

Effect of system parameters on target motion

P.J.D. (Peter-Jan) Vos

BSc Report

Committee:

Dr. S. Misra
M. Abayazid, MSc
Dr. H.K. Hemmes

January 2013

Report nr. 003RAM2013
Robotics and Mechatronics
EE-Math-CS
University of Twente
P.O. Box 217
7500 AE Enschede
The Netherlands

CONTENTS

I	Introduction	1
II	Related work	1
III	Methods	3
III-A	Experimental setup	3
III-B	Target tracking algorithm	4
III-C	Target preparation	5
III-D	Steering experiment	5
IV	Discussion	6
IV-A	Common errors	6
IV-B	Effect of insertion speed on target motion	7
IV-C	Effect of target distance	7
IV-D	Effect of needle diameter	8
IV-E	Effect of bevel angle	9
IV-F	Effect of target size	9
IV-G	Effect of skin thickness	10
IV-H	Steering experiment	11
V	Conclusions and Recommendations	14
V-A	Conclusions	14
V-B	Recommendations	14
V-C	Acknowledgement	14
	References	15
VI	Appendix	16
VI-A	Matlab code	16
VI-A1	Main	16
VI-A2	Import	17
VI-A3	Processing	17
VI-A4	Measurement	17
VI-A5	Quickcheck	19
VI-A6	Plot	19
VI-A7	Roundup	19
VI-A8	Force Measurements	21
VI-B	Plots	24
VI-C	Table of results	29

Abstract

Breast cancer is the most common cancer, comprising 22.9% of all cancer cases in women. Early detection is of key importance for effective treatment. Small breast lesions are increasingly detected by medical imaging modalities. A biopsy of lesions is required to make a definitive diagnosis. During the biopsy, displacement of the target (lesion) occurs as the needle indents and punctures the skin layer and penetrates further into the breast soft tissue. The target motion makes it harder to reach the target. In this study, the effect of system parameters on target motion during flexible needle insertion is investigated in chicken breast.

Target motion is measured using a target tracking algorithm when a bevel-tipped needle is inserted into chicken breast tissue. Then the effects of different parameters on target motion in chicken breast are tested. The tested parameters include skin thickness, insertion velocity, insertion depth, bevel angle, target size and needle diameter. These will be investigated to improve the accuracy of the steering process.

The conducted experiments show that increasing target distance or insertion speed decreases the displacement of the target, while increasing the needle diameter or skin thickness increases the target displacement. Increasing the insertion speed from 1 mm/s by 400% decreases target movement by 37%, while increasing the speed a tenfold will decrease target movement by 86%. Doubling the needle diameter from 0.5 mm increases target movement four times. Adding a 0.6 mm skin layer will double target movement, while adding two skin layers will quadruple it. Increasing the target distance will slightly decrease target movement and doubling the target distance will lower the target movement by 10%. Increasing the distance by four times from 1 cm to 4 cm will halve the target displacement. Target displacement is unaffected by target size and bevel angle in the tested range. The main cause of errors in the experimental data is the inhomogeneous nature of the chicken breast. Another factor is the difference in elasticity between chicken breast samples. These effects account for the differences in magnitude of the displacement between the experiments, but do not influence the trends.

The study also shows that it is possible to steer towards a virtual target inside a biological tissue if the tissue is submerged in gelatine. The gelatine is required to allow a bevel-tipped needle to be steered. The results of this study can be used to improve target motion models and consequently needle steering accuracy.

I. INTRODUCTION

Breast cancer is the most common cancer, comprising 22.9% of all cancer cases in women [1]. Detection and diagnosis in an early stage of the development is important for effective treatment. After the lesions are detected, a biopsy needle is inserted in the breast tissue to extract a lesion sample for screening. Technical progress has provided clinicians with higher resolution ultrasound machines that are capable of finding smaller lesions. The drawback is that the needle placement during biopsy becomes increasingly more difficult due to the trend to more localized and less invasive therapy [2]. Human errors are introduced during these insertions when placing the needle, when the needle is deflected from its intended path or when the target moves during the procedure. The errors result in unnecessary trauma for the patient and additional punctures.

One way to minimize the risks is by using a robotically-steered needle with an asymmetrical tip. By rotating the needle tip, it is possible to guide the needle to reach the target and avoid obstacles, thereby improving targeting accuracy. A steered needle would eliminate most of the problems that arise during biopsy now. However, the lesion can still move during the procedure.

The aim of this study is to investigate the effect of system parameters on target movement during biopsy. A biological tissue, chicken breast, is used in the experiments. The effect of insertion speed, insertion distance, needle diameter, bevel angle, target size and skin thickness are tested.

The relations between these parameters and target movement can be used to improve the path planning for the robot-guided needle. Since it is possible to only detect either the needle tip or the target during the procedure it is useful to have this information beforehand.

All work that is seen in this thesis is made or written by me, Peter-Jan Vos, save for the code that is used to conduct the experiments. The c++ code is written by Guus Vrooijink and Momen Abayazid. All other work, including figures and Matlab code is made by me.

The report is organized as follows; an overview of the related work is given in section 2. Section 3 describes the method that is used for conducting the experiments. The following section, 4, presents the results of the experiments. In the last section, the discussions, conclusions and recommendations are given. Finally, an appendix is attached to present all the data that is not included in the thesis.

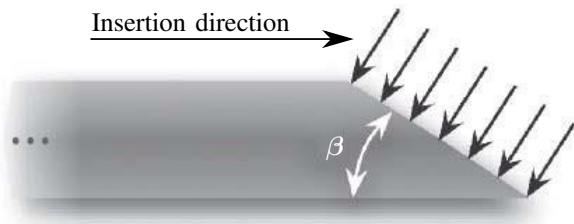


Figure 1: Asymmetric needle tip with bevel angle β [3]. Notice the asymmetric forces on the needle tip that force the needle to move in a downward motion.

II. RELATED WORK

The subject of using robotically steered flexible needles in phantom tissues is well studied. There are several papers that investigate target motion as an effect of needle parameters. In most of these studies an asymmetrical needle tip (bevel tip), Figure 2 is used for steering experiments. Using such a tip allows for greater control over the needle path since the tip asymmetry results in a resultant force normal to the insertion direction, Figure 2. The forces will bend the needle in a curved path and allow for steering. Steering occurs by rotating the needle about its longitudinal axis.

Research by Van Veen et al. has shown that bevel-tip needles will result in the most needle deflection when compared to other shapes such as a diamond or square shape [4]. More deflection results in more steering capabilities and hence as much deflection as possible is desired.

In this study the same needle as Van Veen et al. is used. The needle mimics a biopsy needle, which has a solid tip and consists of two parts: an inner and an outer layer. The inner layer slides out once the destination is reached to take a sample tissue, as can be seen in Figure 2. It is then retracted in the outer layer where it is protected against other surrounding tissues.

There are different ways to describe the curvature of the needle path. A popular way is to describe this curvature by a bicycle or unicycle path, this is done in a coordinate-free fashion (the kinematic needle equations). The equation depends on the front wheel angle and the wheel base which specify the constant κ . A second parameter, l_2 , determines the location along the bicycle that is attached to the needle tip n . For the unicycle model, the l_2 term is omitted. Alongside these parameters, the initial conditions are needed which are the entry point of the needle and the initial deflection angle of the needle.

For a 0.7 mm diameter nitinol cylinder with a bevel tip of 45° , Webster et al. found that the experimentally fit parameter for the unicycle model was $\kappa = 0.0468$ with a 95% confidence interval of ± 0.0001 [5]. The bicycle model fits the data better with a RMS error of 1.3 mm (vs 2.6 for the unicycle). For the model to work correctly it is important to have a simultaneous linear insertion during rotation, otherwise kinks will occur in the model. Model parameters were fit using experimental data.

Glozman et al used X-Ray to steer a needle in soft tissue (turkey breast muscle and beef liver) in real time using closed loop control [7]. The computer calculates the trajectory when



Figure 2: Biopsy needle in an extended position to grab a tissue sample [6].

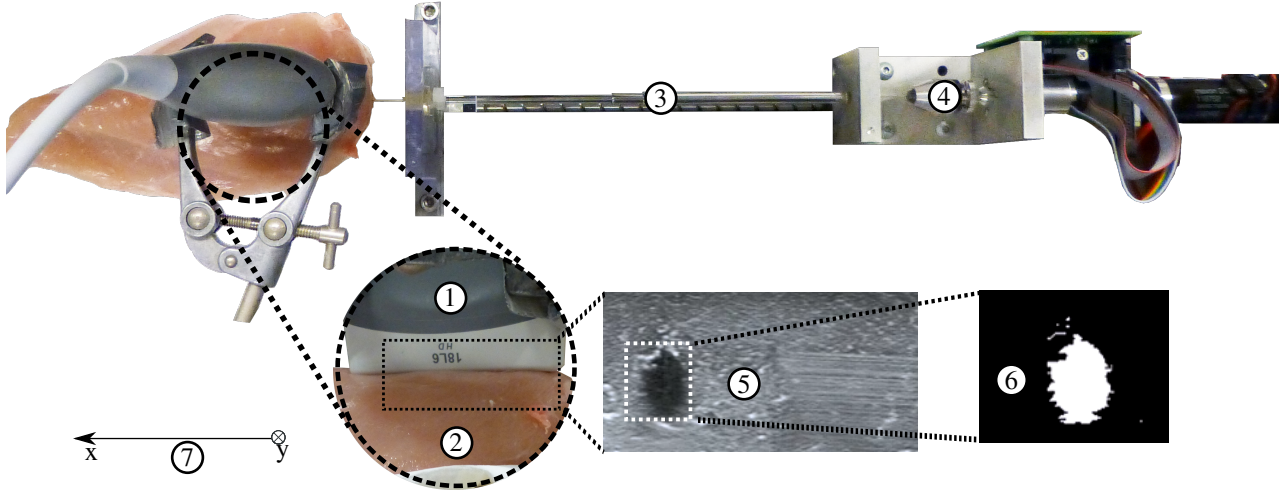


Figure 3: Needle insertion device. (1) Ultrasound probe (Siemens Acoustics S2000, probe 18L6HD), (2) chicken breast tissue, (3) anti-buckling telescope, (4) needle holder that is moved on a linear stage using a motor, (5) ultrasound image, (6) the image processing result and (7) the axis system. The y-direction is out of the paper.

soft-tissue phantom were estimated, and the effects of skin thickness on target motion and insertion force during needle insertion were investigated [12]. The elastic properties of the target, skin, and the surrounding tissue were estimated in vivo using an ultrasound-based approach which uses acoustic radiation force impulse imaging (ARFI) to determine the elastic moduli of tissue. This modulus can be calculated as $E = 2G(1 + \gamma)$ where $G = pv_s^2$.

The effect of skin thickness was calculated using FE calculations by Willson and all [13]. It was calculated that target displacement increases 54% when skin thickness increases from 1.0 mm to 2.0 mm during tissue indentation. Ultrasound images results show a 90.2% increase in insertion force when the skin thickness is increased from 0 mm to 2.5 mm. The target displacement increases 275.9% in the same situation. Normal breast skin thickness ranges from 0.8 mm to 3.0 mm.

To mimic the conditions of the woman's breast a study is conducted to its mechanical properties by Gefen et al [14]. The paper contains a table with all the tissue components of the breast and its elastic modulus and ultimate strength. The numbers that are most relevant for this thesis are the elastic modulus of the skin, that ranges between 200-3000 kPa; adipose tissue (body fat) ranging between 0.5-25 kPa and glandular tissue (the tissue under the body fat) with an elastic modulus between 7.5 and 66 kPa. Total skin thickness varies according to the site from 1 to 3 mm, with an elastic modulus ranging from 0.2 to 3 MPa depending on the age of the person. Also the forces upon the breast during activities were measured during standing (10N), walking (15N), running (50N) or jumping (60N).

The results from this study can be used to improve target motion models in biological tissue. Furthermore it can be useful to reduce target motion during needle insertion. The knowledge that was gained during this study can also be used to better tune the ultrasound machine for biological tissue, and to allow for steering experiments in biological tissue.

III. METHODS

The following section focuses on the experimental setup, the measurement method and data processing. First the experimental setup is described, then the experimental method is explained followed by the algorithm that is used during the experiments. The last subsection focuses on target preparation.

A. Experimental setup

To conduct the experiments that are presented in this study a special setup is made to insert the needles inside the chicken breast. The setup consist of a computer, a Siemens Acuson S2000 (Siemens, Munich, Germany) and a two degrees-of-freedom needle insertion device (NID), Figure 3 [4]. The NID consists of a Misumi translation (type LX3010) stage (MISUMI Group Inc. Tokyo, Japan) actuated with a Maxon motor (type RE25, with GP26B gearhead, transmission ratio 4.4:1). Rotational movement of the needle is accomplished by using a Maxon Motor (type ECGMax22) (MaxonMotor, Sachseln, Switzerland). Two Elmo Whistle 2.5/60 controllers (Elmo Motion Control Ltd, Petach-Tikva, Israel) are used to control the motors. Needle forces and torques are measured using a six-axis Nano17 force/torque sensor (ATI Industrial Automation, Apex, USA) mounted at the needle base. The needle insertion is recorded at 25 fps via an ultrasound machine using the 18L6HD probe. The needles resemble a flexible biopsy needle and are scoured into the right angle. The needles are made from nitinol, a nickel/titanium alloy that allows high flexibility.

All experiments are done in a fresh chicken breast tissue. Default experiment conditions are a silicone target of 4 mm diameter, the size of a clinically significant tumor [10]. The insertion speed is set to 4 mm/s and the position of the target is fixed at 40 mm from the insertion point. This position is chosen because the chicken breast tissue is usually the thickest around this region, resulting in a better ultrasound image and it gives more space to vary the insertion point. The needle used in the experiments is a ϕ 1 mm diameter needle with

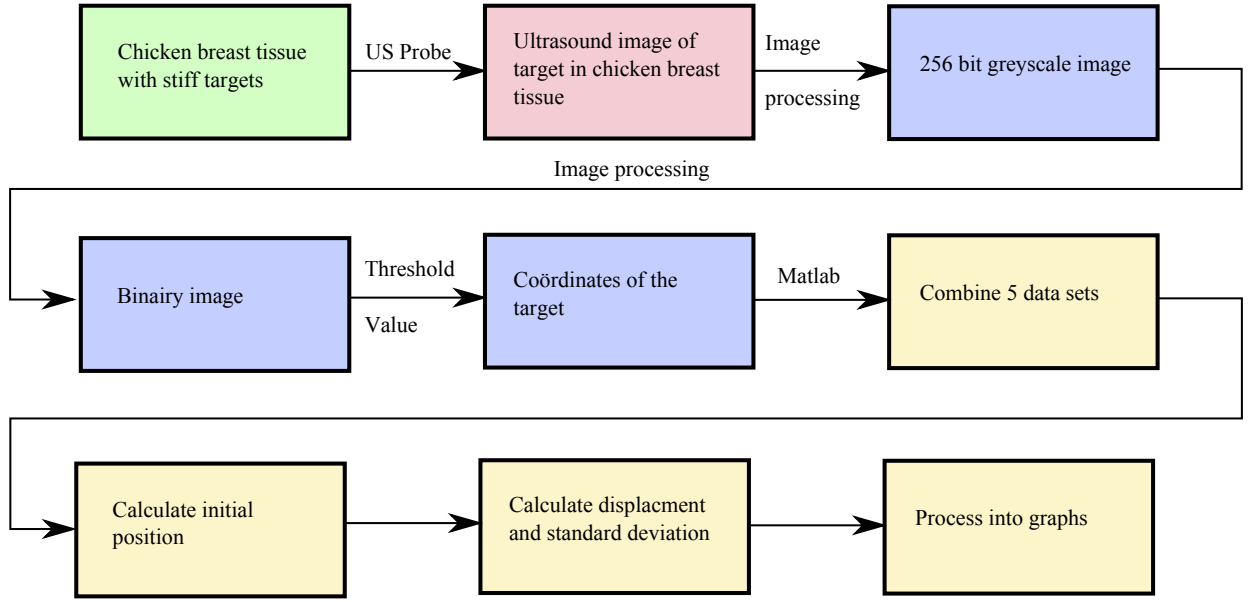


Figure 4: Block diagram of the data acquisition procedure. Green represents the chicken breast tissue, red marks the ultrasound, blue represents the algorithm on the computer and yellow marks the Matlab code.

a 30° bevel angle. An overview of all the experiments is presented in Table I.

