A remote control force feedback interface for MRI guided percutaneous interventions

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Abstract

This thesis reports the design and evaluation of a remote control interface, aimed to simulate the axial forces at the needle during percutaneous interventions on the lower area of a patient’s spinal cord. For evaluation, an in vitro experiment set up of different types of artificial tissues mimicking the varying types of tissue found on the spinal cord were used. The remote control force feedback interface, called the Master Control Device (MCD), controls in real-time the movement of a one-dimensional translation Manipulator (slave) with a needle and a force sensor attached to one end. The Manipulators force sensor data is then conveyed to the MCD handgrip. On the basis of this research it is determined whether the physician performance of tissue transition identification using the MCD compares to the manual identification performance.

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1. Introduction

Lower back pain on humans represents a significant health setback. To relieve pain and reduce swelling drugs are injected around the injured area. This non-invasive procedure is called percutaneous therapy.

The difficulties and dangers of this interventions thorough-the-skin involve the nerves, muscles, arteries and bone that surround the target area around the spinal cord, see Figure 1. Injuring any of these tissues can be very painful and sometimes have negative side effects, which can also irreversible. During percutaneous interventions, to prevent the needle tip from causing unwanted damage on its way to the spinal cord the incisions are performed in steps. The needle is manually inserted in the patient, see Figure 2, and a couple of minutes later at the end of each step the needle tip position is visually monitored either using Computer Tomography (CT) images or Magnetic Resonance Images (MRI).

CT images are easier, faster and cheaper to make. A drawback of CT images is the radiation load the patient and prominently the physician are exposed to. Compared to an MRI image a CT image also shows a lower image contrast of the soft tissues.

From all the imaging techniques available today, conventional high-field MRI scanners present the best-detailed images of the patient’s inner physiology and skeleton, with no known radiation risks. This report will concentrate on percutaneous interventions using this technique.

One of the downsides of MRI scanners is the narrow hole where the patient has to lay still while an image is made. The big magnets surrounding the narrow hole obstruct all access to the patient; see Figure 3.

If the needle insertion to administer drugs around the spinal cord needs to be performed in steps, the inaccessibility to the patient complicates the procedure. For the physician to be able to push the needle forward the patient must be taken out of the MRI, losing all position referencing. After the physician pushes the needle one step further the patient needs to be moved back into the MRI, new position reference points are required while the physician needs to walk back to the isolated control room where the monitor with the image is found. This must be repeated a number of times until the needle tip reaches the target area. These aspects augment the patients strain, procedure time and the physicians workload.

To make this type of intervention possible, an MRI compatible Manipulator, made out of non-ferro materials, and able to fit inside the MRI narrow tube together with the patient, was...
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developed; see Figure 3. The making of this Manipulator is a joint effort between the Forschungszentrum Karlsruhe and Innomedic GmbH, Germany. The Manipulator was named "Manipulator for Interventional RAdiology" (MIRA) and is intended to perform very accurate guided needle punctures followed by medicine administering; see Figure 4.

However, with the manipulator working on the patient inside the MRI the physician still lacks direct mechanical control and haptic feedback. Direct movement control of the needle implies that there is an exact correspondence between the input of the physician and needle movement. Haptic cues help the physician make an accurate diagnose, for example whether to insert the needle further or withdraw, rectify path and start all over again before causing any unnecessary damage.

The purpose of the work presented in this report is to develop a remote control interface, capable to guide in real time the movements of the needle attached at one end of the MIRA Manipulator. Another goal was to include haptic technology to the remote control interface. To achieve this, the MCD was implemented with a force equivalent to the one measured by the Manipulator's force sensor. This produced force would be exerted on the user's hand while holding the handgrip of the remote control interface. Through this report this produced force will be called the force feedback.

A remote control force feedback interface with 4 Degrees Of Freedom (DOF) was designed. Due to a limited time schedule a force feedback interface for only 1 DOF was finally built. The 1 DOF force feedback was designed to simulate the translation motion and exerted forces of a needle insertion procedure. This interface was named the "Master Control Device" (MCD).

There are 3 important aspects the MCD provides the physician. Real-time axial movement control of the needle inside the MRI, visual feedback of the insertion depth directly from the MCD interface and haptic cues in the form of a pushing force equivalent to the tissue stiffness measured by the Manipulator's force sensor.

The potential benefits of a remote control force feedback interface are:

- Increase in safety allowing the physician to feel in real-time when the needle hits something hard like bone. The physician can concentrate on reading the MRI images while intuitively being aware of the needle position.
- Faster procedures, less strain to the patient and less workload for the physician, as the patient remains inside the MRI during the whole procedure.

Furthermore, in conjunction with a prototype Manipulator tests were conducted to evaluate the MCD performance; whether the insertion moment detection using the MCD compares to the detection score when the needle insertion is performed manually. Therefore a series of in vitro experiments were carried out, using a preliminary version of the Manipulator and different combinations of artificial tissues mimicking human tissue's stiffness. The subjects were presented with the MCD needle insertion simulation and the ability to identify the different types of tissue was registered.
2. Design

2.1. Design requirements

After careful deliberation and discussions with the Man Machine Interface (MMI) development members from the Forschungszentrum Karlsruhe and Innomedic GmbH, as well as with the medical supervisor Dr. A. Melzer, a table of requirements and wishes for the position control interface within the MIRA project was established. This table of in total 42 requirements and wishes can be found at Appendix I.

The requirements are the basic functions and structures the interface must support, in correspondence with the Slave Manipulator and control computers. The term KnockOut Requirement (KOR) is here introduced. These are the fundamental requirements; failure to fulfill one or more requirements would not allow the interface to guarantee a true simulation. In this case the complete system reliability and safety could not be assured.

The MCD design knockout requirements are: 150 mm axial traveling range, position control, mechanism stability and force feedback reflection.

The wishes found at the table from Appendix I are cues and conditions that would make the modeling of the interface more realistic for the physician as well as user friendly, important for the marketing success of the device. The lack of fulfillment of one or more wishes will not affect the performance of the interface or that of the robotic arm.

2.2. Design prototypes

Based on the established requirements and wishes, different concepts of the positioning system were assessed.

Rubber friction, see Figure 6

Mechanism uses two wheels surrounded by O-rings. A motor is connected to one of the wheels axle. A metal shaft is placed between the O-rings. The O-rings provide the friction force that translates the circular movement into a linear movement of the metal shaft.

Pros:
- Continuous linear movement of 150 mm absolute distance.

Cons:
- Short lifespan due to unpredicted rubber wear out due to friction.
- Too large, at least 300 mm for linear movement.

Incremental spring system, see Figure 7

By moving the metal shaft a spring exerts a force on the plastic element found at the base. The plastic element rotates around the main axle. An
Design

electric motor is connected to the main axle and is able to produce a counter torque.

Pros:
- Small size.

Cons:
- No absolute traveling range of 150 mm.
- Vague lifespan due to spring stiffness wear out.

**Cantilever**, see Figure 8

Two rods are joined and can rotate about their joining axle. The end of one of the rods is embedded in a gulley. The end of the other rod can rotate freely about an axle. A motor connected to this axle counteracts the torque produced by the gulley rectilinear movement.

Pros:
- Continuous linear movement of at least 150 mm traveling range.

Cons:
- Too big, lengthwise and sideways.
- Mechanism can not function without help of the electric motor in start and finish position since it is physically locked.

**Transmission, slant tooth wheel system**, see Figure 9

Mechanism uses a slant tooth wheel to translate the motor angular movement into the toothed rod rectilinear movement.

Pros:
- Continuous linear movement of at least 150 mm absolute distance.

Cons:
- Too much friction.
- Too large, at least 300 mm for linear movement.
- Expensive precision making and assembly.

**Telescope principle**, see Figure 10

Retractable construction. Rectilinear motion when the construction is pushed is counteracted by a string attached to an electric motor, pushing backwards.

Pros:
- Continuous linear movement of 150 mm absolute distance.
Only 150 mm traveling range are necessary.

Cons:
- Complicated and extremely accurate making are necessary.
- Steady state position movement vulnerability.

Impulse engine with a tightened cord around the axle, see Figure 11

A string is rolled about a motor shaft. The two ends of the string are passed through two pulleys and then are attached to the end of a shaft. The motor torque is in this way translated into a force opposite to the rectilinear shaft movement.

Pros:
- Continuous linear movement of 150 mm absolute distance.
- Only 150 mm traveling range are necessary.

Cons:
- Not suitable for the use of an external brake (outside the impulse engine).
- Already patented system.

Tooth wheel-tooth belt system

An electric motor is connected to a tooth wheel. The tooth wheel in turn is connected to a tooth belt. The torque to force transmission counteracts the pushing force exerted along the tooth belt.

Pros:
- Only 150 mm traveling range are necessary.
- Continuous linear movement of 150 mm absolute distance.

Cons:
- Tooth wheel-tooth belt friction.

2.3. Chosen design prototype

The chosen proposal to actually get built was the tooth-wheel-tooth-belt system. With the use of tooth belts the interface height can be kept as small as possible, while sufficing to the required traveling range of 150 mm linear movement.

It was original designed as a 4 Degrees Of Freedom (DOF) interface, with 1 DOF for force reflection.

At the base an actuator, in the form of an electric motor, would be fixed to one of the tooth wheels. When current signals are sent to the actuator the tooth wheel tooth belt mechanism would translate rotation of the electric motor shaft into linear movement, positioning the on the tooth belt mounted handgrip in place, as well as combining extra force for force reflection.

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The design also includes an encoder for position control and an electric brake for safety reasons.

As the interface task will be that of in real-time remotely control of the positioning of a needle, found at the end of a robotic arm, from this point the interface will be call a **Master Control Device** (MCD). The distant robotic arm with the needle, also known as the Manipulator, will be addressed as the Slave.

### 2.4. Choosing MCD components

To meet the internship time schedule at the Forschungszentrum Karlsruhe it was decided to only build a 1 DOF Master Control Device. The 1 DOF would simulate a linear needle insertion movement including force feedback. The actual fabrication and construction of the MCD would be carried out by the Forschungszentrum workshop.

The limited time schedule was also of big influence in the choosing of the MCD parts. Availability, fast as well as on time reliable delivery were predominant factors on the final decision-making.

