Instrument Guide for MRI-guided Percutaneous Interventions

by

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ABSTRACT

As MRI guided interventions are becoming more widely practiced, the goal of this thesis was to design an instrument guidance device for MRI-guided percutaneous interventions in closed bore systems, namely cryoablation procedures where multiple probes need to be placed to treat a tumor. Multiple meetings with researchers and clinicians at the Brigham and Women’s Hospital were conducted to understand the challenges currently faced by interventionists, to set functional requirements for the design of a system to overcome them, and to help select a clinically viable strategy.

The strategy selected involved making a device that had two degrees of angular freedom about a remote center of motion located at the probe entry point on the skin. This device is designed to be incorporated with a custom built MR coil. Structural and finite element analysis was conducted for a number of different mechanism concepts to examine their stiffness and the effect of structural displacements on the end-point probe placement accuracy. The selected concept was a curved arm piece that travels around the pivot point on a circular base, and an additional needle holder that travels along the curved arm. The sliding parts were designed with five points of constraint so that only sliding motion was possible. Thumb screws were used for preload and locking so that the probe guide could be locked along a specific trajectory.

The device was prototyped via stereolithography as a proof of concept. It was found that sanding was required to fit the parts together because of overbuild in the stereolithography process. The parts functioned as designed and demonstrated that a probe could be angled about a remote pivot point. However, wear of the plastic parts eventually caused increased play between the plastic parts. Further testing and optimization of the device is planned.
Acknowledgements

I would like to thank Professor Slocum for the opportunity to do research in PERG, and Conor Walsh for his support, encouragement and mentoring during the research and writing of this thesis. I have learned a tremendous amount about design and research that I will be able to use in the future. I would also like to thank Dr. Noby Hata and Dr. Kemal Tuncali of the Brigham and Women’s Hospital for their interest and feedback in defining this project.
Table of Contents

1 Introduction ......................................................................................................................... 9
2 Background on Devices ........................................................................................................ 11
  2.1 MRI compatible actuators .................................................................................. 11
  2.2 Current Needle Guide Devices .............................................................................. 11
3 Mechanism Selection ........................................................................................................ 15
  3.1 Functional Requirements .............................................................................. 15
  3.2 Design Parameters .......................................................................................... 17
  3.3 Strategies ........................................................................................................ 19
  3.4 Strategy selection .......................................................................................... 22
  3.5 Concepts ........................................................................................................ 23
  3.6 Concepts Accuracy Analysis ........................................................................ 25
  3.7 Concept Selection ........................................................................................ 35
4 Detailed Design ............................................................................................................ 36
  4.1 CAD of Device ............................................................................................. 36
  4.2 Structural Design .......................................................................................... 37
  4.3 Bearing Design ............................................................................................. 38
  4.4 Release Mechanism Design ........................................................................ 43
  4.5 Design for Manufacturing ............................................................................. 44
5 Prototyping and Evaluation .......................................................................................... 46
6 Conclusions and Future Work ..................................................................................... 49
References .......................................................................................................................... 50
List of Figures

