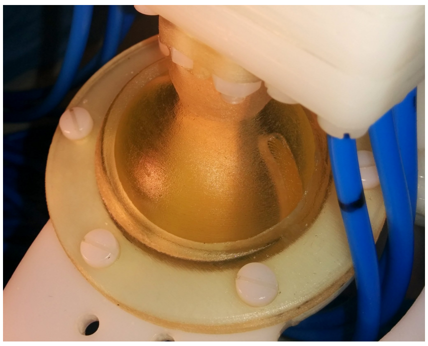


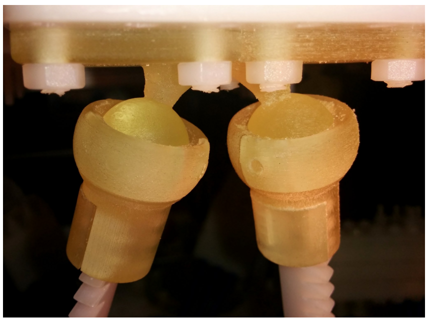
Figure 22: Biopsy robot

The finished biopsy robot can be seen in Figure 22. Six links connect the platform with the base. Each link uses a Delrin linear pneumatic stepper motor actuator (as described in 4.5) to increase or decrease the length of the link.

4.7.1 Ball joints



(a) 40mm ball joint in base



(b) 15mm ball joints in platform

Figure 23

The passive ball joints (Figure 23a and 23b) are 3d-printed with the Objet Eden 250 printer in Vero transparent material. Each joint consists of a ball and a socket. See Appendix 6.1 for schematic drawings.

The 40mm joint connecting to the base has a hole all way through the ball for the rack, and also pin and groove to eliminate the rudimentatry degree of freedom of the link between both ball joints, turning it into a universal joint. This way, the orientation of the stepper motor can be fixed to avoid collisions between the stepper motors of adjacent legs of the Stewart platforms.

Both base and platform ball joints have an angular range of motion of approximately $90°$. The center position is slightly tilted $(10 - 15°)$, because the links between base and platform are angled (respective to the base and platform plates), when the platform is somewhere near the center of the workspace.

It is very difficult to keep both friction and backlash in the ball joints to a minimum. Vero transparent material is not chemically stable: its properties and dimensions change over time, and are also effected by fluids like water, oil, and grease. Freshly-constructed parts are somewhat flexible, which allows snap-fit joints to bend and snap together, but after a couple of weeks the material become brittle and may break under stress.

If friction between ball and socket is too high, then WD-40 oil can be used to wash off the outer layer of the material, after which the friction is soon reduced. But over time, this might also introduce backlash, so it is difficult to apply just enough of it.

A different material (ABS) is also investigated. The problem is that 3d-printed structures in this material are coarser than structures printed with Vero material. So, some finishing like grinding is required to get the ball smooth; grinding the sockets evenly is very difficult. One interesting option to explore later, is to use acetone vapoiur in order to get a smooth finish.

Another option to explore in future, is to use a better socket design which allows to adjust backlash more effectively than the current design, such that tensioning and/or releasing the screws reduces friction and backlash to a minimum.

4.8 Biopsy needle insertion mechanism

One degree of freedom is dedicated to insertion of the biopsy needle. It consists of a sliding plate, on which a 3d-printed structure is mounted with a hole in it. The hole sheath is compatible with the ATEC vacuum-assisted breast biopsy system, currently used in many hospitals. So, the hole has the same function as the gridded holes of existing breast biopsy systems.

One way to use the needle insertion mechanism is to place the needle guide and inner stylet in the hole. These can be fixed in place, and be inserted into the breast by the needle insertion actuator. After reaching the correct depth, the inner stylet can be removed manually (leaving the needle guide in place), and the radiologist can insert the vacuum-assisted biopsy device for the next steps.