**Chosen tooth belt:**

Tooth belts from Hilger und Kern GmbH, made out of polyurethane, with K profile teeth for best grip and precision of small dimensions mechanics were chosen, see Figure 12.

To make sure the expected 150 mm handgrip travel range was covered, a long tooth belt with 501 mm length was chosen. For the other connecting tooth belts a smaller alternative with a length of 165 mm was chosen.

**Chosen tooth wheels:**

The Hilger und Kern synchronized tooth wheels are specially designed to offer the best gearing with the polyurethane K profile tooth belts, see Figure 13.

Tooth wheels with safety lip were chosen above the not as reliable considered regular tooth wheels.

The tooth wheel connecting the motor shaft to the rest of the mechanism were chosen to have a diameter equal to 11 mm, while all other tooth wheels on the mechanism have a diameter equal to 23 mm. This to increase the torque of the driven wheel.
**Chosen linear handgrip bearing:**

To guide smoothly the linear movement of the handgrip, a linear bearing using a ball rail system from the company Rexroth Star was chosen, see Figure 14.

Besides fulfilling the expectations of being as light and as small as possible, being able to adjust the total length of the rail to the desire 150 mm traveling range was of great importance on choosing the miniature-ball-rail bearing.

**Chosen actuator (electric EC-motor):**

As servomotors are electric motors designed specially for high dynamics (i.e. fast acceleration and deceleration) and are extremely powerful for their size, an EC (brushless commutation) electric servomotor was chosen.

The expected maximum feedback force at the handgrip and therefore the maximum expected motor torque was used as the starting point to choose the motor size.

In correspondence with prior studies, see References [9], and adding an error margin of 4 N, the force reflection at the handgrip should be able to simulate a force range from 0 N to 8 N. The needle traveling in the air will be represented by the 0 N while the maximum of 8 N represents the forces acting upon the needle while inside hard tissue like tendons or bone.

The stall torque is the point with the least amount of load from which the motor can no longer turn the axle. Past this point either the motor will overheat due to too much current, or the voltage will drop because there is not enough supplied power. A servomotor made by the firma Maxon GmbH, with a stall torque equal to 0,116 Nm was chosen see Figure 15.

On the design the electric motor shaft will be fixed to a tooth wheels tooth belts mechanism, able to translate the motor torque into a linear force, see Figure 16. With the diameter (d,) of the tooth wheel connected to motor shaft equal to 11 mm, the equation to calculate the maximum available linear force at the handgrip level follows.

\[
T_{\text{stall motor}} = F_{\text{MAX}} * r_i \Rightarrow F_{\text{MAX}} = \frac{T_{\text{stall motor}}}{r_i} = \frac{0,116[Nm]}{0,0055[m]} = 21[N]
\]

Equation 1

The one Degree Of Freedom (DOF) force feedback interface could then have, in theory and ignoring friction forces, at the handgrip level a force reflection up to 21 N. This complies with the 8 N Manipulator’s measured force range of [0-8N].
Chosen encoder (mechanical potentiometer):

For an absolute displacement measurement an analog potentiometer as the measuring instrument was chosen. An analog potentiometer is less susceptible to noise and electromagnetic fields than most of the other digital or electromagnetic gauges.

The potentiometer, from Megatron AG & Co., see Figure 17, measures angular movement that then is translated to the equivalent linear movement.

Based on the 23mm tooth wheel diameter, to be able to measure the expected linear travel range of 150 mm, the number of turns the potentiometer should be able to make most be determined. The tooth wheel perimeter is to,

\[
p = \frac{d^2}{2} \cdot 2 \cdot \pi = 0,0115 \cdot 2 \cdot \pi = 0,072 \text{ [m]}
\]

Equation 2

That means a number of turns equal to,

\[
\frac{0,150}{0,072} = 2,08 \Rightarrow 3
\]

Chosen brake:

The MCD brake should be strong enough to stop all movement. If the controller determines the needle should not move any further, e.g. preventing it from going through bone, there should be no way the operator or any object accidentally hitting the MCD handgrip, can force the handgrip and thus the needle to move forward.

Made by Kendrion, a 28mm diameter cylindrical electromagnetic brake was chosen. The brake’s diameter is similar to that of other MCD components diameters. It also has a 2,2 Nm transmissible torque which means a transmissible axial force of 78 N, larger than the maximum human finger force of 50 N found on literature; see References [1].

Another important safety feature of this electromagnetic brake is that the braking effect is produced by a permanent magnetic field. This means that the required braking force is generated when voltage is removed. In case of an electric failure the brake stops all MCD and consequently Slave movements.

In the design the brake should be directly connected to the main axle. The main axle is directly connected to the handgrip and if necessary the brake should hinder all handgrip movement.
2.5. AutoCad drawings of MCD

For a clearer understanding of the MCD design, a preliminary model was made using a Computer Aided Design (AutoCAD) program. The drawing found on the next page, shows a 4 DOF force feedback interface including all the position measuring potentiometers, safety brakes and safety buttons. In yellow and orange the respectively tooth belts and tooth wheels of the mechanism can be seen. The electric motor is portrayed in red, the potentiometers in purple and the brakes in blue. The handgrip is represented in a magenta color and the linear bearing in green.

Due to the limited time schedule it was later decided to only have built a 1 DOF force feedback interface. Drawings and pictures from this 1 DOF force feedback interface can be seen in the coming chapters of this report.

Before the 1 degree of freedom MCD actually got built by the workshop of the Forschungszentrum Karlsruhe (FZK), the drawings were revised and improved by professional technical drawers. As other people than the author of this thesis sketched these professional drawings, they are not included in this report.
3. MCD-Slave system

After the MCD was built its performance was tested. Besides the MCD, the experimental environment made use of a prototype Manipulator, also called Slave, found at the Forschungszentrum Karlsruhe-Germany. This Manipulator from Amtec-robotics, seen on the right of Figure 19, performed one-dimensional translation motions with a traveling range greater than 150 mm. An encoder and a force sensor, also found at the Manipulator, reported respectively position and axial force changes.

A hollow needle made out of high-grade steel was firmly fastened to the Manipulator’s force sensor. The needle is a “Dispomed epiduralkanüle, 1,10 x 90 mm” type with a 1 mm diameter, and a slanted and curved needle tip by approximately 2 degrees, See Figure 19.

![Diagram of Master control Device (MCD) and Slave (Manipulator with needle)](image)

| y_1: MCD handgrip position          |
| y_2: MCD potentiometer's measured position |
| y_3: Slave needle tip position      |
| y_4: Slave potentiometer's measured position |
| I_1: Slave’s electric motor input current |
| I_2: MCD’s electric motor input current |
| F_{input}: Subject's input force at MCD handgrip |
| F_{sensor}: Measured force on needle |

Figure 19: Flow chart of the Master-Slave testing system

During the experiments the subject interacted with the remote control force feedback interface, the Master Control Device (MCD). When the subject moved the needle simulator, the MCD cylindrical handgrip, the MCD potentiometer captured the position changes (y_1). Every 20 millisecond the computer read the MCD potentiometer data (y_2) and transferred the kinematic sequence to the Manipulator that in real-time reproduced the movement (y_3), earning its title as Slave.

While the Manipulator moved, the fixed needle to one end was inserted in a stack of different types of artificial tissue. On the block diagram of the complete system seen in Figure 20, the stack of
artificial tissue is called the plant. The force sensor attached to the needle read the axial forces actuating on it ($F_{\text{insertion}}$). The force control was implemented in an open loop fashion by the computer. The force information ($F_{\text{sensor}}$) was in real-time sent to the computer, translated by the electronics in the form of a current signal ($I_2$) and received by the MCD electric motor. As the actuator, the electric motor produced a torque ($T_2$) that the tooth-wheel-tooth-belt transmission translated into a linear force. As the MCD handgrip is attached to the transmission tooth belt, by sending the appropriate voltage to the motor, the mechanism produced a linear force opposite to the handgrip movement called the force feedback ($F_{\text{feedback}}$).

Depending on the position of the needle, the subject felt different force reflections (feedback) with a 50 Hz update rate. In theory (ignoring friction) the MCD could exert through the handgrip a 21 N pushing force on the subject’s hand, see Equation 1 and Figure 16.

![Block diagram of the complete Master-Slave system](image)

- $y_1$: MCD handgrip position
- $y_2$: MCD potentiometer’s measured position
- $y_3$: Slave needle tip position
- $y_4$: Slave potentiometer’s measured position
- $I_1$: Slave’s electric motor input current
- $I_2$: MCD’s electric motor input current
- $T_1$: Slave’s electronic motor torque
- $T_2$: MCD’s electronic motor torque
- $F_{\text{forward}}$: Manipulator axial force that makes the needle move forward
- $F_{\text{insertion}}$: Needle insertion force in tissue
- $F_{\text{sensor}}$: Measured force on needle
- $F_{\text{friction}}$: Average friction force of MCD mechanical system
- $F_{\text{feedback}}$: Opposite force to movement felt by subject at MCD handgrip

**Figure 20**: Block diagram of the complete Master-Slave system

The better the MCD’s force feedback reproduces the measured force by the Slave sensor, the better the subject will be able to identify the different types of tissue as it would if the needle insertion was performed directly by hand. In the next chapters other aspects having an effect on this force are considered and experiments to validate the theoretical and practical outcome are carried out.
As previously stated, this report concentrates on the Master Control Device portion of the Master-Slave system, see Figure 21.

![Block diagram of Master Control Device](image)

Figure 21: Master Control Device block diagram
4. Design limitations

4.1. Friction forces on the MCD

Once the Master Control Device was built, in an attempt to determine all the contributing elements to the force feedback, the friction forces were measured and categorized. Using a spring scale the friction forces occurring when trying to move the handgrip were determined. See respectively Figure 22 and Figure 23.
To measure the friction forces acting on the MCD, first the electric motor was disconnected allowing free movement of the shaft. Then the total force needed to move the handgrip from the bottom to the top (150 mm) was measured.

The average force needed to start moving the handgrip was equal to 0,58 N.

The MCD was subsequently taken apart to determine how much each part contributed to the total friction force needed to move the handgrip from the bottom to the top.

Having in place only the MCD’s skeleton, see Figure 25, the needed force to start moving the linear bearing was measured to be 0,06 N.

Then the handgrip was remounted on the linear bearing. The needed force to start moving the handgrip was equal to 0,28 N.