Before each experiment the needle insertion device is pushed all the way back to ensure the same initial conditions. The needle is placed with the tip directed downward to ensure the needle makes a downward path since the needle does not rotate during insertion. A new, fresh chicken breast tissue is used for every parameter experiment since the differences between the chicken breast tissues are substantial. The chicken breast tissue is fixed to the stage using clamps to prevent the chicken breast tissue from moving during the insertion. The insertion distance is set to a distance where the needle hits the target but does not penetrate it, as shown in Figure 5b. Every experiment is done at least five times at a set parameter. The data recording is manually stopped two seconds after the experiment is finished. Because of the inhomogeneous nature of the chicken breast tissue each recorded video is visually inspected after the experiment to check for errors. After each measurement the chicken breast tissue is moved slightly to allow the needle to find a new path inside the chicken breast tissue. When one parameter is fully tested, a different location is picked for the insertion.

For the skin thickness experiment an artificial skin, Dekatest

PU 0,08 (Melab, leonberg, Germany), with 0.8 mm thickness is used and attached to the chicken breast tissue. The skin is first attached to the chicken breast tissue by using silicon glue, which yields better ultrasound images because it removes the air bubbles between the chicken breast tissue and the skin layer.

The skin layer is fixed to the chicken breast tissue by using paper-clips as barbs to attach the skin to the chicken breast tissue. For the 1.6 mm skin, an additional layer is glued on the first layer. Thicker skin was tested, but the experiments were unsuccessful. The chicken breast tissue moved too much, the needle started to buckle and could hardly penetrate through the skin layers. Therefore the results show only these two skin layers.

B. Target tracking algorithm

Target tracking uses an algorithm that grabs the image frames from the ultrasound machine and applies image processing in a selected region of interest (ROI). The image processing converts the grabbed frame into a 256 grey-scale image. The sections of the image that are above the threshold value are transformed to black, and everything below it white. The image is then inverted so that the target is the white area of the image, and the chicken breast tissue the black area. The target is tracked by determining the center of mass of the white area in real time, 25 times per second. The coordinates of the center spot are then saved into a comma separated file. The original images from the ultrasound and the image processed frames are saved so that the results can easily be rechecked for experimental errors.

The ROI, insertion distance and insertion speed must be specified in the code. The insertion distance ensures that the needle stops at the same spot each time and the ROI prevents other dark spots in the image from being tracked. On the ultrasound machine itself the parameters are tuned to obtain a

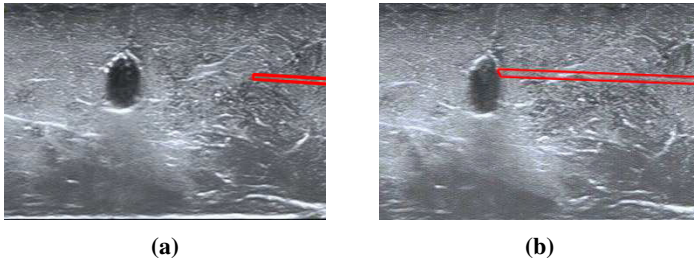


Figure 5: Screenshots of the ultrasound images during the needle insertion. The needle is in the red region. The test is stopped when the needle hits the target as in b. (a) Screenshot when the needle is on its way to the target. (b) Screenshot when the needle is at the target.

high contrast between the target and the surrounding tissue.

The obtained data is analysed in Matlab (v2012b, Mathworks Inc., Natick, USA). The data of the five measurements is combined into a matrix. The mean value of every element in the matrix is taken at each time instance. The mean value of the first 20 measurements are calculated to determine the initial position of the target in the chicken breast tissue. This initial position is then subtracted from the mean matrix to determine the displacement. The displacement in pixels is then converted to a displacement in millimetres. After this step the standard deviation is calculated and the data is processed and presented as curves. An overview of this procedure can be found in the block diagram, Figure 4.

C. Target preparation

The effect of stabbing and slicing in the chicken breast tissue is investigated, placing the target in the tissue should leave no visible marks in ultrasound images. The effect of penetrating a chicken breast tissue is negligible as can be seen in Figure 6, so the target can be inserted using a knife. For the target material a silicon is used. The silicon is made using two different gel components, Wacker SilGel 612A (Wacker Chemie AD, Germany) and Wacker SilGel 612B. This gel is a silicone that vulcanizes at room temperature to a very soft silicone gel [15]. The components are mixed in a 1.5:1 ratio (A to B component) and then cast into a mold. The mold is made in SolidWorks (v2012, SolidWorks Corp, Waltham, USA), Figure 7, and is printed using a 3D-printer. Two molds are used, one for the 2 mm and 4 mm targets, and one for the 3 mm and 6 mm targets.

To simulate the behaviour of a tumor, the target has to meet some requirements. The stiffness of infiltrating ductal carcinomas, the most tumor type cancer in women [16], is very high compared to the surrounding tissue [17]. A test

was conducted to test the target's stiffness. In the test, the target is compressed while the normal force and the gap are measured. The test is done using different speeds to test the speed dependency of the E-modulus (or Young's modulus) of the target. The E-modulus can be calculated using:

$$E = \frac{\sigma}{\epsilon} \quad \text{where} \quad (1a)$$

$$\sigma = \frac{F_n}{A} \quad (1b)$$

$$\epsilon = \frac{Gap - L}{L} \quad (1c)$$

In Equation 1a, E is the E-modulus, σ is the stress in Pascals and ϵ is the dimensionless strain. In Equation 1b, F_n is the normal force in Newton experienced by the compression machine, and A is the surface of the target in square meters. In Equation 1c, the Gap is the initial position of the compression machine and L is the length of the target that varies during the compression.

Due to the deformation of the target, the surface A changes during the compression. The true E-Modulus should be calculated using:

$$A = \frac{A_0 * L}{Gap} \quad (2a)$$

$$\epsilon = \ln \frac{Gap}{L} \quad (2b)$$

Where A_0 is the initial surface in Equation 2a and all other equations are the same as in Equation 1. The results of these calculations can be found in Table II.

D. Steering experiment

The steering experiment uses another code to steer the needle. In order to give the needle enough space to travel along the projected path the chicken is submerged in gelatine. To submerge the chicken in gelatine a thin layer of gelatine (0.5 mm) is casted inside the mold to stiffen, after 15 minutes in the fridge the gelatine is hard enough to place the chicken on the layer. The remaining gelatine is then poured over the chicken and put back in the fridge to stiffen. The gelatine should not be warmer than 45°C to prevent the chicken from cooking. In the experiment the coordinates of the target are entered in the code and the needle is steered towards this targets. To find the coordinates of the target a needle is inserted next to the target to find the right x-position and to get an ultrasound image of the reference needle and the target. The coordinates of the target can then be calculated using the ultrasound image and the ratio between pixels and millimetres. Steering is accomplished in the gelatine by rotating the needle.

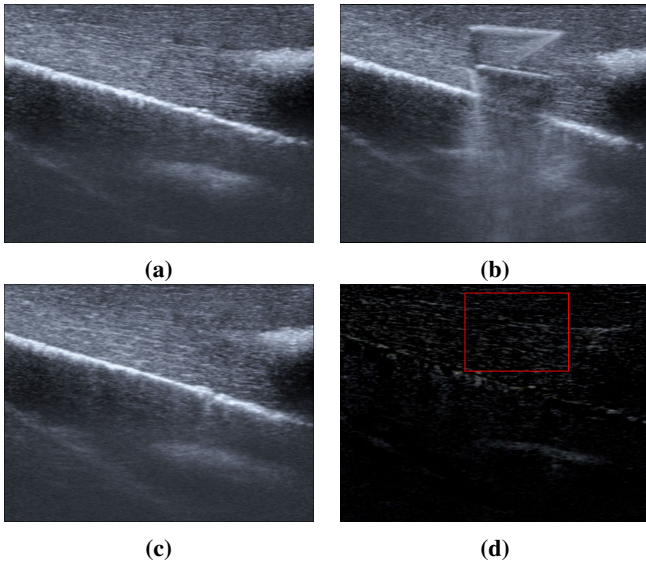


Figure 6: Ultrasound images of the chicken breast tissue. (a) Ultrasound image of a chicken breast tissue before stabbing. (b) Ultrasound image of a chicken breast tissue while penetrating it with a kitchen knife. (c) Ultrasound image of a chicken breast tissue after stabbing. Subtracted image of (6a) and (6c). The red region is the sliced region. The red square in (d) indicates the region where the penetration occurred. Notice the absence of visible damages.

Table II: Youngs Modulus of the target.

Speed [mm/s]	E-Modulus	True E-Modulus
0,01	$6,85 * 10^4$	$5,96 * 10^4$
0,1	$7,81 * 10^4$	$6,79 * 10^4$
1	$1,10 * 10^5$	$9,64 * 10^4$

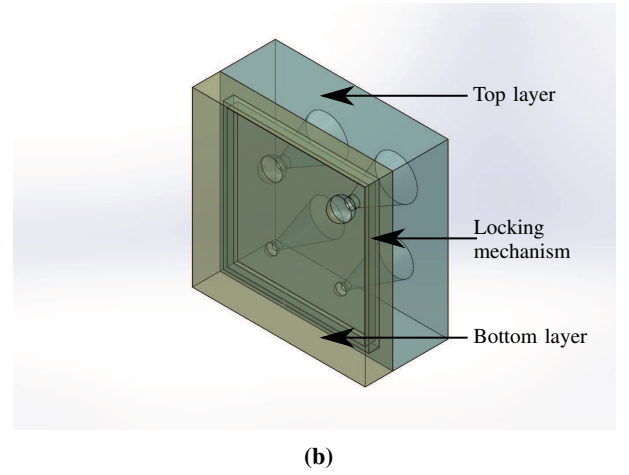
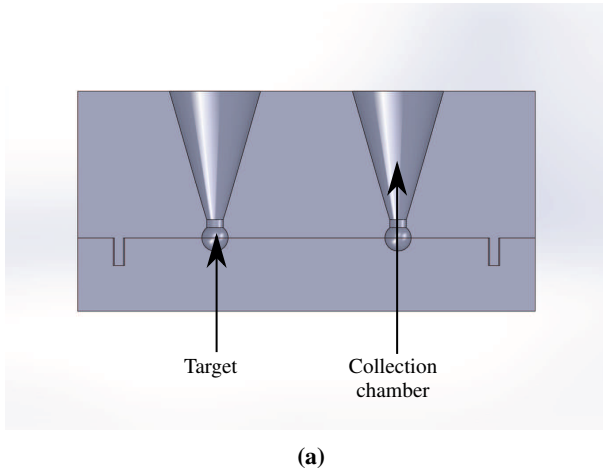


Figure 7: The SolidWorks models of the mold that is used to create the targets. (a) Cross-section of the mold. (b) Isometric view of the mold.

The needle should be placed in the NID with the bottom part of the bevel tip (the large section) faced towards the user. After the parameters are set in the code, the gain sliders on the ultrasound machine are pushed back to make the needle visible inside the chicken breast tissue. If this step is skipped, the needle will not show up clearly in the chicken breast tissue due to other bright spots inside the chicken tissue.

Optionally a second ultrasound probe can be added to the set-up. One probe is used for needle tracking, while the other probe tracks the target. Such a set-up is tried in this study, but the necessary code was too unstable to perform useful experiments.

IV. DISCUSSION

The current section shows some of the measurements conducted during this assignment. An overview of all the conducted experiments are presented in Table I, whereas the results of these experiments can be found in Table V.

A. Common errors

The contrast of the images should be high such that the difference between the target and the chicken breast tissue is as big as possible. A higher contrast increases the size and density of the target, improving the tracking. The target in these experiments shows up black in the ultrasound images,

while air bubbles inside the target show up white. The chicken tissue is white to gray. The tissue can also contain black spots due to insufficient contact between the transducer and the tissue or holes in the chicken breast. These factors result in a processed image that is not an actual representation of the target in the sense that it has another shape and contains holes. The black spots affect the tracking algorithm since the centre of mass is off.

Sometimes the target gets hit off centre, causing more displacement in the y-direction, Figure 8, than a direct hit in the middle would cause. The angle of approach does not effect movement in x-direction (the direction of insertion). The movement in y-direction is almost negligible compared to the movement in x-direction, so an off centre hit does not greatly effect the outcome data. The measurements where the needle moves over the target are discarded. The quality of the target becomes worse over time since it sometimes gets punctured accidentally, creating new air holes.

The experiments are conducted in a matter such that the needle hits the target, but not punctures it. This way, the actual movement due to the system parameters can be determined rather than measuring the effect of a needle puncturing the target. In a couple of measurements the needle punctures the target and these measurements are discarded.

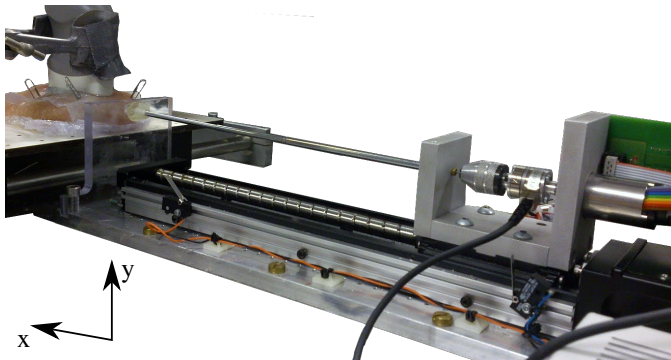


Figure 8: The x- and y-directions depicted on the set-up. The x-direction is along the insertion axis.



Figure 9: Deformation of the ultrasound images during the experiment caused by air in the target, non-conducting chicken breast tissue or needle placement above the target.

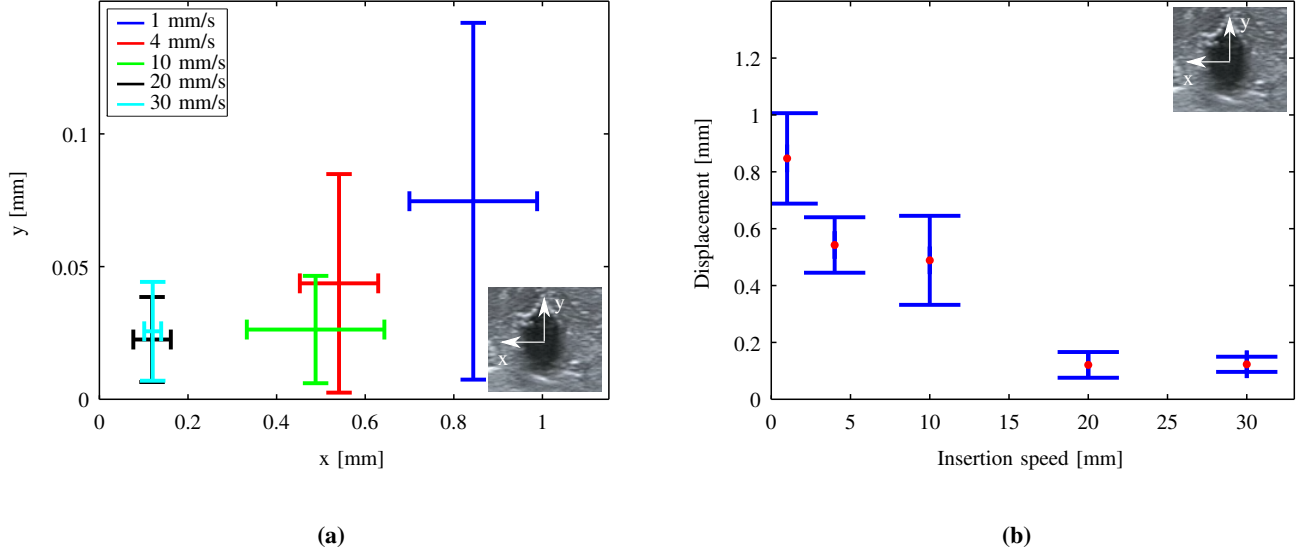


Figure 10: Effect of insertion speed on target motion. (a) Target displacement along x- and y-axes. (b) Overall (root mean square) displacement of the target. Experiment is conducted with a 30° bevel angle, ϕ 1 mm needle and a 4 mm target located at 40 mm insertion depth in the chicken breast tissue. The errorbars display the standard deviation.