A different way is to move the hole in place, and let the radiologist insert the needle guide and inner stylet through the hole into the breast tissue. This manual step has the advantage that the radiologist keeps full manual control of the needle insertion process, and makes system certification easier.

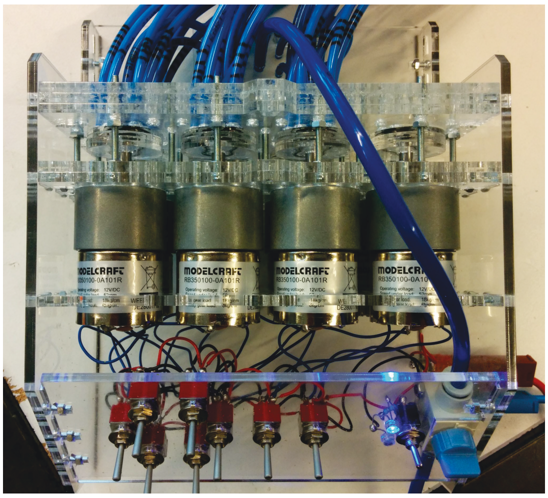
4.9 Control of the biopsy robot

Seven pneumatic linear stepper motors drive the biopsy system. Each stepper motor has three pistons, each having two pressure chambers. So a total of $7 \times 3 \times 2 = 42$ chambers need to be pressurized and decompressed in the right sequence, in order to drive the motors correctly.

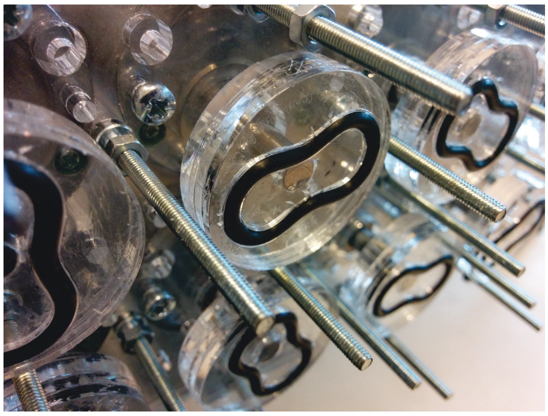
Valves are needed to pressurize and decompress the 42 pneumatic lines. The valves can be controlled in different ways: manually, electronically with solenoid valves, or driven by DC motors. For this prototype, DC motors are chosen because one DC motor can control all six pneumatic lines of one stepper motor at once, reducing the total cost of the system.

4.9.1 Pressure distribution module

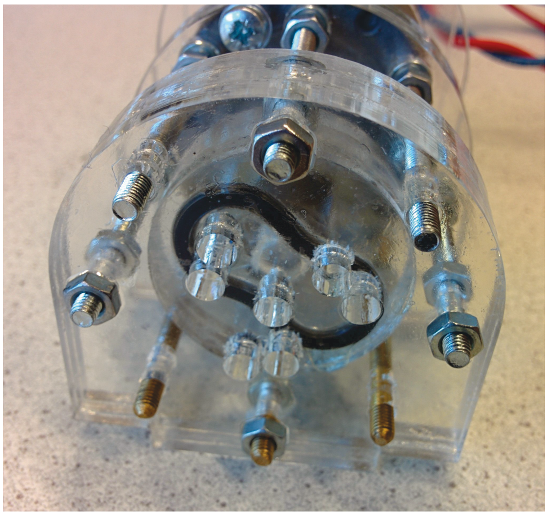
Each DC motor drives an 8-shaped rubber ring (Figure 24b). Air is delivered to the central hole (Figure 24c). The ring is symmetric, so that it does not tilt towards one side (which would be the case with an eccentric circle), and the pressure on the ring is equal everywhere (otherwise it would easily leak). The consequence is that two identical cycles are performed in one full rotation.