As the tooth belts and tooth wheels also convey in friction forces, the next part to be added and tested was the long tooth belt, see Figure 26.

With the long tooth belt and its corresponding tooth wheels included, the needed force to start moving the handgrip was equal to 0,51 N.

To compensate the mechanical structure instability caused by the handgrip weight a counterweight was introduced, see Figure 27. With the needed force to start moving the handgrip was equal to 0,28 N.
To determine the influence of the brake, it was reinstalled, see Figure 28, and then once again the forces needed to move the handgrip were measured.

Brake included, the needed force to start moving the handgrip was equal to 0.28 N, which supported the claim of the manufacturer of a “reliable brake release with zero residual torque in any mounting position”.

Wanting to know what the contribution of the potentiometer was, it was subsequently reinstalled, together with its corresponding tooth belt and tooth wheels, see Figure 29.

With the potentiometer interaction, the needed force to start moving the handgrip was equal to 0.44 N.

At last, the disconnected electric servomotor was connected as well as its corresponding tooth belt and tooth wheels, and the force along the handgrip linear movement was measured.

With all components of the MCD in place and connected, the needed force to start moving the handgrip was again equal to 0.58 N.
To get a better view of the contribution each MCD component made a chart with the percentage contributions of each component is shown below.

![Pie chart displaying the allocation of the MCD friction force](image)

From the chart it is evident that the connecting tooth-belt-tooth-wheels mechanisms are by far the greatest contributors to the friction forces. As the friction forces vary with time, for improved versions of the MCD it is suggested to reconsider new and more efficient transmission mechanisms.
4.2. MCD(Master)-Slave force feedback calibration

Initially the MCD-Slave system was set in a 1:1 ratio in order to get a true simulation of the force measured by the Slave force sensor.

Initial tests revealed that instability occurred within normal operating range. Using an iterative method a force ratio was found that did not lead to instability during normal operation. A force ratio as close as possible to the ideal 1:1 ratio was chosen. This ratio, defined as the quotient of the MCD's motor output force and the measured force at the slave, has a value of 0.7.

The MCD instability is caused by the inertia of the electric motor. First the measured force by the Manipulator’s force sensor is fed back into the Electronic Control Unit (ECU), which in turn sends an electric current to the MCD motor. The angular acceleration of the motor is hereby increased. However, the reaction time of the motor caused by inertia limits the maximum achievable acceleration.

The inertia of the Manipulator’s electric motor also contributes to the instability and affects the performance of the complete system. Because the Manipulator performance was not a part of this study it is not discussed here in depth.

There is also a tracking error ($t_e$) between the Manipulator and the MCD due to inherent reaction time of mechanical systems. This tracking error was set to $-15\text{mm} < t_e < 9\text{mm}$. Exceeding this limit, for example when the MCD handgrip is moved too fast, the safety brake will stop all movement.
4.3. MCD’s force feedback validation

With an already chosen software scaling value $k = 0.7$ and a spring scale to be used as gauge, the theoretical and real force feedback values felt at the MCD’s handgrip were respectively estimated and measured. Later the two were validated against each other.

In theory:

A dynamic model with the MCD’s handgrip force diagram was made, see Figure 31.

\[ m \cdot \ddot{y} = F_{\text{subject}} - F_{\text{drive handgrip}} - F_{\text{friction}} \]

**Equation 3**

To simulate the measured force at the slave’s needle tip ($F_{\text{slave sensor}}$) while also making use of the scale down index to prevent instability the expected electric motor torque becomes,

\[ T_{\text{MCD motor}} = (0.7 \times F_{\text{slave sensor}}) \times r_1 \]

**Equation 4**

Using the force diagram of the MCD’s motor-tooth wheels transmission, see Figure 32, the motor’s tooth wheel delivered force ($F_1$) is equal to,

\[ F_1 = \frac{T_{\text{MCD motor}}}{r_1} \Rightarrow F_1 = \frac{(0.7 \times F_{\text{slave sensor}}) \times r_1}{r_1} \Rightarrow F_1 = 0.7 \times F_{\text{slave sensor}} \]

**Equation 5**

Because all main axle tooth wheels have the same diameter
MCD(Master)-Slave force feedback calibration

$r_2 = r_3$ and $F_1 = F_2$, therefore

$$T_{\text{main \ axle \ main \ axle}} = F_2 \cdot r_2 = F_{\text{drive \ handgrip \ handgrip}} \cdot r_3 \Rightarrow F_{\text{drive \ handgrip \ handgrip}} = 0.7 \cdot F_{\text{Slave sensor \ sensor}}$$

Equation 6

Substituting the estimated friction force in Equation 3 and assuming the handgrip behaves in a stationary manner with $\dot{y} = 0$, the following expression gives the in theory expected force feedback at the MCD’s handgrip,

$$F_{\text{in \ theory \ handgrip \ handgrip \ feedback}} = F_{\text{drive \ handgrip \ handgrip \ feedback}} + F_{\text{friction \ handgrip \ handgrip \ friction}} = (0.7 \cdot F_{\text{Slave sensor \ sensor \ force \ feedback}}) + 0.58$$

Equation 7

The measured force at the Slave ($F_{\text{Slave sensor \ sensor \ force \ feedback}}$) has a range from 0 to 8 Newton.

In practice:

First a pushing force was exerted on the needle found at one end of the Slave Manipulator. Then the force sensor readings ($F_{\text{Slave sensor \ sensor \ force \ feedback}}$), shown on the User Interface screen, were written down, see original document at Appendix II. At the same time a spring scale was attached to the MCD’s handgrip. By pulling the spring scale, opposite to the movement direction, until the handgrip became stationary, the spring scale reading corresponded to the equal but opposite force needed to cancel the electric motor driving force. This procedure was repeated at all different force sensor readings.

Theory and practice validation:

Comparing the in Equation 7 calculated theoretical force feedback values to the in practice measured real values at the MCD handgrip, a model error ($e$) estimation was determined.

$$e = F_{\text{in \ theory \ handgrip \ handgrip \ feedback}} - F_{\text{measured \ handgrip \ handgrip \ feedback}}$$

Equation 8

<table>
<thead>
<tr>
<th>Force sensor output (New)</th>
<th>In theory handgrip force feedback (New)</th>
<th>Average measured force feedback (New)</th>
<th>Model error $e$ (New)</th>
<th>% Deviation of theoretical and measured model</th>
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<td>5</td>
<td>4.08</td>
<td>1.80</td>
<td>2.28</td>
<td>56%</td>
</tr>
<tr>
<td>6</td>
<td>4.78</td>
<td>2.20</td>
<td>2.58</td>
<td>54%</td>
</tr>
</tbody>
</table>

S. Boscán Chapellin
Table 1: MCD real and modeled force feedback data

In Figure 33 it can be seen that the theoretical model does not follow the measured data all the way. The higher the measured value the smaller the theoretical model error becomes. This is to be expected as the friction force from Equation 7 (0.58 N) is considered to be a constant. At low-level force feedback scenarios the friction force has a predominant character, at higher-level force feedback scenarios the other forces take over.

Figure 33: MCD model validation graphic
5. Experiment

In vitro, perceptual experiments were conducted with 9 volunteer subjects in experiment 2 and 11 in experiment 3, aged 25-61. More information on the subjects can be found on Appendix III. Two of the subjects were physicians and one a nurse. They had extensive experience with real needle insertions. The other subjects had had on average low exposure to real needle insertion and seldom exposure to haptic interfaces in the past.

To get the subjects familiar with the protocol and MCD mechanics, the experiments started with a demonstration of what they were expected to do, manually as well as using the MCD.

The actual experiments consisted of 4 different scenarios. The 3 manual scenarios consisted of 2 trials each and the simulation scenario using the MCD of 3 trials. Scenarios and trials were presented in a random order to minimize learning effects. Right before each trial, the order in which three labels with the tissue names were picked from a hat randomly determined the order of the tissues in the stack.

The goal of the first scenario was to document the subject’s identification capability of different types of artificial tissue. The purpose of the other two scenarios was to document the subject’s identification score of the transition moment from one type of tissue to another, when the artificial tissues were stacked on top of each other. For the identification, the subject relied uniquely on the force feedback felt at a needle inserted on the stack of tissues or on the force feedback simulated by the Master Control Device.

During all in vitro experiment, three different types of artificial tissues were used. Depending on their strain resistance characteristics they were labeled Soft, Medium and Hard. The artificial tissue stiffness labeled as Soft simulates that of fat tissue, the one labeled Medium simulates muscle stiffness and the one labeled Hard simulates bone stiffness. More information on tissue type can be found at Appendix IV.

The properties of the needle used in experiment 2 and 3 are:

- Name: Dispomed epiduralkanüle
- Type: 1,10 x 90 mm.
- Material: high-grade steel.
- Diameter: 1 mm.
- Needle tip shape: slanted and curved by approximately 2 degrees.
- Massive or hollow: hollow.

5.1. Experiment 1: pressing individual tissues with fingers

To guarantee the experiment test exclusively on force feedback without any extra cues on other tactile, sound or visual feedback, the test subject was asked to wear thin gloves, earplugs and a blindfold.

The 3 different types of artificial tissue Soft, Medium and Hard were randomly placed in front of the Subject. Then, each individual perception on what is Soft, Medium and
Hard was documented by asking each Subject to press and identify each type of tissue.

5.2. Experiment 2: insertion in a stack while holding the needle directly

To test the subject’s sensitivity to the transition from one material to another, the subject was asked to manually insert a needle on a stack, built out of artificial tissue layers already used in experiment 1. Again, the soft material stiffness was equivalent to fat tissue stiffness, the Medium material equivalent to muscle and the Hard material equivalent to bone.

With 3 different types of tissue, 6 randomly chosen environments were available. See Figure 34

![Figure 34: With 3 types of tissue there are 3! layers order available.](image)

The Soft tissue had a 30 mm height, the Hard tissue a 10 mm height and the Medium type tissue a 31 mm height.

The needle used was that of the same type mounted on the Slave Manipulator, see Chapter 3 MCD-Slave system. To evaluate the Subject’ detection score, on the body of the needle, the height of each transition position was marked in order to identify whether the subject claim to have felt a transition was accurate or not.