B. Effect of insertion speed on target motion

In these sets of experiments the image contrast was high, resulting in a suitable image for target tracking. At 1 mm/s, Figure 21a, one can clearly see the needle making its way through the tissue. The slow speed causes a lot of displacement in the surrounding tissue. The tissue that is behind the needle barely relaxes since the needle drags the tissue along with it. The tissue in front of the needle tip is under constant pressure due to the low speed and the tissue that is being dragged along by the needle tip. The needle hits the target around the centre region.

The path that the 1 mm/s experiment made in the chicken can be seen on the ultrasound images. The chicken was rotated to find a new, scar-free path for the new experiments. The 'scarred' path has not been seen in other experiments that were conducted and seems typical for this slow speed. Increasing the speed to 4 mm/s, Figure 21b, causes the pressure to decline. While the tissue surrounding the needle still moves, it is being pushed away rather than dragged along.

The tissue is pushed away less prominently in the 10 mm/s, Figure 21c. The needle hits the target at or above the centre, although the region the target is hit is smaller than at the 4 mm/s case. The size of this impact region is further reduced if the insertion speed is increased to 20 mm/s, Figure 21d. The needle goes along the same path every try, resulting in a small error. There is no longer any clear movement of the skin or any sign of pressure or stress build up around the needle. The same observations apply for 30 mm/s experiment (Figure 21e). In the results this can also be seen, the displacement of the 20 mm/s and 30 mm/s experiments are the same. There seems to be a certain speed at which the displacement no longer decreases, which can be seen in Figure 10a. In the figure there are three regions: One region where the insertion speed is low and causes a more than 0.5 mm displacement (blue line); one where the insertion speed is high and the needle has a very

constant path with little displacement (0.10 mm, black and cyan) and a region between these extremes (red and green).

C. Effect of target distance

The target is close to the edge of the chicken in the 1 cm experiment, Figure 22a. The region where the insertion can be seen is limited, which may cause some out-of-plane movement to go unnoticed. The target is hit at the centre and the contrast of the images is high. Increasing the insertion distance to 2 cm, Figure 22b, makes the out-of-plane movement better visible. The needle hits the target at the centre, which can be seen in Figure 11a by the low displacement and deviation in the y-direction.

Increasing the target distance to 3 cm results in Figure 22c. In this case the needle occasionally hits the target in the upper-to-centre section of the target, causing more displacement in the y-directions. The deviation in the x-direction is due to the stiffer chicken breast tissue in some sections after the 2 cm point. The increasing stiffness of the chicken causes more displacement of the target. The whole chicken breast tissue moves along the needle as the needles hits this stiff part. The nature of this stiff parts is hard to find, but it is expected that tendons and hardened tissue cause these kinds of behaviour.

Increasing the insertion distance to 4 cm still shows the effect, but in a lesser manner. The added centimetre causes the tissue to somewhat relax as can be seen in Figure 22d. The difference between the measurements is smaller compared to the 3 cm case, where the displacement is directly related to the stiff tissue. The needle hits the target on the upper part of the target this time, causing more displacement in y-direction compared to the 3 cm experiment.

At 5 cm insertion distance the stiff tissue layers no longer causes an effect on the x-direction displacement, as can be seen in Figure 22e. The needle constantly hits the target closer to the centre which can also be seen in Figure 11a.

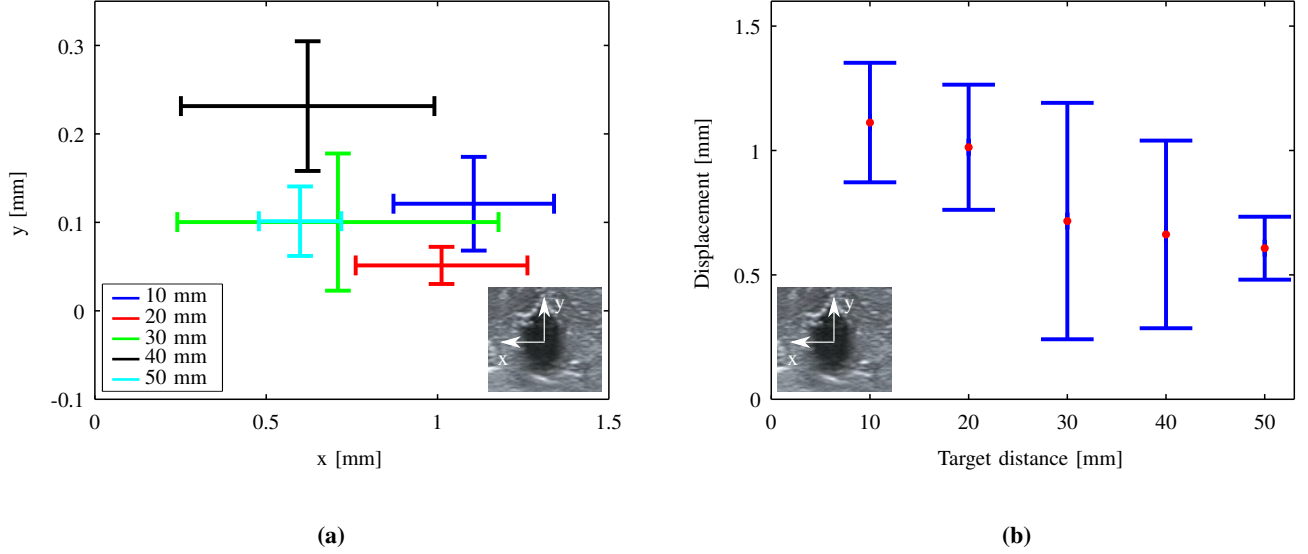


Figure 11: Effect of target distance on target motion. (a) Target displacement along x- and y-axes. (b) Overall (root mean square) displacement of the target. Experiment is conducted with a 30° bevel angle, ϕ 1 mm needle at 4 mm/s insertion speed and a 4 mm target in the chicken breast tissue. The errorbars display the standard deviation.

D. Effect of needle diameter

The plots displayed in Figure 12 show how the target displacement changes with varying needle diameters. For the 0.5 mm needle diameter, Figure 23a, the needle hits the target in the middle. The ultrasound view of the small needle is sometimes obstructed by chicken breast tissue, which may cause out of plane movement to go unnoticed in this case.

For the 0.75 mm needle diameter, Figure 23b, the needle hits the target above its centre point. The contrast in the ultrasound images is lower than in the previous experiment, causing a greater error in the tracking algorithm that can be seen in the ROI images in Figure 9. The centre of Figure 9a is shifted compared to the centre of Figure 9b. The deformation of

the target during the insertion causes part of the error. This can also be seen in the errorbar of Figure 23b compared to Figure 23a.

The 1 mm needle in Figure 23c has a better contrast. The needle hits the target at the centre, causing little displacement in the y-direction. The needle stops right before puncturing the target. The ROI images do not show any abnormalities, although the target seems to lose some mass over time. Target size decreases due to the added air that shows up white in the ultrasound images

The 1.25 mm needle, Figure 23d, hits the target above its centre. The properties of the chicken breast are changing over time and some of the stiffer segments get moved along by

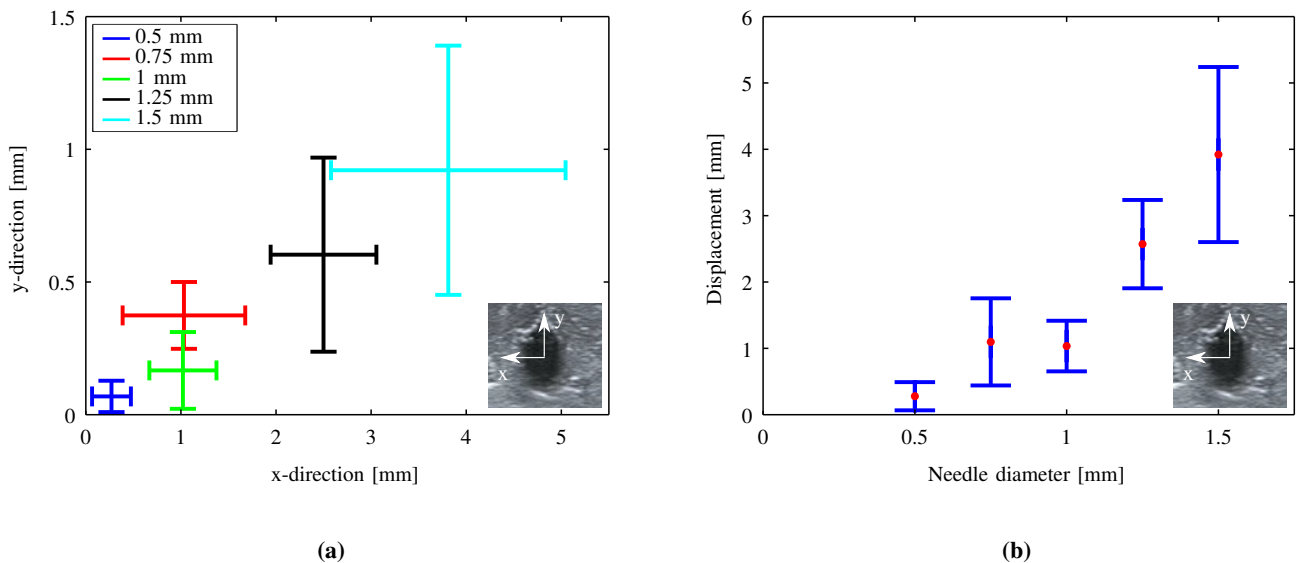


Figure 12: Effect of needle diameter on target motion. (a) Target displacement along x- and y-axes. (b) Overall (root mean square) displacement of the target. Experiment is conducted with a 30° bevel angle at 4 mm/s insertion speed and a 4 mm target located at 40 mm insertion depth in the chicken breast tissue

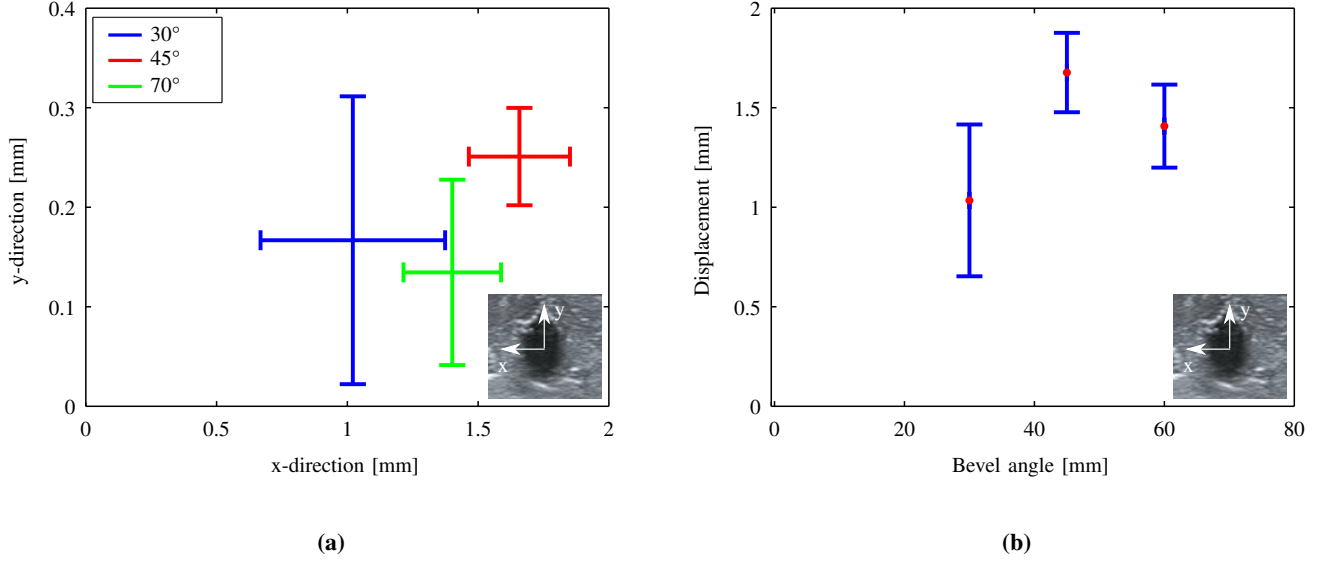


Figure 13: Effect of bevel angle on target motion. (a) Target displacement along x- and y-axes. (b) Overall (root mean square) displacement of the target. Experiment is conducted with a ϕ 1 mm needle at 4 mm/s insertion speed and a 4 mm target located at 40 mm insertion depth in the chicken breast tissue. The errorbars display the standard deviation.

the needle. The tissue covers the target from time to time, casting a shadow over the target. The shadow causes the code to sometimes misplace the target for a short period.

The obstructing of the target continues to be a problem in the experiment for the 1.5 mm needle in Figure 23e. The needle hits the targets above its middle point in most of the measurements.

Figure 12b shows that with increasing needle diameter target displacement increases. The trend is visible in both x- and y-direction, as can be seen in Figure 12a. The data for the 0.75 mm and 1 mm needle diameter show the same displacement in x-direction, and a difference in the y-direction. The difference in the y-direction can be explained by the manner the needle hits the target: for the 0.75 mm needle case the target is hit above the centre, instead of at the centre in the case of a 1 mm needle. The fact that the displacement in x-direction is almost the same may be due to the deviation, which is greater for the 0.75 mm case. The greater deviation may be due to the ultrasound images, the images were sharper for the 1 mm needle.

E. Effect of bevel angle

The ultrasound images for the 30° bevel angle, Figure 20a, are clear with a high contrast. The needle hits the target in the centre and above that. The insertion contains no obstacles along the way. There seems to be some overlap from non-conducting chicken breast tissue that stuck to the needle with the target and casts an acoustic shadow under it. The shadow may cause some added displacement to the x-direction. The effect of the overlap is minimal and does not happen every time. The 45° and 60° bevel angle also have this overlap.

Figure 20b shows the displacement for the 45° bevel angle. The needle hits the target on the top side of the target, causing some displacement in the y-direction but little deviation. During the insertion some additional indentions while

puncturing the chicken are noted, causing a slight bump in the displacement, as can be seen in the data. Although this displacement is not much and the target relaxes after the needle punctured the chicken this may cause some displacement that would not be there otherwise.

The additional displacement is also seen in Figure 20c. The needle still hits the target above the centre. The ultrasound image that is processed is noisier compared to the previous cases causing more variance in the results.

As can be seen in Figure 13b, the bevel angle does not affect target displacement in the tested range. The overview of the individual displacements in Figure 13a shows that displacements in the x- and y-direction are in the same region.

F. Effect of target size

The ultrasound image of the 3 mm target in Figure 24a are not as clear as for the bigger targets, due to the silicon gel that is used. It can not clot together as good as a bigger target does. The problem is absent in the 6 mm target, and still somewhat visible in the 4 mm target.

The 3 mm target is hit around the centre spot as good as possible. The small size of the target and the variation in the needle path cause for a bigger difference in y-displacement than for the bigger targets. The difficulties in the clotting cause bubbles in the target, resulting in a spotted tracking image that results in some additional errors.

These problems are less on the 4 mm target. The needle seems to hits the target around the centre, and the ultrasound image is clearer.