Figure 2.1 The Civco CT Multi-Angle Instrument Guide and associated accessories. ........................................... 13
Figure 2.2: Patient mounted passive needle guidance devices for CT: (a) NeoRad Simplify Needle Holder, and (b) the Radi SeeStar Needle Guide ................................................................. 14
Figure 3.1: Siemens 3T Flex small coil on bed of MRI scanner, and coil placed over patient[11]. ................................................................. 15
Figure 3.2: Dimensions of Siemens 3T Flex small coil. The coil is .625 inches thick but made of compressible material......................................................................................................... 16
Figure 3.3: Strategy A: A coil mounted, single point of entry device. ................................................................. 20
Figure 3.4: Strategy B: Multiple entry point device mounted on the patient. ................................................................. 21
Figure 3.5 Strategy C: A bed mounted strategy where the device places one probe at a time. ................................................................. 21
Figure 3.6 Strategy D: An external gurney mounted strategy. ................................................................. 22
Figure 3.7: Hand sketches of 4 concepts that were developed, each with two angular degrees of freedom. ........................................................................................................ 24
Figure 3.8: Diagram of Cartesian arm concept setup for homogenous transform matrices. ................................................................. 26
Figure 3.9: Diagram of forces in B coordinate frame. ......................................................................................... 26
Figure 3.10: Diagram of forces in the A coordinate frame. ......................................................................................... 27
Figure 3.11: FEA displacement results of the Cartesian arm concept. ................................................................. 28
Figure 3.12: Concept b force diagram for analytical analysis. ......................................................................................... 29
Figure 3.13: FEA displacement results of the spherical arm concept with geometry as analytically modeled. ........................................................................................................ 31
Figure 3.14: FEA displacement results of the spherical arm concept with geometry to accommodate height of coil. ........................................................................................................ 31
Figure 3.15: Worst case loading of concept c. ........................................................................................................ 32
Figure 3.16: Loading of straight beam fixed on both ends. ........................................................................ 32
Figure 3.17: FEA displacement results of the Cartesian bridge concept. ................................................................. 33
Figure 3.18: FEA displacement results of the spherical bridge concept. ................................................................. 33
Figure 3.19: Opening at entry point will create an error in the Cartesian concepts as angles close to vertical would not be constrained. ........................................................................ 35
Figure 4.1: Solid model of device. Two tracks allow for orientation of the needle in two angles. ......................................................................................... 36
Figure 4.2: Diagrams of offset of (a) the base and (b) the arm. ............................................................................... 37
Figure 4.3: Force acting on the arm and kinematic constraint that could support this load. ................................................................. 38
Figure 4.4: Diagram of constraints and on a track that allows for movement along length of the track. ......................................................................................... 39
Figure 4.5: Parameters to find proper groove width to ensure clearance between two parts. ......................................................................................... 39
Figure 4.6: Cross sectional views of the bearing designs used in the arm as well as the probe holder carriage ................................................................................................. 40
Figure 4.7: Saint-Venant’s Principle: l must be less than three times d. ........................................................................ 40
Figure 4.8: FEA stress results of the probe holder carriage. ......................................................................................... 41
Figure 4.9: FEA stress results of the arm base carriage. ......................................................................................... 42
Figure 4.10: FEA results to ensure snap works. (a) stress and (b) displacements results. 43
Figure 4.11: Two different methods of needle release mechanisms that were developed. ........................................................................................................................................... 44
Figure 4.12: The arm part after considerations for manufacturing were made consisting of 2 pieces and screws................................................................. 45
Figure 5.1: Photograph of prototyped instrument guide......................................................... 46
Figure 5.2: Wear has caused loss of contact between the bearing and track ................. 47
Figure 5.3: Device with 2 probe holders on the arm............................................................ 48
List of Tables

Table 3.1: Functional Requirements of Instrument Guide Device ........................................ 15
Table 3.2: Pros and cons of mounting design parameters ...................................................... 18
Table 3.3: Pros and cons of actuation design parameters ....................................................... 18
Table 3.4: Pros and cons of entry point design parameters ................................................... 18
Table 3.5: Pros and cons of protocol design parameters ....................................................... 19
Table 3.6: Pros and cons of registration and sensing design parameters ............................... 19
Table 3.7: Pugh Chart of strategy selection ............................................................................ 23
Table 3.8: Analytical error in mm for Cartesian arm concept ................................................. 28
Table 3.9: Maximum displacement of probe holder of 4 concepts based on FEA ................. 34
Table 3.10: Pugh chart for concept selection ........................................................................ 35
1 Introduction

Magnetic Resonance Imaging (MRI) offers good soft tissue contrast without harmful X-rays, making it an ideal imaging modality for many applications, including helping to guide minimally invasive percutaneous procedures such as biopsies and ablations where instruments are inserted through a single puncture in the skin. While many accessories for MRI are idealized for purely imaging, there are not many commercially available products that address MRI guided interventions. These procedures often consume large amounts of time in the number of scans required to accurately position the instrument to reach the target tissue. After scanning the patient initially to determine an entry point, the interventionist makes a shallow initial insertion and then sends the patient in to be rescanned to confirm the needle path. Needle bending and patient respiratory motion can cause errors that make the needle deviate from the planned trajectory. The patient is then brought back out of the imaging bore to readjust the needle and to insert it deeper. This procedure of scanning, removing the patient from the bore, readjusting and inserting the needle, and sending the patient back into the bore is repeated several times until the target is reached, and then the intervention itself can proceed. An additional challenge of MRI procedures is that more powerful machines are closed bore, limiting the amount of access the interventionist has to the patient.