Once more, to guarantee the layer transition detection to be exclusively due to haptic cues and not due to visual or sound cues, the subject was wearing earplugs and blinded while the experiment was taking place.

5.3. Experiment 3: MCD simulation of needle insertion in stacked tissues

The goal of the third in vitro experiment was to test whether the Master Control Device enables accurate detection of the transition from one layer type to another.

For this test, the same stack of artificial tissue used in experiment 2, in random order, was placed under the needle and force sensor attached to the Manipulator, see Figure 35.
5.4. Picture MCD experiment with subject

The subject was asked to hold the MCD handgrip with 2 fingers; in the same manner he/she would hold a pen. Then, knowing the MCD remotely controlled the Manipulator movements in real-time, they were asked to insert the Manipulator’s needle on the stack of different types of tissue. By pressing a black button the subject could indicate the moment a material transition was felt. The data recorded can be seen in Table 2.

Table 2: Electronically recorded data

<table>
<thead>
<tr>
<th>Time:</th>
<th>Sampling time 20 ms.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Master (MCD) position:</strong></td>
<td>Measured by MCD’s potentiometer.</td>
</tr>
<tr>
<td>a) Slave (robotic arm) position:</td>
<td>Measured by Slave Manipulator’s potentiometer.</td>
</tr>
<tr>
<td>b) Slave (robotic arm) force:</td>
<td>Measured by force sensor at robotic arm.</td>
</tr>
<tr>
<td>c) Current sent to MCD electric motor:</td>
<td>Equivalent to measured force by the Manipulator’s force sensor.</td>
</tr>
<tr>
<td>d) Subject’s moment of material transition detection:</td>
<td>Pressing black button when a transition was felt.</td>
</tr>
</tbody>
</table>

To make sure the subject relied completely on force feedback he/she wore earplugs to prevent sound cues. Also, to impede visual cues of the artificial tissues boundaries, a black screen was placed between the subject and the Manipulator.
6. Results and discussion

During independent identification where each tissue type is expected to be recognized individually, as in experiments 1, the sensitivity levels regarding the subject’s own perception on what is Soft, Medium and Hard are tested. In identifications in series where all tissue types are stacked on top of each other, such as experiments 2 and 3, the history of the needle tip position is also evaluated, as prior tissue’s friction and adhesion forces actuating on the body of the needle add up with each new type of material.

In experiment 1 pressing with the fingers on each artificial tissue individually, not all subjects labeled the three different types of materials as expected. Although most of them did, it is obvious that the sensitivity levels and perception on what is Soft, Medium and Hard varies per individual.

Experiment 2 shows that manual detection of the transition from one type of tissue to another is not always possible, although the transition to a Hard layer with the highest stiffness from all three possible layers type, was well detected. Experiment 3, making use of the MCD needle insertion simulation, shows also a reasonable Hard tissue detection and an inconsistent Soft and Medium tissue detection.

6.1. Experiment 1 results and discussion: pressing individual tissues with fingers

In experiment 1, after each subject pressed with the fingers the three available tissue types, an identification accuracy with a mean of 89% and a median of accurate detection of 91% made clear that the subject’s tactile capabilities were in order; see Figure 36. Although the average score was 89%, half of the subjects had a detection score higher than 91%, namely an 100% accurate detection score.

Not all subjects agreed with the artificial tissues classification of Soft, Medium and Hard. Some would call the Medium tissue a harder tissue than the Soft, after having pressed on both tissue and being able to compare, but would not say the word Medium. Others would call the Hard tissue the hardest of all but would not label it a Hard.

Sensitivity levels vary per person. It is expected that some training can standardize these individual perceptions, as would be the case with radiologists and physicians.
Results and discussion

Experiment 1 score of tactile tissue type identification

Figure 36: Experiment 1 results of tactile tissue type identification with the number of subjects equal to 8.
6.2. Experiment 2 results and discussion: insertion in a stack while holding the needle directly

In experiment 2, inserting a needle manually on a stack built out of three different types of artificial tissue, presented a new set of variables as well as a new set of force characteristics, see Appendix V.

With material transition identification of tissues stacked on top of each other, friction and adhesion forces on the body of the needle add up with each new type of material. Therefore the needle tip path and position are key to the transition detection score. Herewith is the history of the needle tip is also evaluated.

From the results found in Table 3 it was observed that in low-level force feedback scenarios users would not benefit from a 1:1 force feedback simulation. When the Soft tissue was placed under other tissues the identification score was never higher than 67%; the lowest being 0% with the air/H/S/M and air/H/M/S combination. The Soft tissue is the type of tissue equivalent to fat, with a required cutting force of 0,7 N and 4 mJoul work needed to move the needle inside the tissue 10 mm forward; see Appendix IV.

The Medium type of tissue was neither well identified in experiment 2. The highest registered identification score was 50% and the lowest 0% in the air/H/S/M combination. The Medium tissue representing muscle, requires a cutting force equal to 1 N for the needle to get through the surface and 5,5 mJoul work to move the needle forward by 10 mm.

Inserting the needle directly to high-force scenarios, even if the Hard tissue was placed under the other types of tissue, was consistently recognized. A perfect identification score of 100% and the lowest identification score of 75% at the air/M/S/H combination validate this. The Hard tissue equivalent to bone required a cutting force equal to 4 N and a work of 36 mJoul was needed to move the needle forward by 10 mm.

Unexpected, the highest detection score of the Soft material (88%) on the top layer was higher than that of the Medium material (80%) in the first position. It is thought that the inconsistent results are caused by too few total numbers of trials. There were 9 subjects with 3 trials each (from which 1 discarded due to corrupted results). In each trial the three tissues combination on the stack was chosen randomly. The small differences between the two materials, with a cutting force difference of only 0,3 N and 1,5 mJoul difference in work needed to push the needle forward could also have had an effect in the inconsistency. Subject's sensing threshold varied significantly.
### Table 3: Detection scores of tissues in experiment 2.

<table>
<thead>
<tr>
<th>Hand held needle</th>
<th># detected</th>
<th>Total trials</th>
<th>Detection ratio</th>
<th>% detection</th>
</tr>
</thead>
<tbody>
<tr>
<td>air/S</td>
<td>7</td>
<td>8</td>
<td>0.88</td>
<td>88%</td>
</tr>
<tr>
<td>air/M/S</td>
<td>1</td>
<td>4</td>
<td>0.25</td>
<td>25%</td>
</tr>
<tr>
<td>air/H/S</td>
<td>1</td>
<td>2</td>
<td>0.50</td>
<td>50%</td>
</tr>
<tr>
<td>air/M/H/S</td>
<td>4</td>
<td>6</td>
<td>0.67</td>
<td>67%</td>
</tr>
<tr>
<td>air/H/M/S</td>
<td>0</td>
<td>6</td>
<td>0.00</td>
<td>0%</td>
</tr>
<tr>
<td>air/M</td>
<td>8</td>
<td>10</td>
<td>0.80</td>
<td>80%</td>
</tr>
<tr>
<td>air/S/M</td>
<td>1</td>
<td>2</td>
<td>0.50</td>
<td>50%</td>
</tr>
<tr>
<td>air/H/M</td>
<td>1</td>
<td>6</td>
<td>0.17</td>
<td>17%</td>
</tr>
<tr>
<td>air/S/H/M</td>
<td>2</td>
<td>6</td>
<td>0.33</td>
<td>33%</td>
</tr>
<tr>
<td>air/H/S/M</td>
<td>0</td>
<td>2</td>
<td>0.00</td>
<td>0%</td>
</tr>
<tr>
<td>air/H</td>
<td>8</td>
<td>8</td>
<td>1.00</td>
<td>100%</td>
</tr>
<tr>
<td>air/S/H</td>
<td>5</td>
<td>6</td>
<td>0.83</td>
<td>83%</td>
</tr>
<tr>
<td>air/M/H</td>
<td>6</td>
<td>6</td>
<td>1.00</td>
<td>100%</td>
</tr>
<tr>
<td>air/S/M/H</td>
<td>2</td>
<td>2</td>
<td>1.00</td>
<td>100%</td>
</tr>
<tr>
<td>air/M/S/H</td>
<td>3</td>
<td>4</td>
<td>0.75</td>
<td>75%</td>
</tr>
</tbody>
</table>
6.3. Experiment 3 results and discussion: MCD simulation of needle insertion in stacked tissues

After the MCD simulation in experiment 3, using Matlab a custom made program found in the recorded data from Table 2 was translated into charts. To illustrate how this charts look and how the analysis of the data was carried out a few examples are shown in this chapter.

In the graphs, from which three examples are discuss in Figure 37, Figure 38 and Figure 39, the x-axis depicts the traveling distance of the needle tip, starting from the left and ending at the right, and the y-axis depicts the axial forces acting on the needle at each position within the stack of artificial tissues. With the magenta color the beginning of the type tissue Medium is portrayed. In green the beginning of the Soft tissue and in red the beginning of the Hard tissue. Vertical lines portray the expected beginning of each tissue layer without compression. In the same color but with dashed lines the expected material compression is specified. The compression is the result of the needle pushing the material before cutting the material and actually going inside.

The black dots represent the moment the subject pushed the black button indicating the feeling of a new layer transition. For correct layer detection the black dots should be near the dashed lines representing the expected material compression.

The blue trace shows the on the needle tip acting axial force characteristic, measured by the Slave’s force sensor.

Figure 37: Needle tip force characteristic during experiment 3.2 Subject #5. The black dots represent the subject’s felt material transition, M=Medium layer, S=Soft layer and H=hard layer.
The cause of the blue trace fluctuations, it is thought to be the effect of transversal forces on the needle shaft and material inhomogeneity. Parallel experiments with a lubricated needle did not show any improvement on this behavior.

Instrumental noise e.g. force sensor noise and potentiometers noise it is thought to be insignificant as seen on the force (blue) line before the needle enters any material.

An unpredicted outcome of the force characteristics in experiment 3 is that the remarkable force increases or decays do not always correspond with the expected layer transitions. For example, at the Medium to Soft transition on Figure 37, the black dot shows recognition of 1 Newton force increase in a force domain of [2,3-3,3] Newton. Surprising is the lack of recognition of the prior force increase and decrease of 1,5 Newton. It appears that the subject pushed the button too late. This behavior obscure the results. Consequently subject # 5 was considered to have been able to identify all layers transitions in Figure 37.