All problems are absent at the 6 mm target. The target gets hit around the centre every time and the contrast of the ultrasound image is high, creating a solid tracking image. However, the size and solidness of the target cause some form of acoustic shadow, making the target more elliptical than its actual circular shape. The shape of the target does

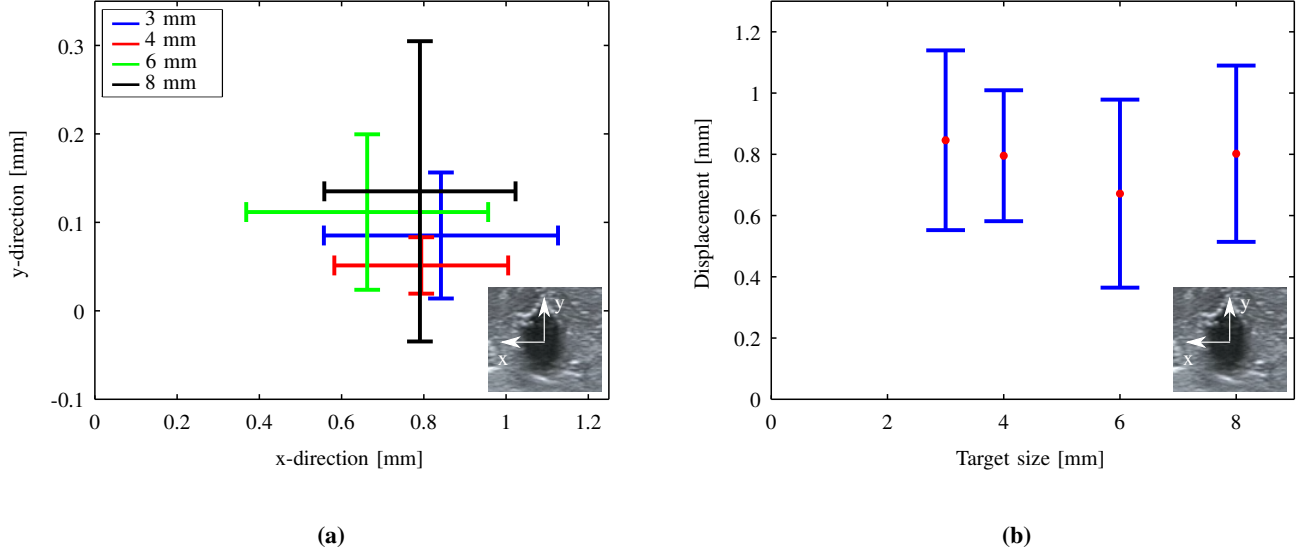


Figure 14: Effect of target size on target motion. (a) Target displacement along x- and y-axes. (b) Overall (root mean square) displacement of the target. Experiment is conducted with a 30° bevel angle, ϕ 1 mm needle at 4 mm/s insertion speed and a target located at 40 mm insertion depth in the chicken breast tissue. The errorbars display the standard deviation.

not affect the calculations since the displacement is calculated based upon the position of the initial centre point.

The trend is also seen for the 8 mm target. A very clear image that is distorted but has a very sharp image to track. Also, because the target is now bigger, almost all experiments hit the target very near the centre.

As can be seen in Figure 14b, the target size does not impact target displacement. Save for the 3 mm target, all targets are within the same region, Figure 14a. The fact that the 3 mm target is outside this region is probably due to the reasons mentioned before. The visibility of the small target is worse, resulting in larger tracking errors (also seen in the figure).

If the tracking does not work properly, the displacement is always bigger due to the shifting centre of the tracking mass. The shift in the centre is due to the loss of 'mass' from the target on one side and this causes the centre to go to the left, resulting in a larger displacement.

G. Effect of skin thickness

In the case that there is no artificial skin layer, the needle hits the target at or above the centre. The target does not change during the insertion and the ultrasound images are sharp, so the tracking error due to the image processing is low.

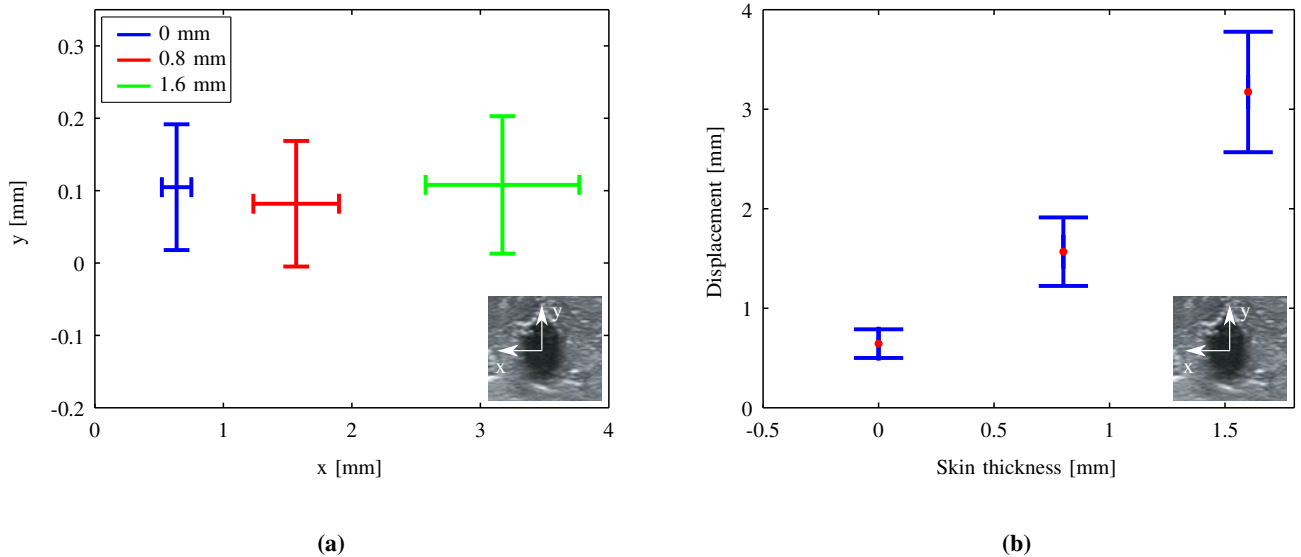


Figure 15: Effect of skin thickness on target motion. (a) Target displacement along x- and y-axes. (b) Overall (root mean square) displacement of the target. Experiment is conducted with a 30° bevel angle, ϕ 1 mm needle at 4 mm/s insertion speed and a 4 mm target located at 40 mm insertion depth in the chicken breast tissue. The errorbars display the standard deviation.

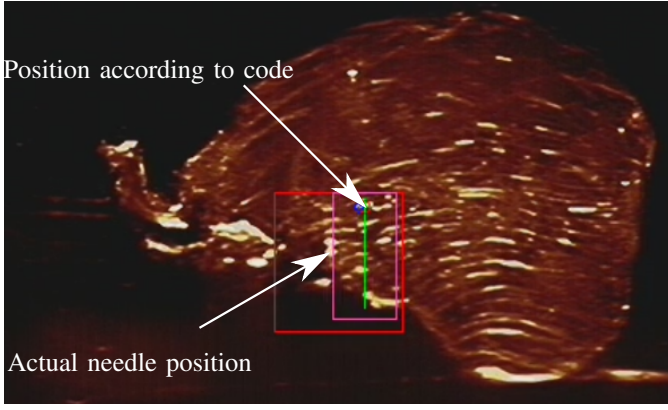


Figure 16: Difference between the actual position of the needle and the position of the needle as perceived by the code. The bright white spots is inhomogeneous chicken tissue.

In the case where there is one artificial skin layer, this layer causes a lot of indentation. The target gets compressed and moves in the x-direction as an effect of this skin layer, resulting in a shift of the x-displacement. After the needle punctures the skin (marked II in the graphs), the target quickly returns to its original position and the chicken breast tissue relaxes. The image processing results give a sharp image due to the high contrast between the target and the chicken in this experiment. For two layers, the target still recovers quickly from this deformation, the chicken breast tissue is more indented however and no longer relaxes after penetration.

In the force data in Figure 18 a distinction can be made between no skin layer and a skin layer. The force increases or stays constant when there is no skin layer (Figure 25a), whereas adding a skin layer causes the force to build up first before penetrating (marked I), and to relax afterwards (marked II). The same trend can be seen in the displacement of the target in both Figure 25b and Figure 25c. The force during the insertion also increases greatly when going from 0.8 mm skin thickness to 1.6 mm skin thickness, while adding a single layer of skin does not seem to have a substantial effect on the magnitude of the force. Increasing the skin thickness greatly increases the displacement of the target, Figure 15b. Figure 15a shows that this displacement solely comes from the x-direction and that adding the skin to the chicken has no effect on the displacement in y-direction.

H. Steering experiment

Needle tracking is tested first, since this is a requirement for needle steering to work. Needle tracking is done throughout the experiment, but is unreliable once the needle enters the chicken. It is seen in Figure 16 that due to the structure of the chicken the fibres or tendons of the chicken tissue can

Table III: Results of steering experiment to (80, 0, 0) (x, y, z). Position value is the final position of the needle tip at x=80 and position n = error n . The standard deviation (STD) is given in the bottom rule.

Experiment:	# 1	# 2	# 3	# 4	mean
Error y	0.07	0.12	0.41	0.24	0.21
Error z	0.04	0.01	0.18	-0.52	0.19
STD y					0.15
STD z					0.31

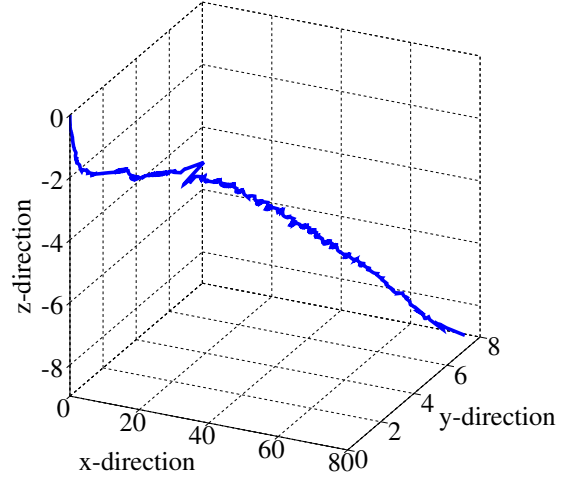


Figure 17: 3D representation of the path followed by the needle of experiment # 1 (Table IV) towards the (80, 8, -8) (x,y,z) coordinate.

be misinterpreted for the needle by the code. The problem can be minimized by decreasing the gain after starting the experiment. It is however not yet possible to steer the needle in the chicken, since the chicken has another curvature as the gelatine. Because of this reason and the challenging needle tracking in the chicken tissue, steering is limited to the gelatine.

The first experiments is to steer towards a real target. Steering towards a real target proved challenging, multiple calibration insertions are needed in the neighbourhood of the target area. Each insertion damages the gelatine which leaves a visible mark on the ultrasound images. The scarred gelatine can be misinterpreted by the needle tracking code for a needle if it loses the needle. Due to this reason, needle steering towards a real target was unsuccessful.

Table III shows the results of the experiment that steer the needle towards the (80, 0, 0) target. The last 10 mm to 20 mm (depending on the insertion position) of these steering experiments are inside the chicken breast tissue. The results show that it is possible to steer a bevel-tipped needle in a straight line with high precision. If a typical 4 mm target would be at the (80, 0, 0) position the needle would hit the target in every experiment since the maximal deviation would be $(80, \pm 2, \pm 2)$.

Table IV displays the results of steering towards (80, 8, -8). The errors in this case are bigger than in the previous case, but all experiments stay within the limit of $(80, 8 \pm 2, -8 \pm 2)$. A 3D representation of the needle path of the the first experiment of Table IV is given in Figure 17.

Table IV: Results of steering experiment to (80, 8, -8) (x, y, z). Position value is the final position of the needle tip at x=80. The standard deviation (STD) is given in the bottom rule.

Experiment:	# 1	# 2	# 3	# 4	mean
Y-position	7.08	6.53	8.02	6.2	6.95
Error y	-0.92	-1.47	0.02	-1.80	1.05
Z-position	-8.53	-6.46	-6.72	-6.72	6.84
Error z	-0.53	1.54	1.28	1.28	1.16
STD y					0.80
STD z					0.96

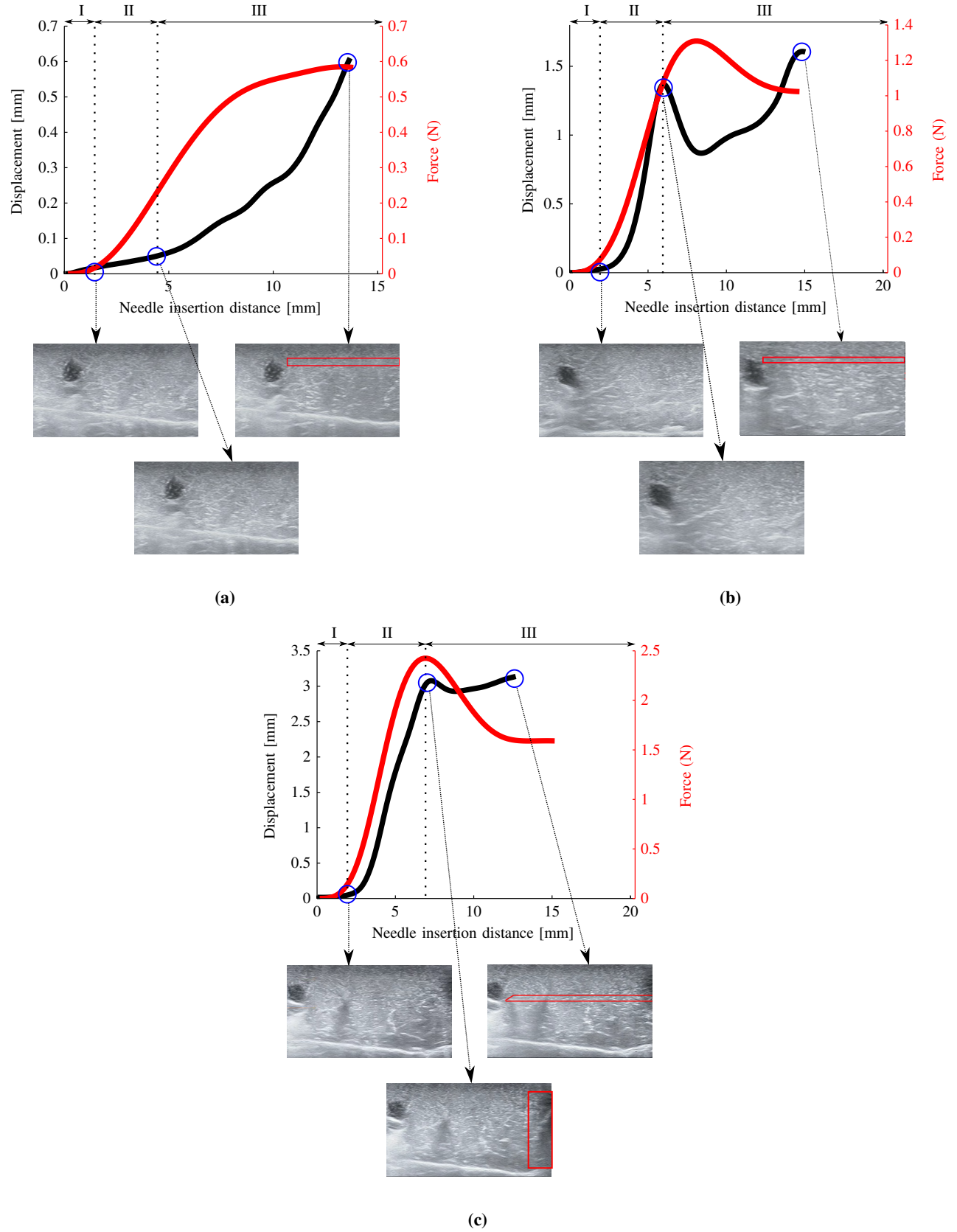


Figure 18: Plot of the mean force and displacement data of the effect of skin thickness on target motion. Force recorded along the insertions axis are in green. The overall root mean square displacement is in black. Stage I is before puncturing the chicken breast tissue, II is when the needle tip is at the artificial skin layer and tries to puncture, III is when the needle punctured the skin layer. (a) No skin layer, (b) 0.8 mm skin layer, (c) 1.6 mm skin layer.

V. CONCLUSIONS AND RECOMMENDATIONS

A. Conclusions

The conducted experiments show that increasing target distance or insertion speed decreases the displacement of the target. Increasing the needle diameter or skin thickness increases the target displacement, corresponding to literature [8] [18]. Target displacement is unaffected by target size and needle angle in the tested range. The main cause of the errors in the experimental data is the inhomogeneous nature of the chicken breast and the variance in elasticity between chicken tissues. These effects cause variation between the experiments. While trends are the same across chicken tissues, the magnitude of the displacements can vary. The study also showed that it possible to steer towards a target, provided that the chicken is submerged in gelatine to allow the needle to steer. The results of this study can be used to improve target motion models and hence improve steering and pre-operational path planning.

B. Recommendations

Some experiments give cause to conduct some additional experiments. For example, the absence of a trend with the needle experiment. One can expect some variance of displacement in the y-direction because of the different paths the needles follows with changing bevel angle. More variance in x-direction can also be expected due to the blunt needle tip which may cause some additional indentation. The fact that this does not happen may be due to the small needle diameter that was used for this experiment. An experiment with a thicker needle would probably give other results.

Adding a second probe to track both the needle and the target, as well as out of plane displacement of the target should be a useful case. Such a set-up was tested during this thesis and should be possible but proved unsuccessful in my attempts due to unstable code.