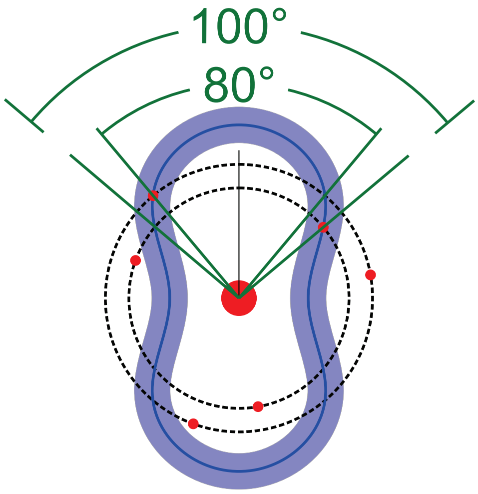
(a) Top view



(b) Motorized rubber rings



(c) Back view of one distributor



(d) Hole configuration drawing

Figure 24: The pneumatic distribution system.

The position of the ring controls which of the six other holes are pressurized, or being decompressed (connected with ambient pressure). See Figure 24d for the hole configuration. Pressure duty cycle is controlled by the distance from the center, and pressure phase by the angle from the vertical. A single piston is always pressurized from one side, so the total duty cycle for both chambers of one cylinder is $180°$, of which the duty cycle of the chamber pressing on the toothed rack is $80°$ and the other one $100°$.

The reason for this asymmetry is that it is not advantageous to have two pistons pushing on the rack at the same time, as this would cause unnecessary stress on the teeth. As the three piston phases are offset by $60°$ (one-third of one cycle), the overlap is now $\frac{20}{60} = 33\%$ which means that in 33% of the time, two pistons are pushing against the rack and in the remaining 67%, one piston pushes at the rack. In practice, the pistons take some finite amount of time to slide from one side to the other, so the actual percentages are a bit lower.

4.9.2 Motor controllers

The DC motors are controlled with double pole double throw (DPDT) switches with spring return and a special center state, all mounted at the control panel (bottom part of Figure 24a). The spring return ensures that the switch goes back to the center state when the switch is released. In the center state, the DC motor is short-circuited to brake it, so that it immediately stops. So the system is manually controlled, which makes testing relatively easy. A computer-controlled pneumatic distribution system could be developed in future.

A master switch at the right side of the control panel enables or disables all eight motor switches. Next to it is a manual pneumatic ball valve to enable or shut off air pressure for the system.

4.9.3 Lack of MRI-compatibility

Because electronic equipment is not MRI-compatible, the pneumatic distributor system cannot be placed near the MRI scanner. It is even not MRI-safe yet. There are several ways to make the system MRI-compatible: with longer pneumatic tubes one can place the distributor outside the MRI room, but this also makes the system react slow due to the increased air volume. Using pneumatic booster modules (small pneumatic valves controlling large airflow) might solve this problem.

Another option is to use non-MRI-compatible components anyway such as electronic valves, and shield off the magnetic and RF noise with a metallic housing. In [9], a metal box was constructed which houses a computer and a valve manifold, and was found to be effectively MRI-compatible.

4.10 Measurements

Several aspects of the system were measured, qualitatively and/or quantitatively.

4.10.1 Speed

The actuator's velocity is $8\,\text{mm/ s}$. One actuator's range is about 150mm, so when one actuator is in the center of the workspace, it can go to either extreme in $\frac{75}{8}\text{s} \approx 9\,\text{s}$.

First, the platform has to be moved to the correct position. This takes $9\,\text{s}$ at most. Next, the biopsy needle has to be inserted towards the lesion. The time depends on the depth of the lesion. In case of 40mm, a higher than average distance, the time is $\frac{40}{8}\text{s} = 5\,\text{s}$. So the total time becomes $9 + 5 = 14\,\text{s}$. This is much less than the time currently required by radiologists to set up the grid and insert the stylet manually (a minute or two).