Cryoablation, which kills tissue with extreme cold, is one such intervention that can be used in conjunction with MRI to treat lesions. Each 17 gauge cryoablation probe produces an ice ball of a certain volume at the tip of the probe to kill tissue. In order to effectively treat an entire lesion, usually multiple probes must be placed. Multiple probes can however interfere with each other and deflect, and inaccurate placement of one probe means the need to recalculate the trajectory of other probes. Placement must also be accurate in order to avoid ablating critical tissue close to the lesion.

This thesis documents the process of designing a device which when interfaced with imaging software, will provide precise and accurate positioning guidance for percutaneous instrument insertion in MRI-guided interventions. The device is initially designed for cryoablation interventions where multiple probes must be placed, but can be used for other interventions. One critical functional requirement for the device is that it
must be MRI compatible; materials and actuators must not be affected by the strong magnetic field, and there must be no image interference due to electronics. This thesis goes through the design process, from first understanding the challenges the interventionist faces and possible strategies to solve these challenges, to selecting the best concepts and designing modules. This project was developed in collaboration with Nobuhiko Hata at the Brigham and Women’s Hospital (BWH), and the final mechanical system should be integrated with image-based software.
2 Background on Devices

Before designing anything, a prior literature review was conducted to examine MRI compatible actuators that could be incorporated into a MRI compatible device, as well current systems, both actuated and passive, which aid in proper needle angulation.

2.1 MRI compatible actuators

To be usable in an MR environment, devices must (1) be MRI-safe, which means they must not be moved or attracted by the magnets, (2) not interfere with the image quality of the scan, and (3) operate as designed in the MRI environment.[1] Non-metals as well as aluminum, some stainless steels, and beryllium copper have been shown to be MRI compatible. There have been several MRI compatible robots documented in the literature, using different actuation mechanisms. Pneumatic systems use compressed air to effect motion and are completely MRI compatible, even in the region of imaging interest. However, pneumatics are difficult to control, and systems tend to be large and storage of compressed air becomes an issue. To obtain more control through pneumatics, a group at the Johns Hopkins University has designed a pneumatic stepping motor, the PneuStep, by sequentially pressurizing different ports that cause an inner hoop gear to travel in a circular translation, which in turn spins a spur gear. [2] Hydraulic actuators, which use an incompressible fluid, are more rigid than pneumatics, but hydraulics are slow and have a chance of fluid leaks which is unacceptable in a sterile environment. The other type of actuator that can be used in MRI compatible systems are piezoelectric motors, which include high frequency ultrasonic motors. These motors work on the principle of a piezoelectric material such as ceramic or crystal changing shape when an electric current is applied. These are nonmagnetic and thus are MRI safe, but use of electric current may cause electromagnetic interference (EMI) and distort the image.

2.2 Current Needle Guide Devices

There have also been prior devices developed to aid needle positioning in image guided interventions. The Robopsy, a system developed at MIT, is a telerobotic device to be used in computed tomography (CT) guided biopsies that allows for continual feedback of needle location with concurrent imaging. [3] The Robopsy is mounted to the patient to
account for respiratory motion, with 4 degrees of freedom: two angles for orientation, one
needle insertion/retraction, and one to grip and release the needle to allow for flexible
movement of the needle within the body. A spherical mechanism, with two concentric
nested hoops each driven by a micromotor, is used to effect the two angular degrees of
freedom. An additional motor and carriage positioned above the hoops controls the
gripping and friction drive for the insertion of the needle.

Other systems have been developed to be MRI compatible as well. The Light
Puncture Robot (LPR) developed in Grenoble provides positioning and insertion of the
needle that is fully compatible with both CT and MR systems.[4] The needle holder
portion of the robot has three degrees of freedom to orient and insert the needle, actuated
by pneumatically actuated pistons and sprocket wheels. The device is strapped over the
patient body with a support frame, with another 2 degrees of freedom available to
position the entry point of the needle by adjusting the straps.

Innomotion, also compatible with both CT and MR, is the only MRI compatible
robot which was commercially available.[5] It is attached to top of the scanner bore, with
an arm that has 5 degrees of freedom, driven by pneumatic linear cylinders and controlled
by a master haptic device. Pneumatically driven needle insertion has been planned but not
implemented in the current model, instead the insertion must be done manually outside
the bore. The first prototype was made with piezoelectric motors, but this design was
discarded due to increased noise during the MRI scanning process, and the risk of
inductive heating from the electric lines.