A useful contribution to the needle steering experiment would be to add a manual probe control to the code. Ideally, one would be able to guide the ultrasound probe to the target location using the arrow keys on the keyboard. Once the probe arrives at the target location, the target can then be selected using the mouse. Based on the position from the probe (which can be read using the encoders) and the selected region on the screen the target coordinates can be determined. The height coordinate of the target can be retrieved using the data from the ultrasound image, since the probe measurement depth is given and a reference length is displayed on the screen. Adding this feature would make the human error that is introduced in the steering experiment much lower and would also increase the effectiveness since now a couple of try-out runs must be conducted first, damaging the gelatine and the chicken tissue.

As for the tracking code, an idea is to make the threshold value not a hard limit. Whereas the threshold value is a hard step function now, one could make some kind of ramp function. This could be achieved by the following example: Imagine the threshold value is set at 58 in the usual case. Now we want to make a slope that runs from e.g. 50 to 66 (so the range is 16, with 58 as medium value). To do this, you'll take

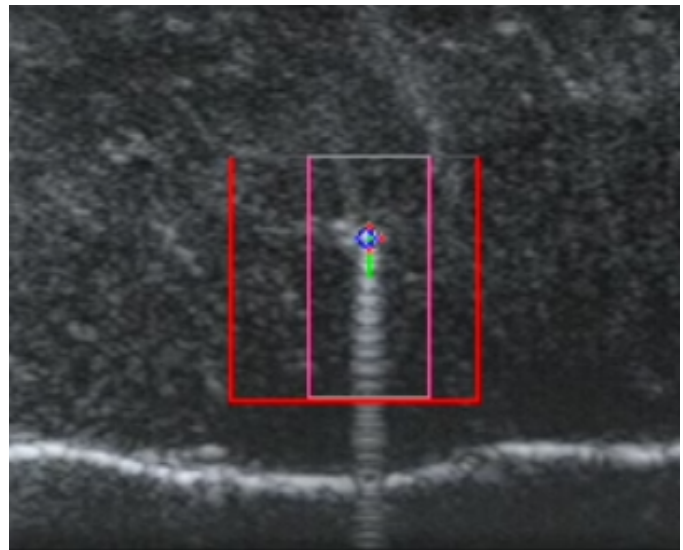


Figure 19: Ultrasound image in pork. Notice the absence of disruptions in the tissue.

the initial value, subtract 50 from this value hereby lowering the otherwise linear line by 50 and then multiply this line by $(256/66)=3,86$ so that it runs into the threshold value (because of the 256 different grey scale colors). Now everything at or above this value should be counted as 1, everything below 50 as 0 and everything in between should be counted as a number between 0 and 1 (linear). In that case the sections of the target that are now blacked out because they are not black enough would be added to the target. In combination with the erode and dilute function this could make the tracking code better in tracking the target and determine the centre of the target with more precision and less noise.

Doing all these experiments in chicken is quite cumbersome and is also the cause of some strange problems. The inhomogeneous nature of the chicken breast may be like the ones you would encounter in a human breast, but make the experiments challenging. The errors of each individual experiment are quite big. The differences between the different experiments with the same experimental conditions are also substantial. Fresh chicken is recommended to obtain the best images.

Another improvement for further testing would be to replace chicken with pork. Preliminary testing has shown that pork tissue (ham) is much more homogeneous than chicken tissue. Ham was tested as a chicken replacement in the steering experiment and proved to have a better contrast as can be seen in Figure 19. Further research is needed to see if pork tissue is a usable substitute for human breast tissue.

C. Acknowledgement

First and foremost I would like to thank Momen Abayazid, my daily supervisor, for his advice, patience, and expertise; Sarthak Misra for his weekly feedback on my work and keeping me sharp during the assignment. Also I would like to thank all students of the Medical Robotics group for the good times and an occasional laugh. From this group I especially want to thank Gustaaf Vrooijink for his help with the set-up and the code, and Kaj Gijsbertse for his help with the

ultrasound and force sensor. Furthermore I would like to thank Han Wopereis for his help with the 3D printer, Llona Vargas for her help in the materials lab and Roy Visser for his work on testing the Young's Modulus for the target.

REFERENCES

- [1] globocan. (2012, Jul) Country fast stat. [Online]. Available: <http://globocan.iarc.fr/factsheets/populations/factsheet.asp?uno=900>
- [2] K. Fuchs *et al.*, "Minimally invasive surgery." *Endoscopy*, vol. 34, no. 2, p. 154, 2002.
- [3] S. Misra, K. Reed, B. Schafer, K. Ramesh, and A. Okamura, "Mechanics of flexible needles robotically steered through soft tissue," *The International journal of robotics research*, vol. 29, no. 13, pp. 1640–1660, 2010.
- [4] Y. van Veen, A. Jahya, and S. Misra, "Macroscopic and microscopic observations of needle insertion into gels," *Proceedings of the Institution of Mechanical Engineers, Part H: Journal of Engineering in Medicine*, vol. 226, no. 6, pp. 441–449, 2012.
- [5] R. Webster, J. Kim, N. Cowan, G. Chirikjian, and A. Okamura, "Non-holonomic modeling of needle steering," *The International Journal of Robotics Research*, vol. 25, no. 5-6, pp. 509–525, 2006.
- [6] C. Medical. (2012, Dec.) Quick core[®] biopsy needle. [Online]. Available: <http://www.cookmedical.com/uro/dataSheet.do?id=1860>
- [7] D. Glozman and M. Shoham, "Image-guided robotic flexible needle steering," *Robotics, IEEE Transactions on*, vol. 23, no. 3, pp. 459–467, 2007.
- [8] M. Abayazid, C. de Korte, S. Misra *et al.*, "Target motion predictions for pre-operative planning during needle-based interventions," pp. 5380–5385, 2011.
- [9] H. Hansen, R. Lopata, C. de Korte, S. Misra *et al.*, "Predicting target displacements using ultrasound elastography and finite element modeling," *Biomedical Engineering, IEEE Transactions on*, no. 99, pp. 1–1, 2011.
- [10] E. Canto, H. Singh, S. Shariat, D. Kadmon, B. Miles, T. Wheeler, and K. Slawin, "Effects of systematic 12-core biopsy on the performance of percent free prostate specific antigen for prostate cancer detection," *The Journal of urology*, vol. 172, no. 3, pp. 900–904, 2004.
- [11] H. Tadayyon, A. Lasso, S. Gill, A. Kaushal, P. Guion, and G. Fichtinger, "Target motion compensation in mri-guided prostate biopsy with static images," in *Conference proceedings:... Annual International Conference of the IEEE Engineering in Medicine and Biology Society. IEEE Engineering in Medicine and Biology Society. Conference*, vol. 2010. NIH Public Access, 2010, p. 5416.
- [12] M. Palmeri, M. Wang, J. Dahl, K. Frinkley, and K. Nightingale, "Quantifying hepatic shear modulus; i_L in vivo/ i_L using acoustic radiation force," *Ultrasound in medicine & biology*, vol. 34, no. 4, pp. 546–558, 2008.
- [13] S. Willson, E. Adam, and A. Tucker, "Patterns of breast skin thickness in normal mammograms," *Clinical Radiology*, vol. 33, no. 6, pp. 691–693, 1982.
- [14] A. Gefen and B. Dilmoney, "Mechanics of the normal woman's breast," *Technology and Health Care*, vol. 15, no. 4, pp. 259–271, 2007.
- [15] Wacker. (2012, Oct) Wacker silgel(r) 612 a/b. [Online]. Available: <http://www.wacker.com/cms/en/products-markets/products/product.jsp?product=10549&country=NL&language=en>
- [16] B. V. Nederland. (2012, Jul) Soorten borstkanker. [Online]. Available: http://www.borstkanker.nl/wat_is_borstkanker_soorten_borstkanker
- [17] T. Krouskop, T. Wheeler, F. Kallel, B. Garra, T. Hall *et al.*, "Elastic moduli of breast and prostate tissues under compression," *Ultrasonic imaging*, vol. 20, no. 4, p. 260, 1998.
- [18] M. Abayazid, C. de Korte, S. Misra *et al.*, "Effect of skin thickness on target motion during needle insertion into soft-tissue phantoms," in *Biomedical Robotics and Biomechanics (BioRob), 2012 4th IEEE RAS & EMBS International Conference on*. IEEE, 2012, pp. 755–760.
- [19] F. Zoergiebel. (2009) ploterr. [Online]. Available: <http://www.mathworks.nl/matlabcentral/fileexchange/22216-ploterr>
- [20] J. Schwizer. (2012) Scalable vector graphics (svg) export of figures. [Online]. Available: <http://www.mathworks.nl/matlabcentral/fileexchange/7401-scalable-vector-graphics-svg-export-of-figures>
- [21] H. Lee. (2006) addaxis. [Online]. Available: <http://www.mathworks.nl/matlabcentral/fileexchange/9016-addaxis>

VI. APPENDIX

A. Matlab code

1) *Main*: The main file is different for each experiment. It contains all information about the layout of the figures and it has different configuration possibilities. The first variable allows to set for different file types to save the figures. The pause function enables or disables a pause after each figure. The last function enables or disables the quickcheck function. In the ex variable the name of the experiment is given, and in the sf an abbreviation of this name is entered. The file is then saved using this abbreviation and its variable. The variables are given in the v-section. Further down the code the folders are set. Finally the measurement data is imported into the program. Note that not all measurement data are necessarily follow ups (e.g. 1, 3, 5, 7, 9). This is due to errors in the experiments that are missing. When the data is imported it is processed in the proc code. This is done for every experiment using the same proc file after which the data of these measurements is combined and the final figures are produced in the roundup code.

```

1 close;
2 clear all;
3
4 %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%:-CONFIG:-%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
5
6 q=2; % Set save function, 1 = EPS 2 = SVG, 0 = no saving, else is both
7 p=1; %Turns pauses on or off, 1 = on
8 qc=0; %Turns quickcheck on or off
9 a=([0 5 0 1.5]); %define axis overview plot
10 ex='Needle diameter';
11 sf='ND';
12
13
14 v_1=.5; %set variables tested
15 v_2=.75;
16 v_3=1;
17 v_4=1.25;
18 v_5=1.5;
19
20 %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%:-END:-%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
21
22 set(0,'defaulttextinterpreter','none')
23 addpath(genpath('D:\Users\Peter-Jan\Dropbox\UTwente\Bachelor ...
    Assignment\Experiments\10-08-2012_Needle Diameter')) %Set root folder
24 addpath 'D:\Users\Peter-Jan\Dropbox\UTwente\Bachelor Assignment\Matlab\Tools'
25 set(0, 'DefaultAxesFontName', 'Times New Roman', 'DefaultAxesFontSize', 8)
26 v=[v_1, v_2, v_3, v_4, v_5];
27
28 % First measurement
29 [x1, x2, x3, x4, x5, y1, y2, y3, y4, y5]=importeren('\0.5mm\1_dataMeasured.txt', ...
    '\0.5mm\3_dataMeasured.txt', '\0.5mm\5_dataMeasured.txt', '\0.5mm\11_dataMeasured.txt', ...
    '\0.5mm\9_dataMeasured.txt'); %insert measurement data with respect to root folder
30 [finalx_1, finaly_1, sx_1, sy_1, phifit1]=proc(x1, x2, x3, x4, x5, y1, y2, y3, y4, y5, v(1), sf, ...
    ex, q, p, qc);
31
32 % Second measurement
33 [x1, x2, x3, x4, x5, y1, y2, y3, y4, y5]=importeren('\0.75mm\1_dataMeasured.txt', ...
    '\0.75mm\15_dataMeasured.txt', '\0.75mm\5_dataMeasured.txt', '\0.75mm\7_dataMeasured.txt', ...
    '\0.75mm\9_dataMeasured.txt'); %insert measurement data with respect to root folder
34 [finalx_2, finaly_2, sx_2, sy_2, phifit2]=proc(x1, x2, x3, x4, x5, y1, y2, y3, y4, y5, v(2), sf, ...
    ex, q, p, qc);
35
36 % Third measurement
37 [x1, x2, x3, x4, x5, y1, y2, y3, y4, y5]=importeren('\1mm\1_dataMeasured.txt', ...
    '\1mm\3_dataMeasured.txt', '\1mm\5_dataMeasured.txt', '\1mm\7_dataMeasured.txt', ...
    '\1mm\9_dataMeasured.txt'); %insert measurement data with respect to root folder
38 [finalx_3, finaly_3, sx_3, sy_3, phifit3]=proc(x1, x2, x3, x4, x5, y1, y2, y3, y4, y5, v(3), sf, ...
    ex, q, p, qc);
39
40 % Fourth measurement
41 [x1, x2, x3, x4, x5, y1, y2, y3, y4, y5]=importeren('\1.25mm\1_dataMeasured.txt', ...
    '\1.25mm\3_dataMeasured.txt', '\1.25mm\5_dataMeasured.txt', '\1.25mm\7_dataMeasured.txt', ...
    '\1.25mm\9_dataMeasured.txt'); %insert measurement data with respect to root folder
42 [finalx_4, finaly_4, sx_4, sy_4, phifit4]=proc(x1, x2, x3, x4, x5, y1, y2, y3, y4, y5, v(4), sf, ...
    ex, q, p, qc);
43
44 % Fifth measurement
45 [x1, x2, x3, x4, x5, y1, y2, y3, y4, y5]=importeren('\1.5mm\1_dataMeasured.txt', ...
    '\1.5mm\3_dataMeasured.txt', '\1.5mm\5_dataMeasured.txt', '\1.5mm\17_dataMeasured.txt', ...

```

```

        '\1.5mm\9_dataMeasured.txt'); %insert measurement data with respect to root folder
46 [finalx_5, finaly_5, sx_5, sy_5, phifit5]=proc(x1, x2, x3, x4, x5, y1, y2, y3, y4, y5, v(5), sf, ...
    ex, q, p, qc);
47
48 roundup(finalx_1, finaly_1, finalx_2, finaly_2, finalx_3, finaly_3, finalx_4, finaly_4, finalx_5, ...
    finaly_5, sx_1, sy_1, sx_2, sy_2, sx_3, sy_3, sx_4, sy_4, sx_5, sy_5, q, v, phifit1, phifit2, ...
    phifit3, phifit4, phifit5, ex, p, sf, 1.75, a)

```

2) *Import:* The importer code uses Matlab's build-in import function to import the txt files that the set-up produces. It selects the columns containing the coordinate information of the target and imports them into the memory of Matlab.

```

1 function [x1, x2, x3, x4, x5, y1, y2, y3, y4, y5]=importeren(fileToRead1, fileToRead2, fileToRead3, ...
    fileToRead4, fileToRead5)
2
3 impl=importdata(fileToRead1); %calls on import data function
4 x1=impl.data(:,4); %imports the 4th row of the measurement data as x-data
5 y1=impl.data(:,5); %imports the 5th row of the measurement data as x-data
6
7 imp2=importdata(fileToRead2);
8 x2=imp2.data(:,4);
9 y2=imp2.data(:,5);
10
11 imp3=importdata(fileToRead3);
12 x3=imp3.data(:,4);
13 y3=imp3.data(:,5);
14
15 imp4=importdata(fileToRead4);
16 x4=imp4.data(:,4);
17 y4=imp4.data(:,5);
18
19 imp5=importdata(fileToRead5);
20 x5=imp5.data(:,4);
21 y5=imp5.data(:,5);
22 end

```

3) *Processing:* The proc package manages the data and checks what to do with it. After it has been processed by the measurement package it is either send to quickcheck and/or to the plot package.

```

1 function [finalx_1, finaly_1, sx_1, sy_1, phi_fit1, t_1, rms_fit1, rmser]=proc2(x1, x2, x3, x4, x5, ...
    y1, y2, y3, y4, y5, v, sf, ex, q, p, qc, di)
2 [finalx_1, finaly_1, dx_1, dy_1, mx_1, my_1, sx_1, sy_1, rms_fit1, phi_fit1, xfit_1, yfit_1, t_1, ...
    rmser]=measurement2(x1, x2, x3, x4, x5, y1, y2, y3, y4, y5, di); %sends data to processing m-file
3 if qc ==1
4     quickcheck2(dx_1, dy_1, mx_1, my_1, ['Target displacement ', num2str(v), ' degrees bevel ...
        angle']); pause; close; %quickcheck for measurement data
5 end
6 plotje2(rms_fit1, phi_fit1, t_1, rmser, v, sf, ex, q, p); %sends the processed data to a plot m-file