4.10.2 Workspace

One advantage of the new biopsy robot is the versatility. There are seven degrees of freedom in total. The Stewart platform has six degrees, and the needle insertion mechanism is the seventh one. But this does not yet mean that biopsies at all locations from all angles are possible. The workspace of a Stewart platform is limited, and singularities are a dangerous aspect of this particular configuration. So it is required to determine the practical work area.

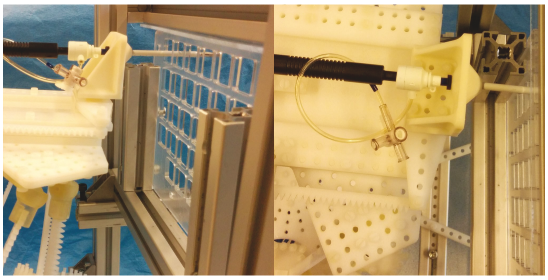
Analyzing the workspace and singularities of a Stewart platform is a highly complex topic on its own. When a single actuator is operated and the length of its link changes, all twelve passive ball joints are being rotated and the platform moves in a complex way [15, 16]. In this analysis, the reachability of certain borderline cases in the workspace is investigated experimentally.

4.10.3 Accessibility of borderline cases

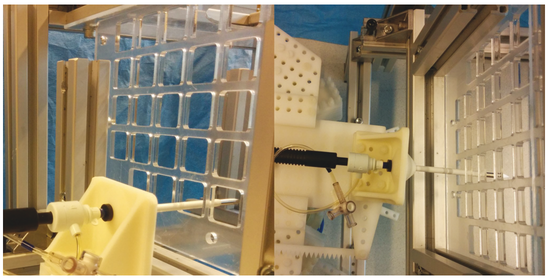
Figure 25a and 25b show that it is possible to access the borderline regions horizontally.

The needle can also be tilted: the extreme angles for the center region are shown in Figure 25c and 25d. The maximum horizontal angle is $27°$; by argument of symmetry, the horizontal angle range is $54°$. The vertical angle rangle is of the same order.

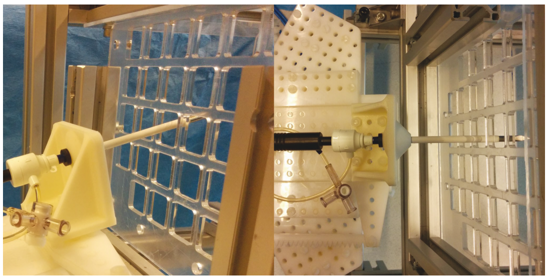
The possible insertion angles are not the same for all regions. In the borderline cases, it is easier to point the needle outwards. This makes it possible to access lesions at hard-to-reach places, such as close to the chest wall.



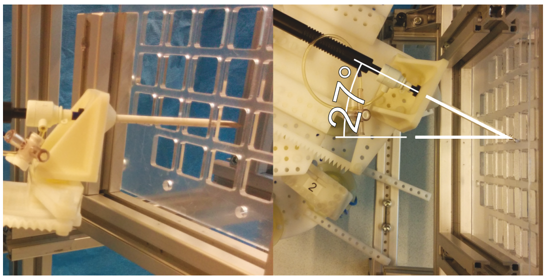
(a) Top-left part



(b) Bottom part



(c) Vertical angle range



(d) Horizontal angle range

Figure 25: Accessibility study of certain borderline cases. Each case is shown from two perspectives.

4.10.4 Accuracy of the biopsy robot

Accessibility is one thing, but accuracy (systematic error), precision (statistical error) and rigidity are also very important. Accuracy could be defined as the (mean) distance from the needle tip's actual position to the calculated position. Rigidity is a measure of the forces needed to move the tip out of place by external forces. In the current setup, the needle is only loosely fixed to the needle mount and the system's base is also loosely attached to the test rig, so it is better to consider the accuracy and rigidity of the needle mount with respect to the biopsy robot's base.