Ultrasonic motors have been used and validated in MRI environments. Hata et. al
developed a needle guide, in which the surgeon changes the angles of the needle which
are read by encoders, and an active linear XY movement guides the needle to the right
position so the needle is still pointed to the target point. [6] The system is mounted to the
bed of the scanner, and driven by ultrasonic motors. Another system by Larson et al.
developed for breast biopsies uses ultrasonic motors driving telescoping rods to achieve
actuation near the breast while keeping the motors away from the image. [7] This
principle has been extended to a more general 7 DOF robot that is attached to a gantry so
the robotic arm may be positioned above the robot, and a cable drive is used for needle
insertion by a master haptic driver, or the insertion may be done manually with aid of the GUI system. [8]

Civco Medical Solutions manufactures a line of passive assistive devices to aid the interventionist. Figure 2.1 below shows the Civco CT Multi-Angle Instrument Guide. This device allows precise positioning of the desired angles and visualization with bubble levels. It includes a quick release mechanism to allow for the disposable needle guide (shown in white in the figure) to be easily released. The device is intended to attach to Civco’s Positioning Arms which are attached to the gantry, via a Fine Adjustment Mechanism interface that allows for fine tuning in the x, y, and z directions of the instrument guide.

![Figure 2.1 The Civco CT Multi-Angle Instrument Guide and associated accessories.](image)

There are also passive patient mounted needle guides that have been developed mainly for CT interventions, which are shown in Figure 2.2. The NeoRad Simplify Needle Holder [9] is composed of needle-holding clips which can be clipped onto an arched support at an angle, and the arch itself can be folded, for two degrees of angular freedom. Multiple clips with needles can also be attached and detached. The Radi SeeStar Needle Guide [10] uses two concentric hoops to position and guide the needle holder over a semi-hemispherical surface, with the guide always pointed at one entry point. A screw mechanism clamps the two concentric hoops together to resist motion and form a stable platform for the guide. However, there are no visual markings as easily record the position of the SeeStar.
Figure 2.2: Patient mounted passive needle guidance devices for CT: (a) NeoRad Simplify Needle Holder, and (b) the Radi SeeStar Needle Guide.
3 Mechanism Selection

This chapter describes the functional requirements of the device and the factors that went into selecting a mechanism.

3.1 Functional Requirements

In order to select the best mechanism, meetings with Conor Walsh and researchers and clinicians at Brigham and Women’s Hospital were conducted to understand the functional requirements of the device. These are listed in Table 3.1 and then discussed below.

Table 3.1: Functional Requirements of Instrument Guide Device

<table>
<thead>
<tr>
<th>Function Requirements</th>
<th>Specifications</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Accommodate coil</td>
<td>Siemens MRI coil</td>
</tr>
<tr>
<td>2. Register and calculate correct trajectory</td>
<td>Can integrate with registration system</td>
</tr>
<tr>
<td>3. Guide probe to correct trajectory</td>
<td>45° angulation from normal</td>
</tr>
<tr>
<td>4. Precision and reliability</td>
<td>Displacement at tip of probe within 2 mm</td>
</tr>
<tr>
<td>5. Accommodate multiple probes</td>
<td>Can place at least 3 17-gauge probes</td>
</tr>
<tr>
<td>6. Allow probe to teach target</td>
<td>Hold probe less than 4 cm above skin.</td>
</tr>
<tr>
<td>7. Release probe after insertion</td>
<td>25° freedom of motion for needle</td>
</tr>
<tr>
<td>8. MRI compatible</td>
<td>Compatible material</td>
</tr>
<tr>
<td>9. Sterilizable</td>
<td>Sterilizable material, simple parts</td>
</tr>
</tbody>
</table>

1. Accommodate coil -- One of the challenges unique to MRI procedures in the 3T Siemens scanner is the necessity of affixing a flexible MRI coil on the patient over the region of imaging interest. Figure 3.1 below shows the Siemens MRI scanner and Small Flex coil on the bed of a 3T Siemens MAGNETOM Verio scanner at BWH, along with a representative image of a coil being placed on a patient.

Figure 3.1: Siemens 3T Flex small coil on bed of MRI scanner, and coil placed over patient[11].
The coil should be placed over the lesion which is to be imaged, as the patient should be between that coil and the coil built into the bed of the scanner. The flex coil creates an additional constraint for the radiologist, as probes must either go through the holes of the coil or to enter the body at an angle from outside the area of the coil. The dimensions of a small coil are presented below in Figure 3.2. Any strategy for improving current procedures must work in conjunction with where the coil is placed.