Figure 38: Needle tip force characteristic during experiment 3.1 Subject #3. The black dots represent the subject’s felt material transition, M=Medium layer, S=Soft layer and H=hard layer. The two black buttons on top of each other at the Hard layer transition simply show the subject’s behavior of double pressing the black button confirming a sensed transition, maybe he/she wasn’t sure the black button was properly pressed the first time.

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In Figure 38 only the transition from the Medium layer to the Hard layer was identified, however one should reflect on the subject's detection of a real decrease in force by 3.5 Newton at the Soft layer, far away from the expected transition line.

The lowest force variation felt was that of 2.7 New, on a force domain of [2.9-5.6] Newton. Compared to Figure 37 it shows different subjects have different tactile threshold, in this case with a 1.7 Newton difference.

In Figure 39 the Hard layer is the first layer the needle goes through. The increase in force amplitude is clear and was detected. At the detected Soft layer a significant discrepancy of the real force decrease and the expected tissue compression could also be seen.

In experiment 3, where the forces acting on the needle were simulated by the MCD, the Soft and Medium tissue were also badly and inconsistently recognized. The lowest recognition of the Soft tissue was equal to 13% and the highest score was equal to 100%. Initially it appears that the MCD performance outstand the detection score when the insertion is performed manually but, the results of these preliminary experiments should be treated with caution. Experiment 2 and 3 had different protocols to determine whether a material transition was identified or not. In experiment 2 a visually coincide labeled needle with each layer's beginning and end, and the subject's judgment were used. In experiment 3 the automatically recorded data and the subject's judgment were used.
Exp.3 MCD handgrip | # detected | Total trials | Detection ratio | % detection
--- | --- | --- | --- | ---
air/S | 2 | 15 | 0.13 | 13%
air/M/S | 2 | 6 | 0.33 | 33%
air/H/S | 3 | 4 | 0.75 | 75%
air/M/H/S | 2 | 3 | 0.67 | 67%
air/H/M/S | 2 | 2 | 1.00 | 100%
air/M | 4 | 9 | 0.44 | 44%
air/S/M | 3 | 4 | 0.75 | 75%
air/H/M | 2 | 2 | 1.00 | 100%
air/S/H/M | 3 | 11 | 0.27 | 27%
air/H/S/M | 1 | 4 | 0.25 | 25%
air/H | 5 | 6 | 0.83 | 83%
air/S/H | 10 | 11 | 0.91 | 91%
air/M/H | 3 | 3 | 1.00 | 100%
air/S/M/H | 4 | 4 | 1.00 | 100%
air/M/S/H | 4 | 6 | 0.67 | 67%

Table 4: Scores of tissue detection in experiment 3.
6.4. Manual insertion (Exp.2) against MCD simulation (Exp.3)

Table 5 shows the results of the detection experiments 2 and 3. From this table it can be concluded that the Hard tissue is better detected than Medium and Soft tissue, in both experiments. Actually the Hard tissue is detected approximately twice as often as the Soft and Medium tissue.

Furthermore the detection score in the experiment with MCD is lower than in the experiment where the needle was held directly by the subject. In the case of Soft tissue the detection score with the MCD is even significantly lower, which implies that further improvements on the MCD for detection in the Soft tissue range are needed. However, it should be mentioned that the tooth-wheel-tooth-belt mechanism in the MCD gives rise to little force fluctuations due to play between the teeth. The force fluctuations may be dominant over the cutting force needed for the Soft tissue, which makes it harder to detect the transition.

Table 5: Detection scores for each tissue (S, M, and H) in experiment 2 and 3.

<table>
<thead>
<tr>
<th>Exp.2</th>
<th># detected</th>
<th>Total trials</th>
<th>Detection ratio</th>
<th>% detection</th>
<th>Exp.3</th>
<th># detected</th>
<th>Total trials</th>
<th>Detection ratio</th>
<th>% detection</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hand held needle</td>
<td>S</td>
<td>13</td>
<td>26</td>
<td>0.50</td>
<td>50</td>
<td>MCD handgrip</td>
<td>S</td>
<td>11</td>
<td>30</td>
</tr>
<tr>
<td></td>
<td>M</td>
<td>12</td>
<td>26</td>
<td>0.46</td>
<td>46</td>
<td></td>
<td>M</td>
<td>13</td>
<td>30</td>
</tr>
<tr>
<td></td>
<td>H</td>
<td>24</td>
<td>26</td>
<td>0.92</td>
<td>92</td>
<td></td>
<td>H</td>
<td>26</td>
<td>30</td>
</tr>
</tbody>
</table>

Table 6: Detection scores for each tissue (S, M and H), classified by the occurrence and order of the other types of tissue on top.

<table>
<thead>
<tr>
<th>Exp.2</th>
<th># detected</th>
<th>Total trials</th>
<th>Detection ratio</th>
<th>% detection</th>
<th>Exp.3</th>
<th># detected</th>
<th>Total trials</th>
<th>Detection ratio</th>
<th>% detection</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hand held needle</td>
<td>air/S</td>
<td>7</td>
<td>8</td>
<td>0.88</td>
<td>88%</td>
<td>MCD handgrip</td>
<td>air/S</td>
<td>2</td>
<td>15</td>
</tr>
<tr>
<td></td>
<td>air/M/S</td>
<td>1</td>
<td>4</td>
<td>0.25</td>
<td>25%</td>
<td></td>
<td>air/M/S</td>
<td>2</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>air/H/S</td>
<td>1</td>
<td>2</td>
<td>0.50</td>
<td>50%</td>
<td></td>
<td>air/H/S</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>air/M/H/S</td>
<td>4</td>
<td>6</td>
<td>0.67</td>
<td>67%</td>
<td></td>
<td>air/M/H/S</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>air/H/M/S</td>
<td>0</td>
<td>6</td>
<td>0.00</td>
<td>0%</td>
<td></td>
<td>air/H/M/S</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>air/M</td>
<td>8</td>
<td>10</td>
<td>0.80</td>
<td>80%</td>
<td></td>
<td>air/M</td>
<td>4</td>
<td>9</td>
</tr>
<tr>
<td></td>
<td>air/S/M</td>
<td>1</td>
<td>2</td>
<td>0.50</td>
<td>50%</td>
<td></td>
<td>air/S/M</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>air/H/M</td>
<td>1</td>
<td>6</td>
<td>0.17</td>
<td>17%</td>
<td></td>
<td>air/H/M</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>air/S/H/M</td>
<td>2</td>
<td>6</td>
<td>0.33</td>
<td>33%</td>
<td></td>
<td>air/S/H/M</td>
<td>3</td>
<td>11</td>
</tr>
<tr>
<td></td>
<td>air/H/S/M</td>
<td>0</td>
<td>2</td>
<td>0.00</td>
<td>0%</td>
<td></td>
<td>air/H/S/M</td>
<td>1</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>air/H</td>
<td>8</td>
<td>8</td>
<td>1.00</td>
<td>100%</td>
<td></td>
<td>air/H</td>
<td>5</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>air/S/H</td>
<td>5</td>
<td>6</td>
<td>0.83</td>
<td>83%</td>
<td></td>
<td>air/S/H</td>
<td>10</td>
<td>11</td>
</tr>
<tr>
<td></td>
<td>air/M/H</td>
<td>6</td>
<td>6</td>
<td>1.00</td>
<td>100%</td>
<td></td>
<td>air/M/H</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>air/S/M/H</td>
<td>2</td>
<td>2</td>
<td>1.00</td>
<td>100%</td>
<td></td>
<td>air/S/M/H</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>air/M/S/H</td>
<td>3</td>
<td>4</td>
<td>0.75</td>
<td>75%</td>
<td></td>
<td>air/M/S/H</td>
<td>4</td>
<td>6</td>
</tr>
</tbody>
</table>
**Results and discussion**

**Figure 40:** Graphic showing all subject’s tissue transition detection score when the needle insertion was performed manually and using the MCD.

Figure 40 shows all detection scores from experiment 2 and 3. When Hard tissue is encountered on top of the stack, the chance of detection of softer tissues below decrease.
7. Conclusion

Accomplishments

The goal of developing a remote control interface including force feedback has been met.

Experiments to evaluate the force feedback interface were performed. Three different types of tissue simulating fat, muscle and bone stiffness were used. Subject’ score of tissues type identification were documented. Using this approach, accurate identification of events during a needle insertion procedure was shown to be possible. The Hard tissue representing bone was the best identified tissue. The Soft and Medium tissue representing respectively fat and muscle were less often detected.

The remote control force feedback interface is a worthwhile concept to implement into the MIRA project. Percutaneous interventions can be improved by using MRI images as visual feedback and the force feedback interface (MCD) for remote movement control. Presenting haptic cues in the form of a produced pushing force allows the physician to feel in real-time when the needle hits something hard like bone.

The MCD prototype was introduced to the public at the 2002 Radiologist Society of North America (RSNA) in Chicago, USA. See Appendix VII.

Experiment conclusions

From experiment 1 it was established that by pushing on each tissue directly with the globed finger the three different types of tissue were well recognized. However, when pushing indirectly using needle, as in experiment 2 and 3, the tissues are harder to detect. As well as holding the needle or using the MCD the soft tissue was the most difficult and by far not always detected. The hard tissue simulating bone was the best identified tissue type.

Using the MCD in experiment 3 and dependent on the occurrence of other tissues found on top of it, the lowest detection score of the Hard tissue was equal to 67% while the highest was equal to 100%. The average detection score was equal to 88% and the median was equal to 91%. Nonetheless, the MCD score does not compare yet to the detection score in experiment 2. When the needle was inserted directly into the tissue the detection score of the Hard tissue was not lower than 75%. The average detection score of the Hard tissue was then 92% and the median was equal to 100%. This leads to the conclusion that although the Hard tissue is in general easily detected when holding the needle directly, this detection may still be troubled when the needle has to penetrate first through several layers of other tissue.

Experiments and MCD design limitations

The small and unequal subject population of nine people in experiment 2 and eleven people in experiment 3 means that the experiment results have to be treated with caution. More tests need to be carried out on a wider range and larger number of
Conclusion

subjects to have a more accurate and reliable outcome of the MCD Master-Slave performance.

The subject as an actuator is very difficult to define. The unique and unpredictable behavior of each subject should always be kept in mind while analyzing the data.