The accuracy has not yet been measured, because there is no motor position tracking system or other feedback system. But we make some observations from the dexterity of the robotic system. There are seven linear actuators, each having a step size of 1.33 mm. Five degrees of freedom are required to position the tip of the needle and the needle's direction in space. When only five actuators are used, the accuracy would be in the order of 2 mm. But the two redundant actuators allow to make mirco-adjustments, greatly improving accuracy, possibly down to 0.1 mm.

The rigidity also turns out to be quite good. With the platform located in the center of the workspace and applying reasonable force by hand (10 N) in different directions, the deviations of the needle mount are in the order of 5 mm. This can be attributed to backlash in the system, and to bending of various parts, especially the base and platform plates.

The backlash is caused by the clearance in the ball joints, which is in the order of 0.2mm. The backlash and rigidity of the platform depends greatly on the actual position: if the distance between base and platform is high, then the backlash is much higher than when the platform is close than the base. This is because the six links are longer and running more parallel. Also, when the platform is tilted by a large angle (over $25°$) and shifted in a certain direction outside the normal workspace, then the system comes close to a singularity (also caused ill-conditioning), where backlash becomes very high and control gets difficult because of the excessively large forces in the actuators [16].

4.11 Conclusion

It can now be checked which requirements are fulfilled:

1. The system shall be able to access all regions within the breast, and allow to approach locations from different angles.

This requirement is fulfilled. If the breast is fixated as in Figure 13a, then the dexterity of the needle is sufficient to bring the needle's tip to anywhere within the breast phantom's volume, from different angles.

2. The system shall be MRI compatible.
   This requirement is theoretically fulfilled (except for the controller part). Only MRI-compatible materials were used for the biopsy robot. Actual MRI scanner tests are needed to properly validate this requirement.

3. The tooltip accuracy shall be in the order of one millimeter. This includes backlash and deflections by gravitational and interaction forces. The interaction forces are in the order of 10N.
   This requirement is probably fulfilled. More measurements involving position feedback and/or real MRI testing, are needed to validate this requirement precisely.

4. The system shall reduce the total time of the MRI-guided breast biopsy procedure time by at least one minute.
   Not enough test data. The robotic system can align and position the biopsy needle much faster than the radiologist can, but whether time is actually saved, depends on the rest of the procedure as well.

Chapter 5

Conclusion and discussion

The coffee gripper concept is employed in a novel breast fixation system. Large and small balloons, air-based and water-based grippers in combination with a range of materials were tried tested on small and large breast models. While the coffee gripper concept is able to effectively fixate the breast in place, considerable hand work is consistently needed to distribute the granular material of the gripper properly around the surface breast. Especially gravity forces are a problem, and the use of lightweight materials and/or water-based grippers cannot fully solve the practical issues yet. More research is needed to optimize the choice of materials, the fixation procedure and other aspects.

In contrast, the semi-automatic biopsy robot system turns out to be very effective in improving accuracy and efficiency of breast biopsies. It aligns the biopsy needle with the lesion with millimeter precision, then the needle is inserted (either automatically or manually), after which the radiologist performs the vacuum-assisted biopsy procedure in the usual manner. The accuracy is better than in the current manual procedure, resulting in less false biopsies and better efficieny. In future work, the system should be made smaller, and the pneumatic control system be computer-controlled and MRI-compatible so that practical testing in real MRI-scanners is possible.