![Figure 3.2: Dimensions of Siemens 3T Flex small coil. The coil is .625 inches thick but made of compressible material.](image)

2. **Register and calculate correct trajectory** – The mechanical device must be able to be integrated with some system that can register the location of the device with respect to the imaging coordinate system.

3. **Guide probes to correct trajectory** – Knowing the correct trajectory, the device must have a way to position the probe in the correct location with the appropriate degrees of freedom. MR coils can be attached to any side of the patient, and current insertion paths generally fall within the ±45° range from normal to the skin, with an extreme to 80° from vertical. The device should accommodate these angulations.

4. **Precision and reliability** – The device must find the same trajectory repeatedly and the trajectory taken by the probe must match what is predicted. Sensing may be incorporated to ensure accuracy. The device must also be rigid enough to maintain the probe along the correct insertion trajectory in the presence of forces during the insertion process.
5. **Accommodate multiple probes** – Few cryoablation interventions are performed with just 1 probe, with the range of 2 – 10 probes per procedure being the norm [personal communication with Dr. Kemal Tuncali of Bingham and Women’s Hospital], so the device must be able to accommodate multiple probes. Most procedures use three 17-gauge probes, so that will be the basis for design.

6. **Allow the probe to reach target** – The average lesion is 12.5 cm deep beneath the skin. The device must not interfere or hold the probes in such a fashion that does not allow the probe to reach the desired depth. Current probes are 17 cm in length. Thus the device should not hold the probe more than 4 cm above the skin surface.

7. **Release probe after insertion** – After the probe reaches the desired target, the device must release the probe so that the probe has the freedom to move with the patient to decrease the risk of injury. The angular range of motion is approximately ±12.5° [personal communication with Conor Walsh].

8. **MRI Compatible** – The device must not interfere with the image quality and must not be affected by the strong magnetic field.

9. **Sterilizable** – Everything in the MRI environment must be sterilized prior to the procedure, so the device must have surfaces and no recessed features that make sterilizing difficult. Else, the device should be designed for 1 time use.

### 3.2 Design Parameters

In order to satisfy the functional requirements above, there are several parameters and design choices that must be made. The following parameters are described along with a table with pros and cons for each choice.

1. **Mounting** – The device can be mounted to (a) an external gurney, (b) to the bed of the scanner, (c) to the patient’s skin, or (d) attached onto the MR coil. These choices have implications for the device structure weight and size.
Table 3.2: Pros and cons of mounting design parameters

<table>
<thead>
<tr>
<th>Mounting</th>
<th>Pros</th>
<th>Cons</th>
</tr>
</thead>
<tbody>
<tr>
<td>Over coil</td>
<td>· moves with patient in case of large unexpected motions</td>
<td>· coil is flexible</td>
</tr>
<tr>
<td></td>
<td>· could easily attach with snap features</td>
<td>· not ideal to place motors close to coil</td>
</tr>
<tr>
<td></td>
<td>· compact structure</td>
<td></td>
</tr>
<tr>
<td>On body</td>
<td>· no interference with the coil</td>
<td>· body is unstable platform</td>
</tr>
<tr>
<td></td>
<td>· compact structure</td>
<td>· robot arms may be heavy for body</td>
</tr>
<tr>
<td>On bed</td>
<td>· rigid base platform</td>
<td>· very limited space</td>
</tr>
<tr>
<td></td>
<td></td>
<td>· larger structure needed</td>
</tr>
<tr>
<td>Separate gurney</td>
<td>· very rigid platform</td>
<td>· could not go into imaging bore</td>
</tr>
<tr>
<td></td>
<td>· more easily actuated</td>
<td>· large arm needed for stiffness</td>
</tr>
<tr>
<td></td>
<td>· can be positioned over or on side of patient</td>
<td>· expensive</td>
</tr>
</tbody>
</table>

2. Actuation methods – The device must guide probes to a specified trajectory, and this movement can be achieved manually or with actuation.