Because of instability the MCD was not able to achieve a 1:1 force feedback simulation. An indexing with a factor 0.7 was successfully introduced to realize a stable performance of the MCD.

Due to the MCD’s friction forces, the force feedback had from the start an average bias of 0.58 Newton. The tooth-belt-tooth-wheels mechanisms are the primary contributors to the friction forces.

Suggestions for improvement of the MCD design

Because of the encountered tooth play and the friction forces that are inherent in tooth-wheel-tooth-belt mechanisms, one suggestion for improvement here is to reconsider other, more efficient transmission mechanisms for use in the MCD.

Force transfer from the needle to the MCD should be improved aiming at 1:1 force feedback simulation.

For a stable mechanical structure, implementing a counterweight to balance the handgrip weight was essential.

Sudden wrist movements (impulses) while holding the MCD handgrip were observed. For a better movement control implementing a support under the user’s wrist is suggested.

Although a potentiometer is a reliable absolute distance gauge, its rotating mechanical system encounters friction and does have a short lifespan. Linear Variable Differential Transformer (LVDT) position sensors have zero friction, therefore no wear out. An LVDT position sensor might be a better choice for the in the future improved MCD. However, it should be thoroughly verified that the MRI electromagnetic field would not interfere with the LVDT performance, even if this is found at the isolated control room. Another alternative for the potentiometer could be found in optical sensors. Optical sensors have also zero friction, therefore no wear. Using an optical encoder might therefore be a better choice for the in the future improved MCD.

As the detection of Soft proved to be difficult, an additional sensor at the needle may be required. Adding an electrical conductivity sensor [15] to the needle attached to the Manipulator, the force indexing could be manipulated to allow the operator to feel the electrical resistance between two surfaces such as the boundary between arteries and/or veins, normally impossible to be sensed. However, the MRI magnetic field influence in all electrical equipment might significantly affect the sensor.

Acquired knowledge
Conclusion

For reliability, the position sensor should never be directly connected to the motor shaft. If the motor starts spinning without control and/or the motor connection to the mechanism is damaged, the potentiometer will still only measure the handgrip movement and not the motor shaft movement.

For a clearer analysis of the results, the way in which the tissue order in a stack was randomly determined should be modified. The method that was used here resulted in an unequal distribution of tissue order combinations. A better method would ensure that every combination would occur an equal amount of times, so that the results with each different tissue order can be compared with each other.

Counterweight balancing is essential, to ensure mechanism stability.

Friction forces can have a major impact in the performance of the mechanism. As friction forces vary with time, they are very complex forces to control. As early as at the design stage should be avoided or kept to a minimum.

Randomly choosing the different available permutations to be presented to a subject prevent a trend from having an influence in the results. Making sure through the whole experiment each combination was available the same number of times, facilitate and clarify the data and results analysis.
8. *Future work*

From later experiments at the Forschungszentrum, not carried out by this study, needle insertions in real bio-tissue from the belly of a dead pig were performed.

It is envisage that the force feedback interface will be redesigned to be smaller, have less friction forces and more DOF than 1.

![Figure 41: A portion of the belly of a dead pig under the Manipulator with the needle attached to it.](image)
9. Bibliography


10. Publications

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- http://www.iai.fzk.de/medtech/medrob/index.htm
- http://www.scientificamerican.com/
- http://haptic.mech.nwu.edu/
- http://www.select-it.de/hapticio.html
- http://www.britannica.com/
Appendix I: Compilation all design requirements

After careful deliberation and discussions with the MMI development members from the Forschungszentrum Karlsruhe and Innomedic GmbH, as well as with the medical supervisor Dr. A. Melzer, a table of requirements and wishes for the MCD needed within the MIRA project has been established. This table will be presented in the following pages where the Master Control Device will consistently be shortened to MCD from now on.

The requirements are the basic functions and structures the MCD must suffice, in correspondence with the telerobotic arm and control computers. Failure to fulfill one or more requirements would not allowed to guarantee the true modelling of the MCD, nor the complete system reliability, nor the patient’s or operator’s safety. These requirements must be seen in narrow connection with the Man Machine Interface (MMI) as a whole. Therefore, references to the MMI as a total, as well as to the graphic display (GUI) are also registered in the table.

In here, one also assumes that the software for controlling/steering the MCD, runs in the MMI-computer. In many cases, where a demand stands in the column MMI, refers to this part of the control.

The wishes are cues and conditions that would make the modelling of the MCD more realistic for the operator, comfortable and easier to understand. The lack of fulfilment of one or more MCD wishes will not affect the performance of the robotic arm or the safety of the patient or operator.

The requirements and wishes will be denoted with a :
D = Demand  
W = Wish

<table>
<thead>
<tr>
<th>MMI</th>
<th>GUI</th>
<th>MCD</th>
<th>Request’s current number</th>
<th>Operational Aspects</th>
<th>Comments/Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>D</td>
<td>D</td>
<td>D</td>
<td>1</td>
<td>Position control principle without scaling and indexing.</td>
<td>1:1-Model. All Axes synchron.</td>
</tr>
<tr>
<td>D</td>
<td>D</td>
<td>D</td>
<td>2</td>
<td>For the purpose of visual Feedback only to be used together with GUI, device does not stand-alone.</td>
<td></td>
</tr>
<tr>
<td>D</td>
<td></td>
<td></td>
<td>3</td>
<td>Suitable for operating through a protective plastic cover.</td>
<td>A7 (See Appendix I).</td>
</tr>
<tr>
<td>D</td>
<td></td>
<td></td>
<td>4</td>
<td>To be used in a field-strength &lt; 3mT; survival ability up to a field-strength of 20mT.</td>
<td>A3 (See Appendix I).</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td><strong>Kinematics/Mechanical Aspects</strong></td>
<td></td>
</tr>
<tr>
<td>D</td>
<td></td>
<td></td>
<td>5</td>
<td>At least 2 axes (insertion and rotation) max. 4 axes (supplementary due to correction in orientation).</td>
<td>See axes denotation in Appendix II.</td>
</tr>
<tr>
<td>D</td>
<td></td>
<td></td>
<td>6</td>
<td>Movement range for rotation</td>
<td>Specially during</td>
</tr>
</tbody>
</table>

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| D | 7 | ±180° in accordance with the PRT therapy requirements. |
| W | 8 | Stable equilibrium of all axes, especially when left alone, without hand contact. |
| W | 9 | Appreciation of the stand/situation of the needle is obvious at the MCD. |
| W | 10 | Ergonomic grip, preferable with a penholder shape (tweezers grip). |
| D | 11 | Mechanical brakes for all degrees of freedom. |
| W | D | Force transmission components for resistance and insertion axle 1 (Force feedback). |
| W | D | Supports initial position synchronization. |
| D | 12 | The MCD seats/lies steadily on a flat surface. |
| | | **Hardware:** electrical electronic complimentary equipment of the MCD |
| D | 14 | Connecting cable to the MMI-computer has the same length as the one used for the MMI-touch-screen (at least 30 m). |
| W | 15 | Preferably also power supply through this connecting cable. |
| D | 16 | Signal transmission based on the current field bus data transmission technique. |
| M | 17 | Measurement and control signals transmission rate of 50 Hz. |
| D | 18 | LED as indicator of general functioning. |
| W | 19 | LED as indicator of activated manual control mode. |
| D | 20 | Intuitively activating (safety) button during grip. |
| W | 21 | 1 button for medicine administering and regulation. |
| D | 22 | Continuous control of axle 1. |
| D | 23 | Continuous control of the alignment (axle 2) of the needle. |

**Steering aspects**

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| W | W | 23a | Continuous control of the orientation of the needle. | Cartesian control technology. |
| W | D | W | 24 | If necessary insertion in steps possible. | AMO (See Glossary). |
| W | D | W | 25 | If necessary retrieval in steps possible. |  |
| D | 26 | Continuous control of the needle rotation. |  |
| V | 27 | A minimal path measurements resolution of the 10 Bit. |  |
| W | D | 28 | Maximum velocity limit in axis 1. |  |
| W | W | 28a | Maximum velocity limit in axis 2. |  |

**General requirements:**

| 29 | Assessable programming interface. |  |

**User-friendly**

| D | 29a | Clear visual feedback of the absolute needle position. |  |
| D | 30 | Design for intuitive use, e.g. handgrip. |  |
| W | 30a | Forearm/wrist support. |  |
| D | 31 | Design for intuitive use regarding LEDs and steering elements. |  |
| D | 32 | One-hand use. |  |
| W | 33 | Labeling should not prohibit other applications. | As less as possible on it, axiomatic. |

**Appearance/Dimensions**

| D | 34 | Size, as small as possible. |  |
| D | 35 | Weight less than 5 kg. |  |
| W | 36 | Design matching the MIRA general design. |  |

**Costs**

| D | 37 | Costs limits of the MCD are to be considered in sensible relation to the MMI general costs budget. |  |

**Safety aspects**

<p>| D | 38 | Produces no electromagnetic field interference with other equipment within the room. |  |
| D | 39 | Causes no distortion of the MRT imaging process when used according to regulations. |  |
| D | D | D | 40 | MCD functioning only possible when all components are |  |</p>
<table>
<thead>
<tr>
<th>D</th>
<th>W</th>
<th>41</th>
<th>MCD provides clear haptic feedback when forward translation of the needle (forward or backwards) should not take place.</th>
</tr>
</thead>
<tbody>
<tr>
<td>D</td>
<td></td>
<td>42</td>
<td>Smooth, easy to clean surfaces.</td>
</tr>
</tbody>
</table>
### Appendix II: Original MCD force feedback calibration data

<table>
<thead>
<tr>
<th>Kal. Kraftsensor: 100g</th>
<th>(0.96, \text{mV} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>gemessene Kraft Sensor</td>
<td>(0.07, \text{Kraftskala}+)</td>
</tr>
<tr>
<td>(0.0, \text{mV} )</td>
<td>(0.0, \text{Kraftkontroll}+)</td>
</tr>
<tr>
<td>(1.0)</td>
<td>(0.0)</td>
</tr>
<tr>
<td>(1.5)</td>
<td>(0.2)</td>
</tr>
<tr>
<td>(2)</td>
<td>(0.45)</td>
</tr>
<tr>
<td>(3)</td>
<td>(0.8)</td>
</tr>
<tr>
<td>(4)</td>
<td>(1.2)</td>
</tr>
<tr>
<td>(5)</td>
<td>(1.6)</td>
</tr>
<tr>
<td>(6)</td>
<td>(2.0)</td>
</tr>
<tr>
<td>(7)</td>
<td>(2.8)</td>
</tr>
</tbody>
</table>

**Figure 42:** Copy of the original master-slave (MCD-Force sensor) force data.
Appendix III: Subject’s information

To pursue subject’s anonymity, each subject was numbered:

1. Name: Dr. Voges
   Year of birth: 1946
   Gender: M
   Right handed or left-handed: Left.
   Profession: Scientist.
   Hobbies where hand control is required: -

2. Name: Mr. Junker
   Year of birth: 1942
   Gender: M
   Right handed or left-handed: Right.
   Profession: Machines builder and technical drawer.
   Hobbies where hand control is required: Airplanes and ships modeling.