Chapter 6

Appendices

6.1 Ball joints

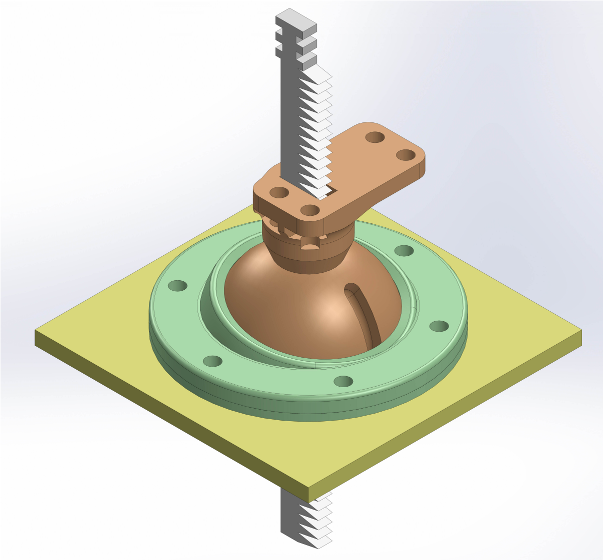


Figure 26: Isometric view of a ball joint in the base. The ball diameter is 40mm.

See Figure 26 for an isometric view, and Figure 27 for a schematic drawing of one ball joint in the base. The diameter of the ball is 40mm. It is important that the sliding surfaces of the ball and socket are as smooth as possible; any deviation from the ideal spherical shape may result in excessive friction and/or clearance.