Table 3.3: Pros and cons of actuation design parameters

<table>
<thead>
<tr>
<th>Actuation</th>
<th>Pros</th>
<th>Cons</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manual</td>
<td>· no electromagnetic interference</td>
<td>· time consuming</td>
</tr>
<tr>
<td></td>
<td></td>
<td>· potential for physician error</td>
</tr>
<tr>
<td>Motorized</td>
<td>· fast</td>
<td>· need to ensure MRI compatibility</td>
</tr>
<tr>
<td></td>
<td>· remote actuation (could keep patient in bore)</td>
<td>· may lead to many coils that are in the way</td>
</tr>
<tr>
<td></td>
<td>· high accuracy and repeatability</td>
<td>· expensive</td>
</tr>
</tbody>
</table>

3. Entry points – Percutaneous probes can either share an entry point or enter the skin through multiple holes.

Table 3.4: Pros and cons of entry point design parameters

<table>
<thead>
<tr>
<th>Entry points</th>
<th>Pros</th>
<th>Cons</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shared entry points</td>
<td>· smaller wound</td>
<td>· increased risk of needle interference with each other</td>
</tr>
<tr>
<td></td>
<td>· more compact mechanism and structure</td>
<td></td>
</tr>
<tr>
<td>Multiple entry points</td>
<td>· more flexibility to pick good entry points</td>
<td>· multiple wounds on patient and risk of damage to internal organs</td>
</tr>
</tbody>
</table>
4. **Multiple fixed guides or single movable guide** – The system can be one rigid body built with permanent fixtures for multiple probes, or it can be a system that places one probe, releases the probe, and then places the next.

<table>
<thead>
<tr>
<th>Protocol</th>
<th>Pros</th>
<th>Cons</th>
</tr>
</thead>
<tbody>
<tr>
<td>multiple fixed guides</td>
<td>· can hold needles in place while other is inserted to avoid collisions during insertions</td>
<td>· increased parts</td>
</tr>
<tr>
<td>single removable guide</td>
<td>· smaller package</td>
<td>· time intensive</td>
</tr>
</tbody>
</table>

5. **Registration method** – To register the location, there can either be a Z-frame that is incorporated with the device for registration during imaging [12], or if the coordinates of an external setup are known, a coordinate transformation can be used to find the location. The other option is manual registration, measuring location and angle with ruler and protractor, but this would be time consuming and prone to error.

<table>
<thead>
<tr>
<th>Registration and Sensing</th>
<th>Pros</th>
<th>Cons</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manual (ruler and protractor)</td>
<td>· cheap</td>
<td>· very time consuming</td>
</tr>
<tr>
<td>Z Frame</td>
<td>· well known</td>
<td>· requires imaging of the Z-Frame</td>
</tr>
<tr>
<td>Fixed External Coordinate Transform</td>
<td>· imaging or measurements not required</td>
<td>· requires calibration each time</td>
</tr>
</tbody>
</table>

3.3 **Strategies**

Based on the above functional requirements and design parameters, four different strategies were solid modeled and presented to Dr. Kemal Tuncali at BWH.

**Strategy A**

Figure 3.3 illustrates a strategy where the device is mounted to the coil. The device would direct probes to a shared entry point with multiple probes that can travel around a circular base, and telescoping arms that travel in an arc such that the probes would all convene to one spot on the patient’s skin. It is possible to imagine a custom coil that
could also be used for registration, and this device could have features that would allow for accurate positioning to the coil, such as via kinematic couplings. This would allow for easy registration and mounting.

Figure 3.3: Strategy A: A coil mounted, single point of entry device.

**Strategy B**

Figure 3.4 below illustrates Strategy B, where the mechanism is attached elsewhere next to the coil on the body. The mechanism has three arms that reach over the coil to access the body through a hole. Having arms means that the movement is controlled at some distance away from where the probes are inserted, so it would be easier to motorize. However, this device may become too heavy for a body, and the body is a soft surface that can move, causing errors. From this figure, the interventionist also shared his reservations about the variable heights of the holding the probes and that the system might not be intuitive for manual control.
Figure 3.4: Strategy B: Multiple entry point device mounted on the patient.

**Strategy C**

This strategy in Figure 3.5 below is one that is mounted to the bed and would place one probe at a time. The bed is very stable and it could be easily actuated, but given the variability in size of patients, there could easily be not enough space on the bed. Placing one probe at a time also gives flexibility to the positions and angles of insertions.

Figure 3.5 Strategy C: A bed mounted strategy where the device places one probe at a time.
Strategy D

This strategy shown in Figure 3.6 uses a robot arm to place the needles while remaining entirely outside of the imaging bore. This would be relatively easy to actuate as no parts enter the bore. After a scan the patient would have to be removed from the scanner on the bed so that the probe could be placed with the robot, then the needle would be released and patient rescanned. As such, this strategy would require the patient be brought in and out of the scanner, using valuable time.