```

4) *Measurement:* The measurement package processes the imported data according to the block diagram that was seen in Figure 4.

```

1 %Imports the txt files from set location and assigns a value to it. Uses
2 %importeren.m file
3
4 %8.67 pixels ~ 1mm
5 function [finalx_1, finaly_1, dx_1, dy_1, mx_1, my_1, sx_1, sy_1, rms_fit1, phi_fit1, xfit_1, ...
    yfit_1, t_1, rmser]=measurement2(x1, x2, x3, x4, x5, y1, y2, y3, y4, y5, di);
6
7 S=[length(x1), length(x2), length(x3), length(x4), length(x5)]; %Create vector with lengths of the ...
    measurements
8 B=min(S); %Calculate the shortest vector to make equal length
9 x1=abs(x1(1:B)); %Cut off every vector to adjust the length to the shortest vector
10 x2=abs(x2(1:B)); x3=abs(x3(1:B)); x4=abs(x4(1:B)); x5=abs(x5(1:B));
11 y1=abs(y1(1:B)); y2=abs(y2(1:B)); y3=abs(y3(1:B)); y4=abs(y4(1:B)); y5=abs(y5(1:B));
12 time=length(B)/25; %total time elapsed
13 t_1=(1:B)/25;
14
15 xp=[x1, x2, x3, x4, x5]; %Creates a matrix of the vectors
16 yp=[y1, y2, y3, y4, y5];
17
18 xi=[mean(xp(1:20,1)), mean(xp(1:20,2)), mean(xp(1:20,3)), mean(xp(1:20,4)), mean(xp(1:20,5))]; ...
    %Calculates initial position

```

```

19 yi=[mean(yp(1:20,1)), mean(yp(1:20,2)), mean(yp(1:20,3)), mean(yp(1:20,4)), mean(yp(1:20,5))];
20
21 xmi=[(ones(B,1))*xi(1), (ones(B,1))*xi(2), (ones(B,1))*xi(3), (ones(B,1))*xi(4), ...
      (ones(B,1))*xi(5)]; %Create a matrix with initial positions
22 ymi=[(ones(B,1))*yi(1), (ones(B,1))*yi(2), (ones(B,1))*yi(3), (ones(B,1))*yi(4), (ones(B,1))*yi(5)];
23
24 dx_1=abs(xp-xmi); %Calculates displacement
25 dx_1=dx_1/8.67; %Converts pixels to mm
26 % dxa_1=abs(xp-xmi); %Absolute displacement
27 % dxa_1=dxa_1/8.67;
28
29 dy_1=abs(yp-yi);
30 dy_1=dy_1/8.67;
31 % dya_1=abs(yp-yi);
32 % dya_1=dya_1/8.67;
33
34 for i = 1:B
35     mx_1(i)=(dx_1(i,1)+dx_1(i,2)+dx_1(i,3)+dx_1(i,4)+dx_1(i,5))/length(S); %mx calculates averages ...
        value of the measurements for x as a vector
36 end
37
38 for i = 1:B
39     my_1(i)=(dy_1(i,1)+dy_1(i,2)+dy_1(i,3)+dy_1(i,4)+dy_1(i,5))/length(S); %mx calculates averages ...
        value of the measurements for x as a vector
40 end
41
42 for i=1:B
43     sx_1(i)=std([dx_1(i,1),dx_1(i,2),dx_1(i,3),dx_1(i,4),dx_1(i,5)]); %calculates standard ...
        deviation per matrix entry (from !non-absolute! value)
44 end
45
46 for i=1:B
47     sy_1(i)=std([dy_1(i,1),dy_1(i,2),dy_1(i,3),dy_1(i,4),dy_1(i,5)]); %calculates standard ...
        deviation per matrix entry (from !non-absolute! value)
48 end
49
50 for i=1:size(dx_1) %calculates mean displacement
51     mdx_1(i)=mean(dx_1(i,1:5));
52 end
53
54 for i=1:size(dy_1)
55     mdy_1(i)=mean(dy_1(i,1:5));
56 end
57
58 rms_1=sqrt(mdx_1.^2+mdy_1.^2); %determines rms sqrt(x^2+y^2)
59 len=length(rms_1); %determines length of the vector
60 ins_t1=round(length(t_1)*.5); %calculates time before visible insertion on US
61 mdy_1([1:ins_t1]) = mean(mdy_1(ins_t1:(ins_t1+20))); %calculates average initial value
62 mdx_1([1:ins_t1]) = mean(mdx_1(ins_t1:(ins_t1+20))); %calculates average initial value
63
64 for i=1:(len) %calculates phi
65     phi_1(i)=atan((mdy_1(i)-di)/mdx_1(i));
66 end
67 phi_1(isnan(phi_1))=0; %replaces NaN with zeros
68 phi_degl=(phi_1*180)/pi; %transforms radians to degree
69 [ b, a ] = butter(3, 0.03); %Smoothing
70 rms_fit1 = filter(b, a, rms_1(1:length(rms_1))); %Applies smoothing
71 phi_fit1 = filter(b, a, phi_degl(1:length(phi_degl)));
72 [ b, a ] = butter(3, 0.03);
73 xfit_1 = filter(b, a, mx_1(1:length(mx_1)));
74 yfit_1 = filter(b, a, my_1(1:length(my_1)));
75
76 rmser=sqrt(sx_1.^2+sy_1.^2); %Calculates rms error of the total
77 for i = 1:length(rmser), if rem(i, 20), rmser(i) = 0; end; end; %reduces the ammount of errorbars
78 rmser(rmser==0) = NaN; %Replaces the zero's with NaN (preventing errors)
79
80 xe=[mean(dx_1(min(S)-20:min(S),1)), mean(dx_1(min(S)-20:min(S),2)), mean(dx_1(min(S)-20:min(S),3)), ...
      mean(dx_1(min(S)-20:min(S),4)), mean(dx_1(min(S)-20:min(S),5))]; %calculates avergae finale ...
      values based on last 20 measurements
81 ye=[mean(dy_1(min(S)-20:min(S),1)), mean(dy_1(min(S)-20:min(S),2)), mean(dy_1(min(S)-20:min(S),3)), ...
      mean(dy_1(min(S)-20:min(S),4)), mean(dy_1(min(S)-20:min(S),5))];
82
83 finalx_1=mean(xe); %saves averaged out end values
84 finaly_1=mean(ye);

```

5) *Quickcheck*: The quickcheck gives the user a quick overview of the five measured sets and the average value, giving one the possibility to check for errors or big variances.

```

1 %Quick measurement check
2 function quickcheck2(dx_1, dy_1, mx_1, my_1, titel)
3 plot(1:length(dx_1), dx_1, 'LineWidth', 1)
4 hold
5 plot(1:length(dx_1), mx_1, 'LineWidth', 5)
6 hleg1 = legend('1', '2', '3', '4', '5', 'mean');
7 xlabel('Measurements')
8 ylabel('Displacement in x-direction (mm)')
9 title(titel)
10 pause
11 close
12 plot(1:length(dy_1), dy_1, 'LineWidth', 1)
13 hold
14 plot(1:length(dy_1), my_1, 'LineWidth', 5)
15 hleg1 = legend('1', '2', '3', '4', '5', 'mean');
16 xlabel('Measurements')
17 ylabel('Displacement in y-direction (mm)')
18 title(titel)

```

6) *Plot*: The plot function plots the data of each set of five measurements. The results of these plots is find in section VI. The plot code uses the ploterr [19] package that is available from the Matlab File Exchange.

```

1 function [rms_fit1, phi_fit1, t_1, rmser, v_1, sf, ex]=plotje2(rms_fit1, phi_fit1, t_1, rmser, v_1, ...
    sf, ex, q, p)
2 hfig = figure; %create variable figure
3 h = ploterr(t_1,rms_fit1,[],rmser,'r','hhy',5); %use ploterr (MFE)
4 set(h, 'MarkerSize', 4); %increase thickness marker of data points
5 set(h(2), 'LineWidth', 2); %increase thickness lines
6 xlabel([num2str(ex), ' [mm]'], 'FontSize', 8); ylabel('Displacement [mm]', 'FontSize', 8); %Creates ...
    the errorbar of the RMS displacement
7 set(hfig, 'units', 'centimeters', ...
    'NumberTitle', 'off');
8 pos = get(hfig, 'position');
9
10 ymax=axis; %get axis data
11 axis([0 ymax(2) ymax(3) ymax(4)]); %set axis to start at 0
12 set(hfig, 'position', [pos(1:2), 8, 6]); %set figure size
13 if q==1
14     matlabfrag([num2str(sf), num2str(v_1*100)]); % Function call is laprint(fig. num. , filename)
15 elseif q==2
16     plot2svg([num2str(sf), num2str(v_1*100), '.svg']) %save as svg
17 elseif q==0
18     else
19         plot2svg([num2str(sf), num2str(v_1*100), '.svg']) %save as both
20         matlabfrag([num2str(sf), num2str(v_1*100)])
21     end
22 if p==1 %pauses function to take a look at it
23     pause
24     close %closes the figure
25 else
26     close
27 end

```

7) *Roundup*: The roundup package combines the measurement data and produces the curves that are seen in the thesis. It also save the image as a Scalable Vector Graphic using the plot2svg [20].

```

1 function [fxv, fyv, fxyv, sxi, syi]=roundup(finalx_1, finaly_1, finalx_2, finaly_2, finalx_3, ...
    finaly_3, finalx_4, finaly_4, finalx_5, finaly_5, sx_1, sy_1, sx_2, sy_2, sx_3, sy_3, sx_4, ...
    sy_4, sx_5, sy_5, q, v, phifit1, phifit2, phifit3, phifit4, phifit5, ex, p, sf, xmax, a)
2
3 erx=0.05*(a(4)-a(3)); %calculates optimal size errorbars in x
4 ey=0.05*(a(2)-a(1)); %calculates optimal size errorbars in y
5
6 S=[length(phifit1), length(phifit2), length(phifit3), length(phifit4), length(phifit5)]; %Create ...
    vector with lengths of the measurements
7 B=min(S); %Calculate the shortest vector to make equal length
8 phifit1=(phifit1(1:B)); %Cut off every vector to adjust the length to the shortest vector
9 phifit2=(phifit2(1:B)); phifit3=(phifit3(1:B)); phifit4=(phifit4(1:B)); phifit5=(phifit5(1:B));
10 phifit1=transpose(phifit1); phifit2=transpose(phifit2); phifit3=transpose(phifit3); ...
    phifit4=transpose(phifit4); phifit5=transpose(phifit5); %transposes data to fit them in vector

```

```

11 phifit=[phifit1, phifit2, phifit3, phifit4, phifit5]; %Creates a matrix phifit of the vectors
12 phifitt=[mean(phifit(min(S)-20:min(S),1)), mean(phifit(min(S)-20:min(S),2)), ...
    mean(phifit(min(S)-20:min(S),3)), mean(phifit(min(S)-20:min(S),4)), ...
    mean(phifit(min(S)-20:min(S),5))]; %Calculates mean values of the latest phi measurements
13
14 fxv=[finalx_1, finalx_2, finalx_3, finalx_4, finalx_5]; %Creates vector of all the final values
15 fyv=[finaly_1, finaly_2, finaly_3, finaly_4, finaly_5];
16 frms1=sqrt((finalx_1).^2+(finaly_1).^2); % Calculates RMS Value of the x and y vector
17 frms2=sqrt((finalx_2).^2+(finaly_2).^2); frms3=sqrt((finalx_3).^2+(finaly_3).^2); ...
    frms4=sqrt((finalx_4).^2+(finaly_4).^2); frms5=sqrt((finalx_5).^2+(finaly_5).^2);
18 fxyv=[frms1, frms2, frms3, frms4, frms5]; %Creates the vector of the RMS final values of all ...
    measurements
19 sxi=[mean(sx_1(length(sx_1)-10:length(sx_1))), mean(sx_2(length(sx_2)-10:length(sx_2))), ...
    mean(sx_3(length(sx_3)-10:length(sx_3))), mean(sx_4(length(sx_4)-10:length(sx_4))), ...
    mean(sx_5(length(sx_5)-10:length(sx_5)))]; %Calculates the mean value of the last 10 standard ...
    deviation values
20 syi=[mean(sy_1(length(sy_1)-10:length(sy_1))), mean(sy_2(length(sy_2)-10:length(sy_2))), ...
    mean(sy_3(length(sy_3)-10:length(sy_3))), mean(sy_4(length(sy_4)-10:length(sy_4))), ...
    mean(sy_5(length(sy_5)-10:length(sy_5)))];
21 rmsserr=sqrt(sxi.^2+syi.^2); %Calculates the RMS error based upon the last 10 std values
22
23 %-:RMS DISPLACEMENT:-%
24 hfig = figure;
25 h = ploterr(v,fxyv,0, rmsserr, 'r.', 'hhxy',2); %use ploterr (MFE)
26 set(h, 'MarkerSize', 10); %increase thickness markersize
27 set(h(2), 'Color', 'b', 'LineWidth', 1.25), set(h(3), 'Color', 'b', 'LineWidth', 1.25) %increase thickness ...
    errorbars
28 xlabel([num2str(ex), ' [mm]'], 'FontSize', 8); ylabel('Displacement [mm]', 'FontSize', 8); %Creates ...
    the errorbar of the RMS displacement
29 set(hfig, 'units', 'centimeters', ...
30 'NumberTitle', 'off', 'Name', 'ex03');
31 pos = get(hfig, 'position');
32 ymax=axis;
33 axis([0 xmax 0 ymax(4)]) %set axis
34 set(hfig, 'position', [pos(1:2), 8, 6]); %set figure size
35 if q==1
36     matlabfrag([num2str(sf), '_RMSDisplacement']); % Function call is laprint(fig. num. , filename)
37 elseif q==2
38     plot2svg([num2str(sf), '_RMSDisplacement.svg'])
39 elseif q==0
40     else
41         plot2svg([num2str(sf), '_RMSDisplacement.svg'])
42         matlabfrag([num2str(sf), '_RMSDisplacement'])
43     end
44
45
46 if p==1
47     pause
48 end
49 close;
50
51 hold on %Plots the overview of all displacements on x- and y-direction
52 axis(a)
53 h1=ploterr([-1 fxv(1)], [-1 fyv(1)], [0 sxi(1)], [0 syi(1)], 'b.', 'abshhy', ey, 'abshhx', ex);
54 ymax=axis;
55 axis(a)
56 set(h1(2), 'Color', 'b', 'LineWidth', 1.25), set(h1(3), 'Color', 'b', 'LineWidth', 1.25)
57 hasbehavior(h1(3), 'legend', false); % will remove the 3rd legend entry.
58 hasbehavior(h1(2), 'legend', false); % will remove the 2nd legend entry.
59 axis(a)
60 h2=ploterr([-1 fxv(2)], [-1 fyv(2)], [0 sxi(2)], [0 syi(2)], 'r.', 'abshhy', ey, 'abshhx', ex);
61 set(h2(2), 'Color', 'r', 'LineWidth', 1.25), set(h2(3), 'Color', 'r', 'LineWidth', 1.25)
62 ymax=axis;
63 hasbehavior(h2(3), 'legend', false); % will remove the 3rd legend entry.
64 hasbehavior(h2(2), 'legend', false); % will remove the 2nd legend entry.
65 axis(a)
66 h3=ploterr([-1 fxv(3)], [-1 fyv(3)], [0 sxi(3)], [0 syi(3)], 'g.', 'abshhy', ey, 'abshhx', ex);
67 set(h3(2), 'Color', 'g', 'LineWidth', 1.25), set(h3(3), 'Color', 'g', 'LineWidth', 1.25)
68 ymax=axis;
69 axis(a)
70 hasbehavior(h3(3), 'legend', false); % will remove the 3rd legend entry.
71 hasbehavior(h3(2), 'legend', false); % will remove the 2nd legend entry.
72 h4=ploterr([-1 fxv(4)], [-1 fyv(4)], [0 sxi(4)], [0 syi(4)], 'k.', 'abshhy', ey, 'abshhx', ex);
73 set(h4(2), 'Color', 'k', 'LineWidth', 1.25), set(h4(3), 'Color', 'k', 'LineWidth', 1.25)
74 ymax=axis;
75 axis(a)
76 hasbehavior(h4(3), 'legend', false); % will remove the 3rd legend entry.