3. Name: Dr. List
   Year of birth: 1953
   Gender: M
   Right handed or left-handed: Right.
   Profession: Medical doctor.
   Hobbies where hand control is required: guitar playing.

4. Name: Mrs. Lösch
   Year of birth: 1944
   Gender: F
   Right handed or left-handed: Right.
   Profession: Medical technical assistant (nurse).
   Hobbies where hand control is required: -

5. Name: Mr. Breitwieser
   Year of birth: 1952
   Gender: M
   Right handed or left-handed: Right.
   Profession: Informatics Engineer.
   Hobbies where hand control is required: -

6. Name: Beckmann
   Year of birth: 1978
   Gender: M
   Right handed or left-handed: Right.
   Profession: Trainee information technologies.
   Hobbies where hand control is required: -
7. Name: Mr. Zilly  
   Year of birth: 1952  
   Gender: M  
   Right handed or left-handed: Right.  
   Profession: Scientist.  
   Hobbies where hand control is required: Playing guitar.

8. Name: Dr. Melzer  
   Year of birth: 1960  
   Gender: M  
   Right handed or left-handed: Right.  
   Profession: Medical doctor.  
   Hobbies where hand control is required: Handcrafting.

9. Name: Torsten  
   Year of birth: 1969  
   Gender: M  
   Right handed or left-handed: Right.  
   Profession: Scientist.  
   Hobbies where hand control is required: Handcrafting.

10. Name: Hanny  
    Year of birth: 1955  
    Gender: F  
    Right handed or left-handed: Right.  
    Profession: Informatics Engineer.  
    Hobbies where hand control is required: Piano playing.

11. Name: Heinz  
    Year of birth: 1948  
    Gender: M  
    Right handed or left-handed: Right.  
    Profession: Scientist.  
    Hobbies where hand control is required: Piano playing.
Appendix IV: Tissue properties

Experimental data [9] was used to develop a tissue model. The different types of artificial tissue were chosen to have the equivalent cutting force needed for the needle to penetrate the tissues during lumbar percutaneous interventions. The most penetrated organs by the needle during lumbar percutaneous insertions are: fat, muscle/skin and bone.

The first material to be chosen was called "artificial flesh" from Simulab Corp.; specially designed to simulate the consistency of muscles. In this report this tissue will be called Medium; see Figure 43. Figure 44 shows a linear force characteristic of the Medium tissue with a cutting force equal to 1 N. The hysteresis is the result of the effect of transversal forces and of a minor inhomogeneity of the material. From the characteristic it is determined that the work needed to move the needle 10 mm forward is equal to 5.5 mJoule.

To represent bone a type of rubber with a cutting force of 4 N and a higher stiffness than that of the "artificial flesh" was chosen; see Figure 45. This type of tissue will be called Hard in this report. With a similar speed used with the Medium tissue, a force characteristic of the Hard tissue was specified. The characteristic behaves linearly and presents a work of 36 mJoule needed to move the needle forward by 10 mm.

To represent fat, a type of foam was chosen with a lower stiffness than the other two; see Figure 46. In this report this type of tissue will be labeled as the Soft tissue. Using a similar speed to the one used with the other two a force characteristic was specified; see Figure 47. The characteristic behaves linearly, depicts a cutting force equal to 0.7 N and 4 mJoule are needed to move the needle 10 mm forward.

   Height (S) = 30 mm.

b. Material B = Hard (H).
   Height (H) = 10 mm.

c. Material E = Medium (M).
   Height (M) = 31 mm.

Measured single material's pictures and force characteristics

1.
Figure 43: Medium material deformation before needle insertion.

Figure 44: Force characteristic of needle insertion on medium material.
Figure 45: Force characteristic of needle insertion on hard material.

Figure 46: Soft material deformation before needle insertion.
Figure 47: Force characteristic of needle insertion on soft material.
Appendix V: Force characteristic of the six tissue’s order occurrence

For experiments 2 and 3 the different types of tissue were stacked on top of each other. Manually or using the MCD a needle was then inserted on the stack. At the same time the subject was asked to identify the moment the needle tip crossed different types of tissue. With three different types of material six different permutations of tissues stacked on top of each other were possible. To be used as reference, a force characteristic of all six possible permutations were specified and are found hereunder.

Figuur 1 shows a picture of one of the available permutations, namely starting the needle insertion with the Hard layer, followed by the Medium layer and ending with the Soft layer.

Figuur 1: A layered stack in HMS order.
Figure 48: Force characteristic of needle insertion on a SMH layer stack. S=beginning of the Soft tissue, M=beginning of the Medium tissue and H the beginning of the Hard tissue.

Figure 49: Force characteristic of needle insertion on a SHM layer stack. S=beginning of the Soft tissue, H the beginning of the Hard tissue and M=beginning of the Medium tissue.

Due to a corrupt file, the force characteristic of the Soft-Hard-Medium permutation was not available. Because the in vitro experiment set was found at the Forschungszentrum new measurements were not possible.
Figure 50: Force characteristic of needle insertion on a HSM layer stack. H the beginning of the Hard tissue, S=beginning of the Soft tissue and M=beginning of the Medium tissue.

Figure 51: Force characteristic of needle insertion on a HMS layer stack. H the beginning of the Hard tissue, M=beginning of the Medium tissue and S=beginning of the Soft tissue.
Figure 52: Force characteristic of needle insertion on a MHS layer stack. M=beginning of the Medium tissue, H the beginning of the Hard tissue and S=beginning of the Soft tissue.

Figure 53: Force characteristic of needle insertion on a MSH layer stack. M=beginning of the Medium tissue, S=beginning of the Soft tissue and H the beginning of the Hard tissue.
Appendix VI: Matlab programs

ReadExpDatawithWood.m

clear
clc
close all
format compact

%To run the program fast:
%nummer=1430;
% Subject='Hanny';
% ExpNr='4.2';
% FirstLayer='S';
% SecondLayer='H';
% ThirdLayer='M';

%Get extra data
Subject=input('Subject name: ','s');
ExpNr=input('Experiment number: 4. ','s');
FirstLayer=input('Top layer consistency (S, M or H): ','s');
SecondLayer=input('Middle layer consistency (S, M or H): ','s');
ThirdLayer=input('Bottom layer consistency (S, M or H): ','s');

% open file
nummer = input('file number: ');  
%tuis
%filename = ['C:\Afstuderen\Experimenten\',num2str(Subject),'\NB_Protokoll',num2str(nummer),'.dat'];
%Computerzaal
filename = ['L:\Afstuderen\Experiments\Data\',num2str(Subject),'\NB_Protokoll',num2str(nummer),'.dat'];
fid = fopen(filename);

%Layer order possibilities
%?if FirstLayer=='S' 'M' 'H' & SecondLayer=='S' 'M' 'H' & ThirdLayer=='S' 'M' 'H'
%?if (FirstLayer~='S' 'M' 'H') | (SecondLayer~='S' 'M' 'H') | ThirdLayer~='S' 'M' 'H'
%?if [FirstLayer~='S' 'M' 'H' SecondLayer~='S' 'M' 'H' ThirdLayer~='S' 'M' 'H']
% error('Wrong layer type or input not in capital!')
%?else
if FirstLayer=='S' & SecondLayer=='M' & ThirdLayer=='H'
    Layer_order=5
end

if FirstLayer=='S' & SecondLayer=='H' & ThirdLayer=='M'

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Layer_order=3
end

if FirstLayer=='H' & SecondLayer=='S' & ThirdLayer=='M'
    Layer_order=1
end

if FirstLayer=='H' & SecondLayer=='M' & ThirdLayer=='S'
    Layer_order=2
end

if FirstLayer=='M' & SecondLayer=='H' & ThirdLayer=='S'
    Layer_order=4
end

if FirstLayer=='M' & SecondLayer=='S' & ThirdLayer=='H'
    Layer_order=6
end

% end

% lees data
FileInfo = fgetl(fid);
disp(FileInfo)
Leeg = fgetl(fid);
SubjectExpnr = fgetl(fid);
Leeg = fgetl(fid);
Date = fgetl(fid);
disp(Date)
Time = fgetl(fid);
disp(Time)
for i=1:3
    Leeg = fgetl(fid);
end

AllData = fscanf(fid,['%f'],[9 inf]);
GrootteAllData = size(AllData);

% Eliminate data of needle moving backwards after the end of the stack (base) was reached:
grad=diff(AllData(:,3));
for k=1:length(AllData)-1;
    % if (grad(k)<0) & (AllData(k,2)>0.1233)
    % % doe niks
    base=k;
    % break
    % end
end

% Collect data only when MCD in function (red button hit, column 6 = 1):
j=1;
for k=1:base;
    if (AllData(k,6)==1)
        MCDfunctioning(j,:)=AllData(k,:);
        j=j+1;
    end
end

GrootteMCDfunctioningData = size(MCDfunctioning);

% Felt transition moment (black button hit, column 7 = 2):
isTwee=0;
m=1;
for i=1:GrootteAllData(1)
    if (AllData(i,7)==2) & (isTwee==0)
        BlackB(m,:)=AllData(i,:);
        m=m+1;
        isTwee = 1;
    end
    if (AllData(i,7)==0)
        isTwee = 0;
    end
end

%Graphics:
x=MCDfunctioning(:,3);
%!Waarde 3^Respons(:,5);vervangen door juiste waarde kolommen 4 en 5 relatie.
y=MCDfunctioning(:,4);
xb=BlackB(:,3);
yb=BlackB(:,4);
%?Coordinates_black_black_button=[xb yb]