Figure 3.6 Strategy D: An external gurney mounted strategy.

3.4 Strategy selection

Table 3.7 presents a Pugh Chart with parameters that factored into the decision. **Intuitive** describes how easy it would be for an interventionist to know how the device worked without explanation. **Actuability** describes the ease of attaching motors while maintaining full MRI compatibility. **Novelty** comes from a concern to develop a device that has not been made before. **Weight** is an important factor as it contributes to safety, ease of use, and cost. **Risk** refers to how likely a device designed is likely to be safe and meet specifications.
### Table 3.7: Pugh Chart of strategy selection

<table>
<thead>
<tr>
<th></th>
<th>Strategy A</th>
<th>Strategy B</th>
<th>Strategy C</th>
<th>Strategy D</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intuitive</td>
<td>+</td>
<td>-</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Actuability</td>
<td>-</td>
<td>-</td>
<td>0</td>
<td>+</td>
</tr>
<tr>
<td>Novelty</td>
<td>++</td>
<td>0</td>
<td>0</td>
<td>-</td>
</tr>
<tr>
<td>Weight</td>
<td>+</td>
<td>-</td>
<td>--</td>
<td>-</td>
</tr>
<tr>
<td>Risk</td>
<td>0</td>
<td>-</td>
<td>-</td>
<td>+</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>+3</strong></td>
<td><strong>-4</strong></td>
<td><strong>-3</strong></td>
<td><strong>0</strong></td>
</tr>
</tbody>
</table>

Upon discussion with Dr. Tuncali at BWH and going through the above Pugh Chart, Strategy A seemed to be the most attractive for its simplicity, as well as the intervention’s intuitive feeling for how the device works, which is crucial for clinicians to adopt it. The interventionist had some reservations over non-intuitive mechanisms such as Strategy B and C, and the heavy arm that would be necessary in Strategy D. This type of coil mounted strategy presented in A also had the possibility of developing into a novel integrated MRI coil device for interventionists. There are currently no commercially available MRI coils designed for specific use with interventions. This device and coil would aid interventionists who specifically require the MRI in performing their procedures.

### 3.5 Concepts

After deciding on the strategy, 4 different concepts were developed and sketched by hand, as presented following in Figure 3.7. Each concept is a single entry point device with two rotational degrees of freedom that could be mounted onto the coil.
Figure 3.7: Hand sketches of 4 concepts that were developed, each with two angular degrees of freedom. (a) Cartesian arm concept: angulation is achieved by a constraint at the central entry point and carriages that move horizontally. (b) Spherical arm concept: Multiple curved beams allow carriages to traverse with the center at the entry point. (c) Cartesian bridge concept: A single full rectangular support with a horizontal track that allows for angularion. (d) A full semicircular bridge with the center at the entry point.

The 4 different concepts all provide 2 angular degrees of freedom: rotation about the entry point normal to the patient’s body surface (θ), and angulation that deviates from the normal axis (φ). Changes in φ can be changed either through a hemispherical track (Figure 3.7 b and d), or a horizontal track with a support at the entry point that constrains that point. (Figure 3.7 a and c) It was also decided that instead of having telescoping arms, to have a carriage system that rides over a support system. The carriage provides more range of motion, and it may make the system easier to manufacture from plastic. It is also possible to have individual arms that support different probes (Figure 3.6 c and d), or to have a full support that traverses the span of the device and have individual carriages pass over. (Figure 3.6 c and d) The full bridge concepts would require the probe to be released from the mechanism before placing another probe, as well as the
order for placing probes must be calculated beforehand as some paths may be blocked. While the individual arms idea would however take less time as the interventionist could insert multiple probes and hold the needles in position before inserting subsequent needles, the arm ideas would require one arm to be longer than other possible arms, such that the needle could still reach the vertical position.

To aid in the selection of the best concepts, the error associated with each concept along with the convenience for the interventionist were considered.