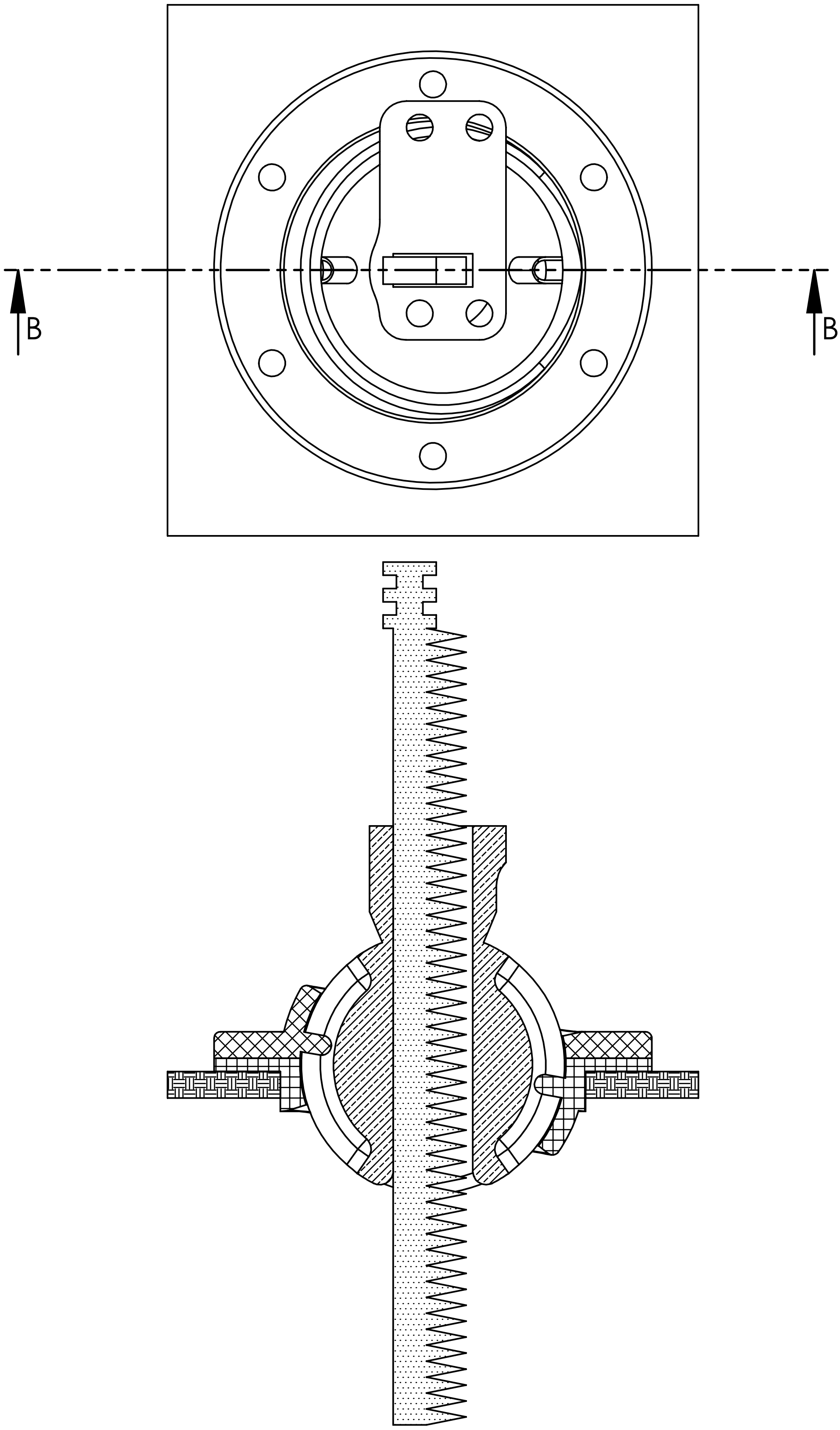


Figure 27: Top view and cross-section drawings of a ball joint in the base, scale 1:1.

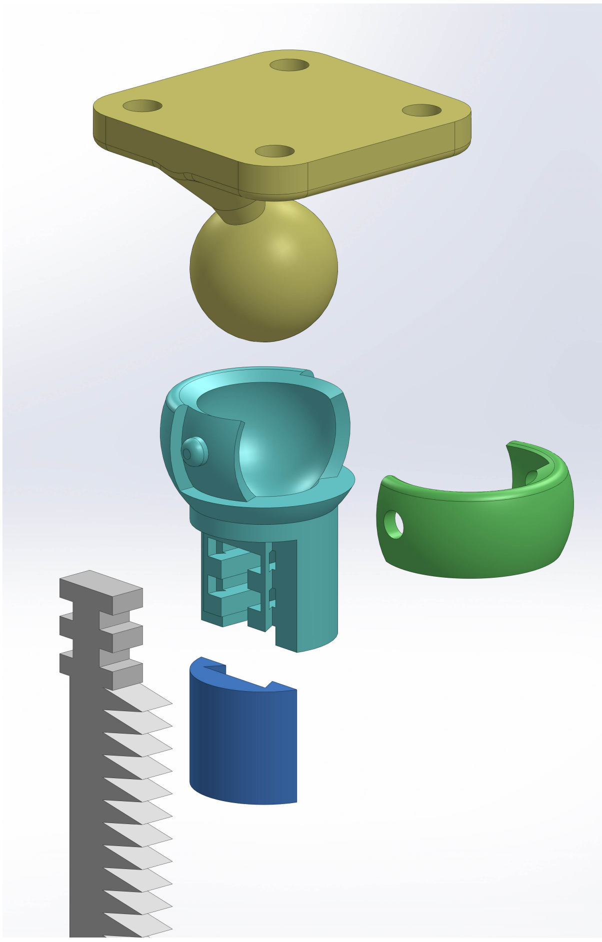


Figure 28: Exploded view of a ball joint in the platform. The ball diameter is 15mm.

6.2 Linear pneumatic stepper motor

The linear pneumatic stepper motor can be laser-cut from 4mm acrylic and/or Delrin. The drawings of the different parts are shown in Figure 29.

Note that the pistons have to slide freely, a clearance of 0.1mm to 0.2mm is required. This can be created with spacers (e.g. 0.2mm polyester sheet, laser-cut with the same drawings), or by precisely measuring material thickness prior to lasercutting.

After laser-cutting the parts, brims have to be removed with a knife or fine sand paper. Next, the three small teeth pieces can be mounted on the three pistons. Silicone rubber parts are needed to seal off the pistons. Finally, the stepper motor can be assembled by stacking the pieces together in the correct order, and fixing them together with screws. A bit of vaseline grease helps to make the housing airtight when using plastic screws.