```

```

77 hasbehavior(h4(2),'legend',false); % will remove the 2nd legend entry.
78 h5=ploterr([-1 fxv(5)],[-1 fyv(5)],[0 sxi(5)],[0 syi(5)],'c.','abshhy',ey,'abshhx',erx);
79 set(h5(2),'Color','c','LineWidth',1.25), set(h5(3),'Color','c','LineWidth',1.25)
80 ymax=axis;
81 axis(a)
82 hasbehavior(h5(3),'legend',false); % will remove the 3rd legend entry.
83 hasbehavior(h5(2),'legend',false); % will remove the 2nd legend entry.
84 h6=ploterr([-1 0.01],[-1 0.01],[6 0],[6 0],'w.','hhxy',1.5);
85 set(h6(2),'Color','w','LineWidth',2), set(h6(3),'Color','w','LineWidth',2)
86 axis(a)
87 h=legend([num2str(v(1)), num2str(v(2)),num2str(v(3)),num2str(v(4)),num2str(v(5))], 'Location', 'Best');
88 xlabel('x [mm]','FontSize',8); ylabel('y [mm]','FontSize',8);
89 set(gcf,'box','on')
90 set(gcf,'PaperUnits','centimeters','PaperPosition',[0 0 8 6]) %set size for figure
91 set(gcf,'Units','centimeters','position',get(gcf,'PaperPosition'))
92
93 hold off
94 if q==1
95     matlabfrag([num2str(sf), '_Overview']); % Function call is laprint(fig. num. , filename)
96 elseif q==2
97     plot2svg([num2str(sf), '_Overview.svg'])
98 elseif q==0
99     else
100         plot2svg([num2str(sf), '_Overview.svg'])
101         matlabfrag([num2str(sf), '_Overview'])
102     end
103 if p==1
104     pause
105 end
106
107 close

```

8) Force Measurements:

a) *Force main:* The main file of the force measurements is an adjusted version of the regular main file. It uses a lot of the same functions, but some are new for the force data.

```

1 close;
2 clear all;
3
4 q=2; % Set save function, 1 = EPS 2 = SVG, 0 = no saving, else is both
5 p=0; %Turns pauses on or off, 1 = on
6 qc=0; %Turns quickcheck on or off
7 a=([0 4 -0.2 0.35]); %define axis overview plot
8 ex='Skin thickness';
9 sf='ST';
10
11 v_1=0; %set variables tested
12 v_2=0.8;
13 v_3=1.6;
14
15
16
17 %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
18 v=[v_1, v_2, v_3];
19 set(0,'defaulttextinterpreter','none')
20 addpath(genpath('D:\Users\Peter-Jan\Dropbox\UTwente\Bachelor ...
    Assignment\Experiments\11-09-2012__Skin Layer\')) %Set root folder
21 addpath('D:\Users\Peter-Jan\Dropbox\UTwente\Bachelor Assignment\Matlab\Tools')
22 set(0, 'DefaultAxesFontName', 'Times New Roman', 'DefaultAxesFontSize', 8)
23
24
25 % First measurement
26 [x1, x2, x3, x4, x5, y1, y2, y3, y4, y5]=importeren('\NoLayer\3_dataMeasured.txt', ...
    '\NoLayer\7_dataMeasured.txt', '\NoLayer\9_dataMeasured.txt', '\NoLayer\11_dataMeasured.txt', ...
    '\NoLayer\13_dataMeasured.txt'); %insert measurement data with respect to root folder
27 [finalx_1, finaly_1, sx_1, sy_1, phifit1, t_1, rms_fit1, rmser]=proc(x1, x2, x3, x4, x5, y1, y2, ...
    y3, y4, y5, v(1), sf, ex, q, p, qc);
28 [fz1fit, fz2fit, fz0fit] = imprt; %imports force data
29 fplot(rms_fit1, fz0fit, t_1, rmser, v(1), sf, ex, q, p);
30
31 % Second measurement
32 [x1, x2, x3, x4, x5, y1, y2, y3, y4, y5]=importeren('\OneLayer\20_dataMeasured.txt', ...
    '\OneLayer\22_dataMeasured.txt', '\OneLayer\8_dataMeasured.txt', ...
    '\OneLayer\14_dataMeasured.txt', '\OneLayer\16_dataMeasured.txt'); %insert measurement data ...
    with respect to root folder

```

```

33 [finalx_2, finaly_2, sx_2, sy_2, phifit2, t_1, rms_fit1, rmser]=proc(x1, x2, x3, x4, x5, y1, y2, ...
34   y3, y4, y5, v(2), sf, ex, q, p, qc);
35 fplot(rms_fit1, fz1fit, t_1, rmser, v(2), sf, ex, q, p);
36
37 % Third measurement
38 [x1, x2, x3, x4, x5, y1, y2, y3, y4, y5]=importeren('\RedoneTwoLayer\1_dataMeasured.txt', ...
39   '\RedoneTwoLayer\5_dataMeasured.txt', '\RedoneTwoLayer\7_dataMeasured.txt', ...
40   '\RedoneTwoLayer\17_dataMeasured.txt', '\RedoneTwoLayer\15_dataMeasured.txt'); %insert ...
41   measurement data with respect to root folder
42 [finalx_3, finaly_3, sx_3, sy_3, phifit3, t_1, rms_fit1, rmser]=proc(x1, x2, x3, x4, x5, y1, y2, ...
43   y3, y4, y5, v(3), sf, ex, q, p, qc);
44 rms_fit1=rms_fit1(90:length(rms_fit1));
45 rmser=rmser(90:length(rmser));
46 t_1=t_1(1:(length(t_1)-89));
47 fplot(rms_fit1, fz2fit, t_1, rmser, v(3), sf, ex, q, p);
48
49 roundup3(finalx_1, finaly_1, finalx_2, finaly_2, finalx_3, finaly_3, sx_1, sy_1, sx_2, sy_2, sx_3, ...
50   sy_3, q, v, phifit1, phifit2, phifit3, ex, p, sf, 1.8, a);

```

b) Import force data: The import code is adjusted to import the excel data the force sensor produces. It also contains a small processing part to fit all the data in a vector.

```

1 function [fz1fit, fz2fit, fz0fit] = imprt
2 addpath(genpath('D:\Users\Peter-Jan\Dropbox\UTwente\Bachelor ...
3   Assignment\Experiments\11-09-2012__Skin Layer\OneLayer')) %Set root folder
4 f1=abs(importfile('1data.xlsx'));
5 f2=abs(importfile('2data.xlsx'));
6 f3=abs(importfile('3data.xlsx'));
7 f4=abs(importfile('6data.xlsx'));
8 f5=abs(importfile('5data.xlsx'));
9 S=[length(f1), length(f2), length(f3), length(f4), length(f5)]; %Create vector with lengths of the ...
10   measurements
11 B=(min(S)-10); %Calculate the shortest vector to make equal length
12 fz1=[f1(20:B,3), f2(20:B,3), f3(20:B,3), f4(20:B,3), f5(20:B,3)];
13 for i=1:size(fz1) %calculates mean displacement
14   fz1(i)=mean(fz1(i,1:5));
15 end
16 [ b, a ] = butter(3, 0.03); %Smoothing
17 fz1fit = filter(b, a, fz1(1:length(fz1)));
18
19 addpath(genpath('D:\Users\Peter-Jan\Dropbox\UTwente\Bachelor ...
20   Assignment\Experiments\11-09-2012__Skin Layer\TwoLayers')) %Set root folder
21 f1=abs(importfile('1data.xlsx'));
22 f2=abs(importfile('2data.xlsx'));
23 f3=abs(importfile('8data.xlsx'));
24 f4=abs(importfile('4data.xlsx'));
25 f5=abs(importfile('7data.xlsx'));
26 S=[length(f1), length(f2), length(f3), length(f4), length(f5)]; %Create vector with lengths of the ...
27   measurements
28 B=(min(S)-10); %Calculate the shortest vector to make equal length
29 fz2=[f1(20:B,3), f2(20:B,3), f3(20:B,3), f4(20:B,3), f5(20:B,3)];
30 for i=1:size(fz2) %calculates mean displacement
31   fz2(i)=mean(fz2(i,1:5));
32 end
33 fz2fit = filter(b, a, fz2(1:length(fz2)));
34
35 addpath(genpath('D:\Users\Peter-Jan\Dropbox\UTwente\Bachelor ...
36   Assignment\Experiments\11-09-2012__Skin Layer\NoLayer')) %Set root folder
37 f1=abs(importfile('1data.xlsx'));
38 f2=abs(importfile('2data.xlsx'));
39 f3=abs(importfile('3data.xlsx'));
40 f4=abs(importfile('4data.xlsx'));
41 f5=abs(importfile('5data.xlsx'));
42 S=[length(f1), length(f2), length(f3), length(f4), length(f5)]; %Create vector with lengths of the ...
43   measurements
44 B=(min(S)-10); %Calculate the shortest vector to make equal length
45 fz0=[f1(20:B,3), f2(20:B,3), f3(20:B,3), f4(20:B,3), f5(20:B,3)];
46 for i=1:size(fz0) %calculates mean displacement
47   fz0(i)=mean(fz0(i,1:5));
48 end
49 fz0fit = filter(b, a, fz0(1:length(fz0)));

```

c) *Force plot*: The force plot code is tailored to plot two lines in one plot. for this it uses the addaxis package [21].

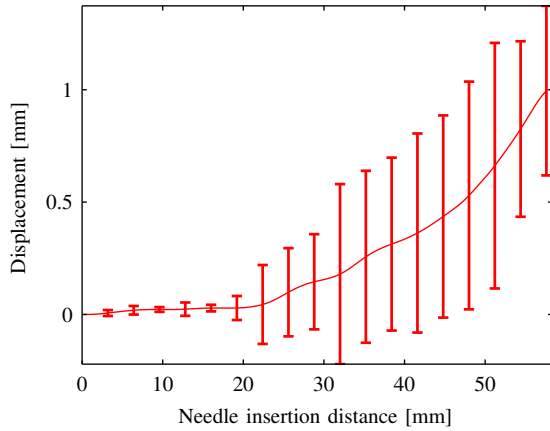
```

1 function [rms_fit1, phi_fit1, t_1, rmser, v_1, sf, ex]=fplot(rms_fit1, phi_fit1, t_1, rmser, v_1, ...
   sf, ex, q, p);
2
3 t=(1:length(phi_fit1))/6;
4
5 hfig = figure;
6 plot(t_1, rms_fit1, 'k', 'LineWidth',3)
7 xlabel('Needle insertion distance [mm]','FontSize',8); ylabel('Displacement [mm]','FontSize',8, ...
   'FontName', 'Times New Roman');
8 addaxis(t,abs(phi_fit1), 'r', 'linewidth',3); %Adds phi_fit plot
9 set(hfig,'units','centimeters',...
10 'NumberTitle','off','Name','ex03');
11 pos = get(hfig,'position');
12 set(hfig,'position',[pos(1:2),8,6]);
13 addaxislabel(2,'Force (N)', 'FontSize',8); %Adds label to the right side
14     if q==1
15         matlabfrag(['F', num2str(sf), num2str(v_1*100)]); % Function call is laprint(fig.num. , filename)
16     elseif q==2
17         plot2svg(['F', num2str(sf), num2str(v_1*100),'.svg'])
18     elseif q==0
19     else
20         plot2svg(['F', num2str(sf), num2str(v_1*100),'.svg'])
21         matlabfrag(['F', num2str(sf), num2str(v_1*100)])
22     end
23 if p==1
24     pause
25 end
26
27 close;close;

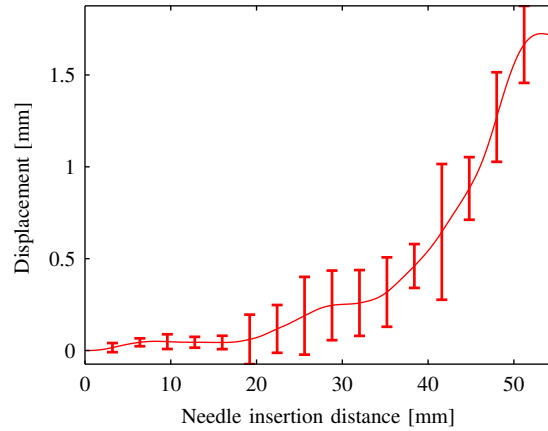
```

B. Plots

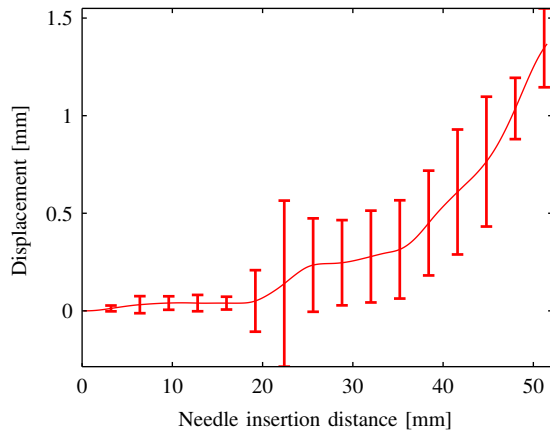
In this section the individual plots of each set of five measurements is displayed. The errorbars display the standard deviation from the medium of the five measurements at a certain insertion distance. The number of errorbars is reduced to make the plots more clear.