%Layers position and deviation:
hS=0.028775;
hSd=0.006;
hM=0.02956;
hMd=0.002;
hH=0.010434;
hHd=0.004;
%1st layer position and possible deviation, 2nd layer position:
xt1=0.080631-0.025;
xBBase=0.15;
xBWood=0.15-0.025;
color4='k';
if FirstLayer=='S'
    xt1d=xt1+hSd;
    xt2=xt1+hS;
    color1='g';
end
if FirstLayer=='M'

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xt1d=xtl+hMd;
xt2=xtl+hM;
color1='m';
end
if FirstLayer=='H'
    xt1d=xtl+hHd;
    xt2=xtl+hH;
    color1='r';
end
%2nd layer possible deviation, 3rd layer position:
if SecondLayer=='S'
    xt2d=xt2+hSd;
    xt3=xt2+hS;
    color2='g';
end
if SecondLayer=='M'
    xt2d=xt2+hMd;
    xt3=xt2+hM;
    color2='m';
end
if SecondLayer=='H'
    xt2d=xt2+hHd;
    xt3=xt2+hH;
    color2='r';
end
%3rd layer possible deviation:
if ThirdLayer=='S'
    xt3d=xt3+hSd;
    color3='g';
end
if ThirdLayer=='M'
    xt3d=xt3+hMd;
    color3='m';
end
if ThirdLayer=='H'
    xt3d=xt3+hHd;
    color3='r';
end
hold on
plot(x,y)
plot(xb,yb,'ok','MarkerFaceColor','k')
FirstRealLayerTr=line([xt1 xt1],[-1 10],'Color',color1);
FirstPossibleLayerTr=line([xt1d xt1d],[-1 10], 'LineStyle',':', 'Color',color1);
xStext=xt1d+0.001;
Stext=text(xStext,-0.5,FirstLayer,'Color',color1,'FontSize',12);
SecondRealLayerTr=line([xt2 xt2],[-1 10], 'Color',color2);
SecondPossibleLayerTr=line([xt2d xt2d],[-1 10], 'LineStyle',':', 'Color',color2);
xHtext=xt2d+0.001;
Htext=text(xHtext,-0.5,SecondLayer,'Color',color2,'FontSize',12);

ThirdRealLayerTr=line([xt3 xt3],[-1 10],'Color',color3);
ThirdPossibleLayerTr=line([xt3d xt3d],[-1 10],'LineStyle','--','Color',color3);
XMtext=xt3d+0.001;
Mtext=text(xMtext,-0.5,ThirdLayer,'Color',color3,'FontSize',12);

%Draw Wood line on graphic:
WoodTr=line([xWood xWood],[-2 10],'Color',[.9 .7 .4], 'LineWidth',4);
Woodtext=text(xWood+0.002,'Wood','Color',[.9.7.4], 'FontSize',10);

%Draw Base line on graphics:
BaseLine=line([xBase xBase],[-1 10],'LineWidth',4,'Color','k');
xBasetext=xBase+0.001;
Basetext=text(xBasetext,-0.5,'Base','Color',color4,'FontSize',10);

%Text inside graphics:
text(0.025,0.4,'Insertion direction \rightarrow ','Color','b', 'FontSize',8)

% Draw MCD measured force feedback axle:
XMCDffline=.02;
MCDffLine=line([xMCDffline xMCDffline],[-1 10],'Color','k');
MCDfftext=text(xMCDffline,-0.5,'MCD measured force
[New]', 'Rotation',90, 'Position',...
[xMCDffline-0.01 1 0],'Color','k','FontSize',10);
% offset MCDff/Slave indexing =0.4:
offset=0.4;
% Perpendicular lines and numbers of MCD force feedback axle:
for i=1:12
  y=i-2;
yMCD=y*offset;
line([xMCDffline xMCDffline+0.0015], [y y],'Color','k');
text(xMCDffline-0.001,y,num2str(yMCD), 'HorizontalAlignment','right','FontSize',8);
end

axis([0.15 -1 10])
xt1=round(xt1*100)/100;
xt2=round(xt2*100)/100;
xt3=round(xt3*100)/100;
set(gca,'XTick', [0.0 0.05 xt1 xt2 xt3 xBase],'FontSize',8);

hold off

Head=title(['Layer transition ',FirstLayer,SecondLayer,ThirdLayer, ' 4.', ExpNr,...
' ',Subject]);
LookForTitle=findobj(Head,'type','text');
set(LookForTitle,'FontSize',12)
xlabel('Needle tip position [m]', 'FontSize', 10)
ylabel('Slave measured force [N]', 'FontSize', 10)

% Draw legend:
Description = legend('Force/position characteristic', '...
'Felt layer transition (black button pushed)',...'Air-' FirstLayer' transition'],...
['Deviation ' FirstLayer' layer'],['FirstLayer '-' SecondLayer' transition'],...
['Deviation ' SecondLayer' layer'],[SecondLayer '-' ThirdLayer' transition'],...
['Deviation ' ThirdLayer' layer'],2);
LookFor = findobj(Description, 'type', 'text');
set(LookFor, 'FontSize', 7)

% Felt points coordinates and force change slope:
nBlackPressed = input('Within the stack limits, how many times was the black button pressed?');
if nBlackPressed ~= 0
    DubblenBlackPressed = 2 * nBlackPressed;
    [xcoor, ycoor] = ginput(DubblenBlackPressed);
end
xy = [xcoor ycoor]
for i = 1:2:DubblenBlackPressed
    Slopline(i) = line(xcoor(i:i+1), ycoor(i:i+1));
    Slope(i) = [(ycoor(i+1) - ycoor(i))/(xcoor(i+1) - xcoor(i))];
    rad(i) = atan(Slope(i));
    deg(i) = (rad(i) * 180)/pi;
    Deground(i) = round(deg(i) * 100)/100;
    set(Slopline(i), 'Color', [1 0.9 0], 'LineWidth', 1.5)
    text(xcoor(i) - 0.01, ycoor(i) + 0.4, num2str(Deground(i)), ...
        'Color', [1 0.9 0], 'FontSize', 8)
end
SlopeDeg = [Slope' Deground']
end

%Saves(gcf, 'C:\Afstuderen\Experimenten\', num2str(Subject), '.jpg')
figfile = ['L:\Afstuderen\Experiments\IndividualResults Analysis\', Subject, '\', Subject, '-', num2str(ExpNr), '.jpg']
feval('saveas', gcf, figfile);

SendExcel.m

function SendExcel(M, position)
[r, c] = size(M);

% open channel
channel = ddeinit('excel', 'BoscarLResults.xls');
domain = ...
[r, num2str(position(1)), c, num2str(position(2)), ': r', num2str(r + position(1)), c, num2str( c + position(2))];
rc = ddepoke(channel, domain, M);
rc = ddeterm(channel);
Feasibility of Manual Control Device for Robotic Assisted Needle Insertion in CT and MRI

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In cooperation with Innomedic GmbH, Hennef, Germany.

Purpose
CT and MRI guided percutaneous interventions are well established. However, both image guidance and the operation from the needle are critical. CT provides excellent knowledge of the closed bone MRI, although superior in image quality to low-field open MRI and CT. The flexibility of the latter is very limited due to the specific operators and specific image adjustments. The project MCD includes robotic assisted needle insertion to take advantage of really MRI, low-field open MRI, and CT, general purpose, for specific applications on the remote location of the surgical team. However, the interventionalists have all remote feedback from the intervention team. Our goal is to implement a remote control interface that stimulates force feedback and provides an ergonomic control of interventional movements.

Advantages of a remote control force feedback interface:
- Preserves monitored needle position inside the patient's body with CT/MRI detailed images.
- Guarantees operator's control. The robot inside the CT/MRI follows the remote control interface movements.
- Allows for direct visual control of the needle insertion depth.
- Provides strong, real-time force feedback when hitting any hard structure like bone, equivalent to direct manual insertion.

Manual Control Device (MCD)
The Manual Control Device is designed and manufactured by Innomedic (DOF) interface, with 5 DOF for force feedback up to 15 N for needle insertion. This mainboard includes a dedicated sensor for a path that provides a traveling range of 150 mm. It is driven by an automated controller, including a Navigator (Harbous, Germany) to return the position control for, placed on defined problem safety, remote. It has a typical setup including the MCD and as slave to a master computer controlled motion axis from Innomedic. Both Germany firms also include a force sensor and needle has been built up for in vivo evaluation purpose. The force control is implemented in an open loop fashion by a PC.

Experiment
The goal of the test is to test experiment was to test whether the device enables accurate detection of needle hitting bone during insertion. Direct manual insertion and insertion with the MCD were compared using an ethical code.

Conclusions
The MCD was designed as a manual control device with force feedback for remote needle insertion in the CT/MRI. The potential benefits are:
- Increased safety allowing the operator to feel in real-time when the needle hits something hard like bone.
- Faster procedures as the operator can concentrate on reading the CT/MRI images while intuitively being aware of the needle position.

Results
During direct manual insertion all subjects (100%) were able to detect the moments of transition from air to firm, firm to medium, medium to soft, and soft to hard tissue by a hard tissue representing bone, 50% of the subjects detected the transition from soft to hard. It is believed that tissue viscosity and experience of some of the subjects made the soft to hard transition more difficult to detect.

Performing the same tasks with the force feedback interface, the transition to a hard tissue was detected by a majority of the subjects (70% from air to hard, 50% from soft to hard and 60% from Medium to Hard).

Later experience using fresh belly pork which was not separated from the ribs, allowed significantly better feeling of bone by force feedback than the foam materials used.

Direct vs. MCD Needle Insertions
A stack of three foam materials was used to model different transitions to hard tissue. Natural stiffness characteristics were chosen appropriately:
1. Hard = Bone
2. Medium = Tissue
3. Soft = Fat

<table>
<thead>
<tr>
<th>Transition Type</th>
<th>Direct Manual Needle Insertion</th>
<th>MCD Needle Insertion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ratio detected transitions</td>
<td>8/0</td>
<td>100%</td>
</tr>
<tr>
<td>% detected transitions</td>
<td>100</td>
<td>80%</td>
</tr>
</tbody>
</table>

S. Boscán Chapellin 63