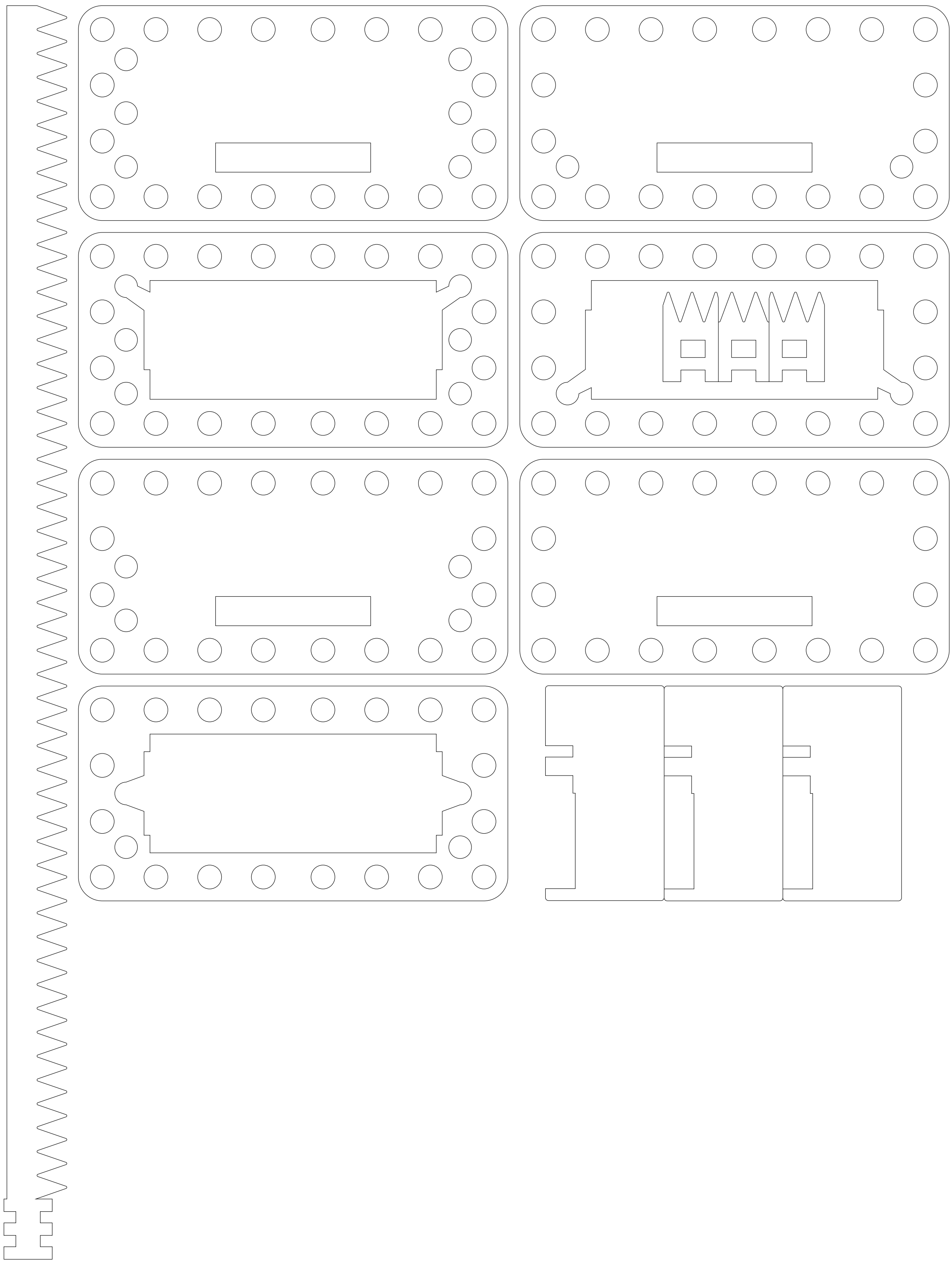


Figure 29: Drawings for laser-cutting the stepper motor.

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