(a) 30 degrees

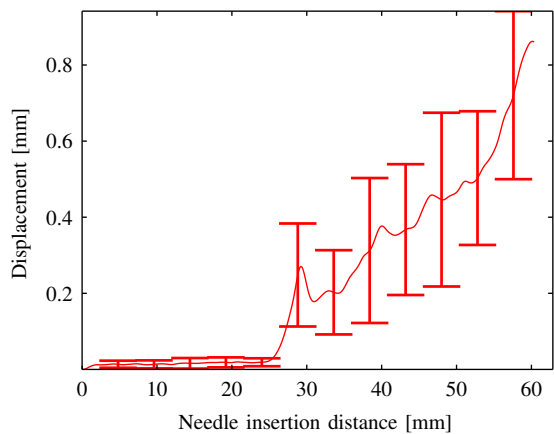


(b) 45 degrees

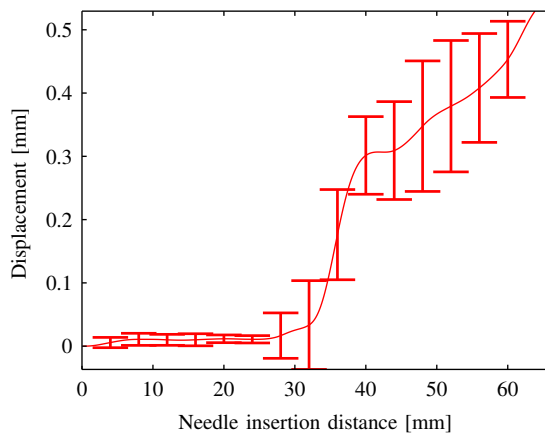


(c) 60 degrees

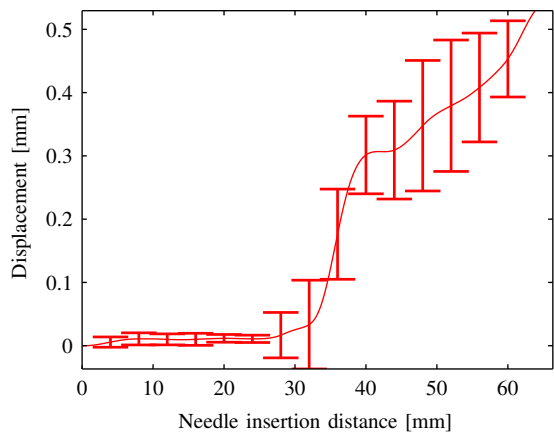
Figure 20: Effect of bevel angle



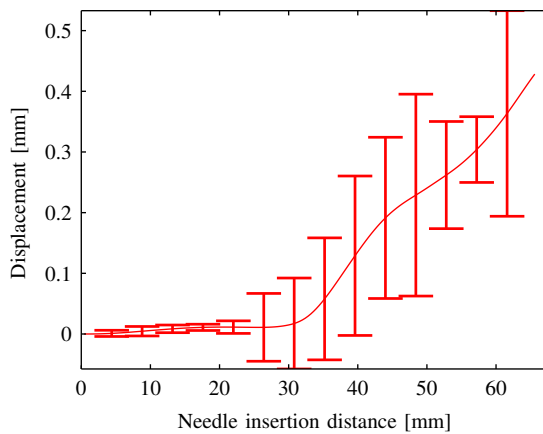
(a) 1 mm/s



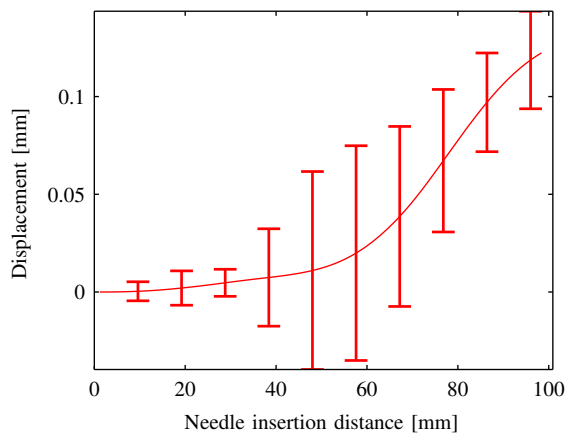
(b) 4 mm/s



(c) 10 mm/s

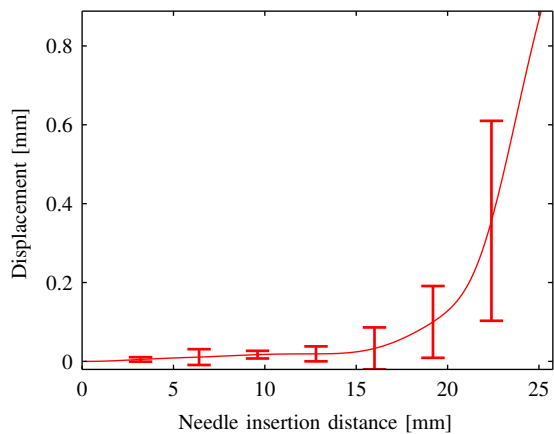


(d) 20 mm/s

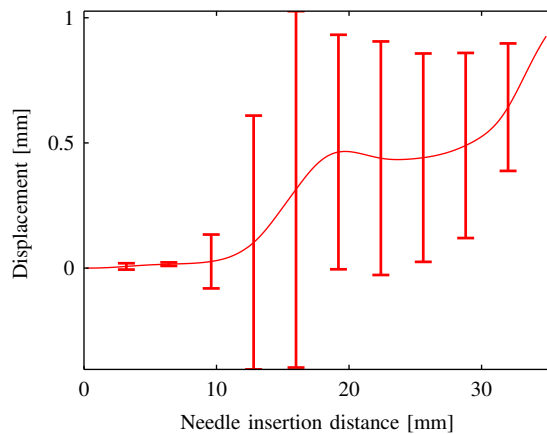


(e) 30 mm/s

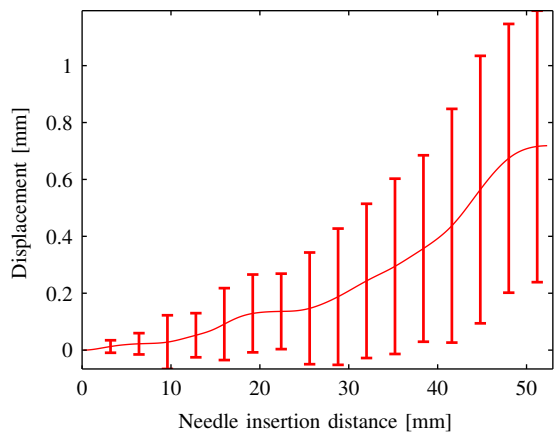
Figure 21: Effect of insertion speed



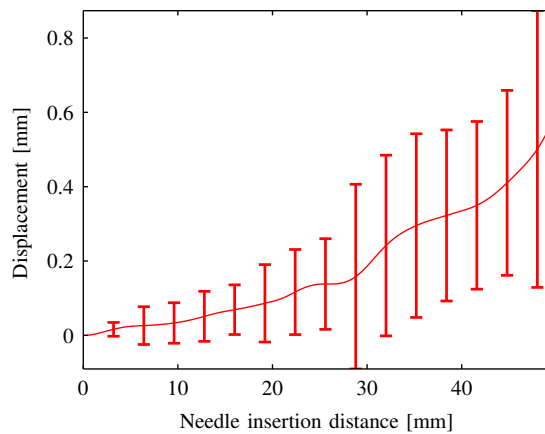
(a) 10 mm



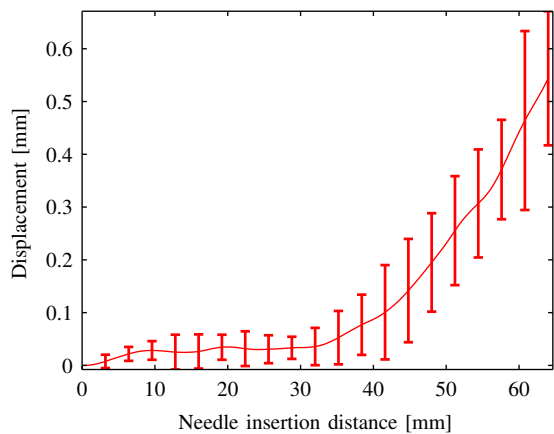
(b) 20 mm



(c) 30 mm

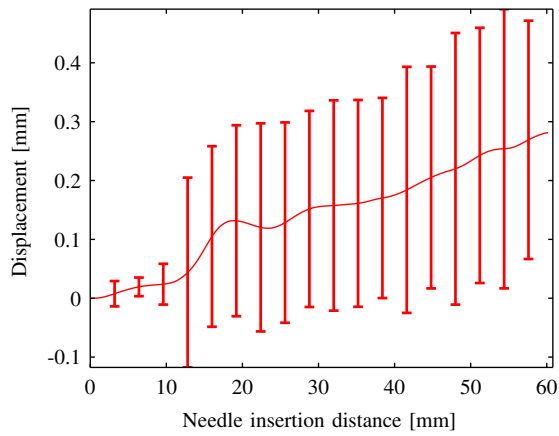


(d) 40 mm

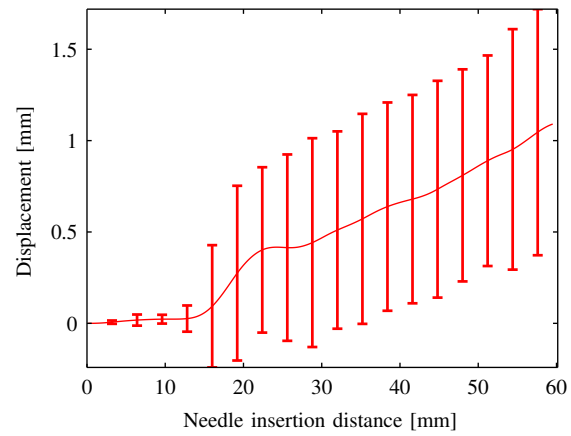


(e) 50 mm

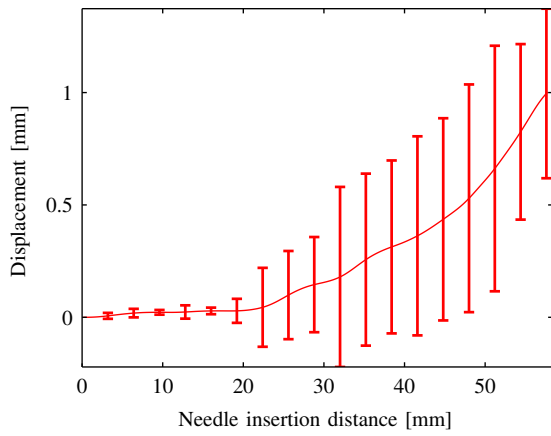
Figure 22: Effect of target distance



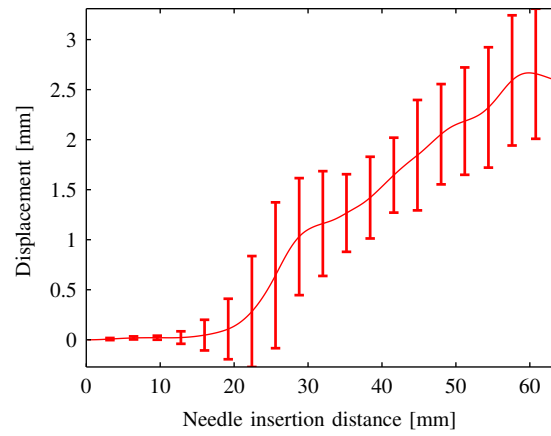
(a) 0.5 mm



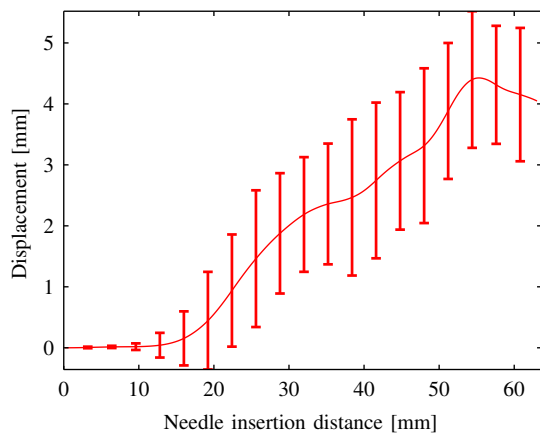
(b) 0.75 mm



(c) 1 mm

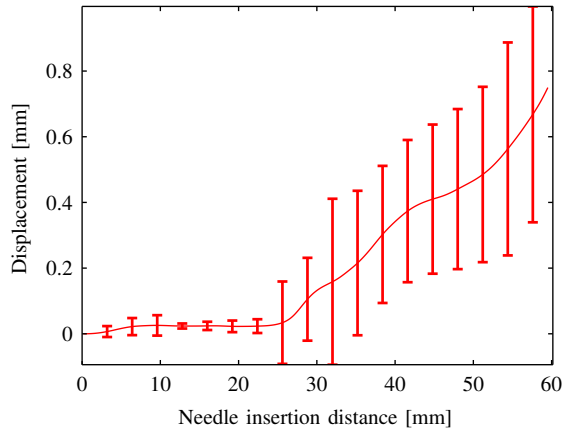


(d) 1.25 mm

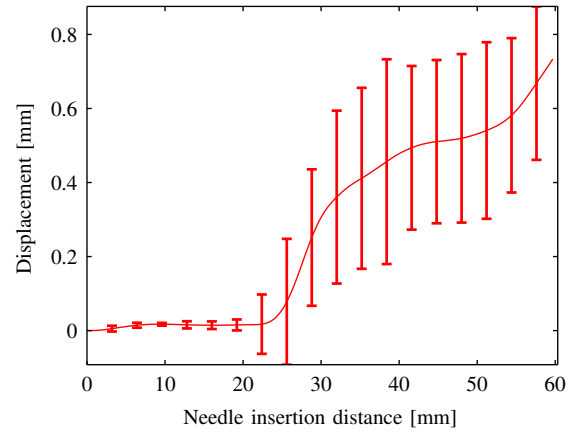


(e) 1.5 mm

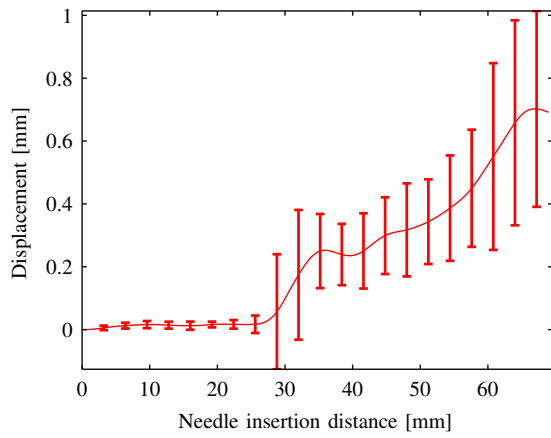
Figure 23: Effect of needle diameter



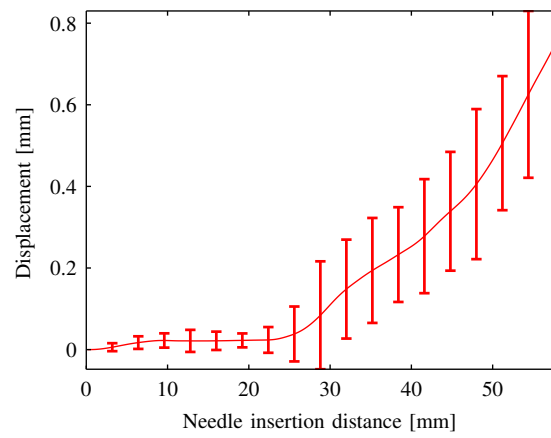
(a) 3 mm target



(b) 4 mm target



(c) 6 mm target



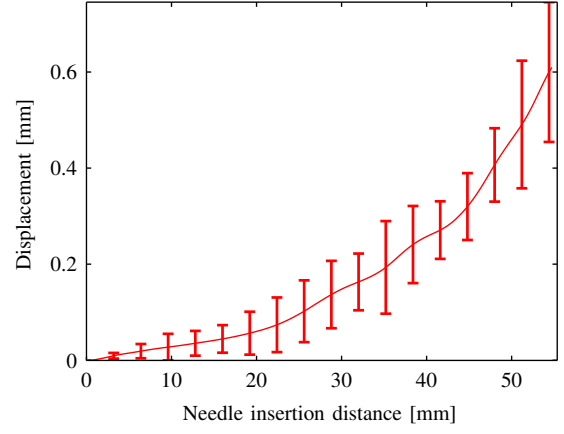
(d) 8 mm target

Figure 24: Effect of target size

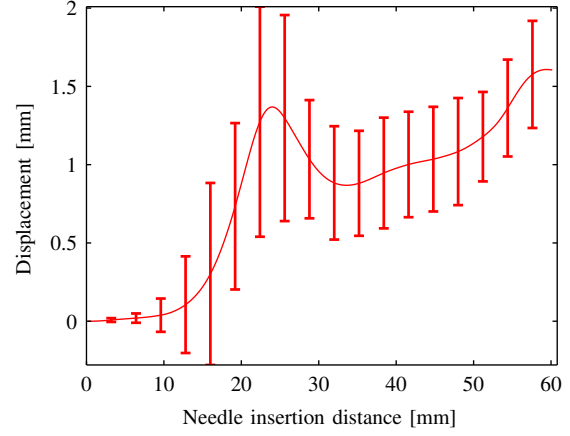
C. Table of results

Table V: Results of the experiments.

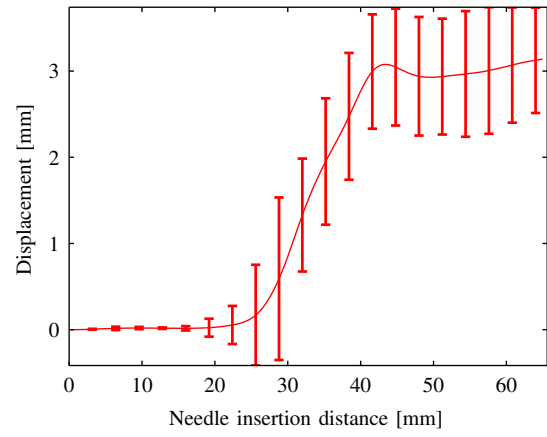
	Insertion speed [mm/s]				Bevel Angle [ϕ]			Needle Diameter [mm]				Skin Thickness [mm]				Target Distance [mm]				Target Size [mm]					
	1	2	4	6	8	30	45	60	0.5	0.75	1	1.25	1.5	0	0.8	1.6	10	20	30	40	50	3	4	6	8
Displacement [mm]	0.85	0.54	0.49	0.12	0.12	1.03	1.68	1.41	0.28	1.10	1.04	2.57	3.92	0.64	1.57	3.13	1.11	1.01	0.72	0.66	0.61	0.85	0.80	0.67	0.80
Standard deviation [mm]	0.16	0.10	0.16	0.05	0.03	0.38	0.20	0.21	0.21	0.66	0.38	0.67	1.32	0.14	0.34	0.61	0.24	0.25	0.48	0.38	0.13	0.29	0.21	0.31	0.29



(a) No skin layer



(b) One skin layer



(c) Two skin layers

Figure 25: Effect of skin thickness