3.6 Concepts Accuracy Analysis

This device should be more accurate than the interventionist himself, and we have specified an accuracy of 2 mm. The device is to be made out of plastic to ensure MRI compatibility. Beam bending principles can be used to determine how much components will shift. Finite element analysis was also conducted in SolidWorks via Simulation Xpress, to check the calculations and ensure that the plastic would not exceed its maximum allowable stress. Analysis of the worst case scenarios were conducted by modeling a force of 10 N going normal to the skin and the structures was modeled by beams with a rectangular 8 mm by 8 mm cross section. The cross sectional area \( A \) is then 64 mm\(^2\) and the second moment of area \( I = \frac{1}{12}bh^3 = 341\text{mm}^4 \). The material properties of the plastic are those of acrylic, with a Young’s Modulus \( E \) of 2.4 GPa and a Poisson’s ratio \( \nu \) of .35. The deformation results from beam bending theory and finite element analysis are listed in Table 3.9.

Concept a: Cartesian arm

This concept was the most-straight forward to analyze, and the goal was to see the error in the probe holder as well as at the tip of the needle as a function of the angle away from normal to the skin surface (\( \alpha \)). Assuming that the force applied to the device will be a point force along the insertion line, the force \( F \) can then be decomposed into two forces, \( F_x \) and \( F_y \). Homogeneous transform matrices (HTMs) were used, with the coordinates as shown in Figure 3.8 below, to find the new positions of the probe holder (point C).
Using HTM’s the problem can be split up into smaller pieces. First, how coordinate C in the reference frame of B will act due to the insertion force was found, as seen in Figure 3.9.

By beam bending, the displacement in the y direction is given by the equation

$$\delta_y = \frac{F_y l^3}{3EI}$$  \hspace{1cm} (1)

Displacement due to the tension force in the x direction is given by

$$\delta_x = \frac{F_x l}{EA}$$  \hspace{1cm} (2)

So, point C in the reference frame of B is

$$X_C = l + \frac{F_x l}{EA}$$  \hspace{1cm} (3)

$$Y_C = -\frac{Fl^3}{3EI}$$
The position of the coordinate B in the A coordinate frame can be found in similar fashion as in Figure 3.10.

![Diagram of forces in the A coordinate frame.](image)

Figure 3.10: Diagram of forces in the A coordinate frame.

The equations to find B in the frame of A are

\[
X_B = \frac{F_y h^3}{3EI} + \frac{(F_y l) h^2}{2EI}
\]

\[
Y_B = h - \frac{F_y h}{EA}
\]

\[
\theta_B = \frac{F_y h^2}{2EI} + \frac{(F_y l) l}{EI}
\]

(4)

To find the new coordinates, the following matrices were used to find the new point C in the reference of coordinate A:

\[
\begin{bmatrix}
X_A \\
Y_A \\
Z_A \\
1
\end{bmatrix} = ^A H_B \cdot \begin{bmatrix}
^B X_C \\
^B Y_C \\
^B Z_C \\
1
\end{bmatrix}
\]

(5)

\[
^A H_B = ^A H_B (\theta_z) ^A H_B (\Delta) = \begin{bmatrix}
\cos(\theta_B) & -\sin(\theta_B) & 0 & 0 \\
\sin(\theta_B) & \cos(\theta_B) & 0 & 0 \\
0 & 0 & 1 & 0 \\
0 & 0 & 0 & 1
\end{bmatrix} \cdot \begin{bmatrix}
1 & 0 & 0 & X_B \\
0 & 1 & 0 & Y_B \\
0 & 0 & 1 & Z_B \\
0 & 0 & 0 & 1
\end{bmatrix}
\]

(6)

From these calculations, new X,Y values for coordinate C in the reference frame of A were found and subtracted from the nominal coordinates of X = l and Y = h to find the
error at the probe holder. From this, the deviation of the tip of the probe from the ideal value was calculated by finding the new angle $\alpha$ and knowing the length of the needle.

We set model parameters $h = 25$ mm and $w = 45$ mm to allow for up to $50^\circ$ angulation. The vertical posts were 8 mm by 10 mm rectangles, while the horizontal beam has a cross section of 8 mm by 8 mm as described previously. Assuming that the probe goes 15 cm under the skin, the error results while changing the angle are presented in Table 3.8.

<table>
<thead>
<tr>
<th>$\alpha$</th>
<th>0°</th>
<th>10°</th>
<th>20°</th>
<th>30°</th>
<th>40°</th>
<th>50°</th>
</tr>
</thead>
<tbody>
<tr>
<td>Holder $\delta X$</td>
<td>0.104</td>
<td>0.100</td>
<td>0.092</td>
<td>0.082</td>
<td>0.069</td>
<td>0.054</td>
</tr>
<tr>
<td>Holder $\delta Y$</td>
<td>-0.553</td>
<td>-0.472</td>
<td>-0.377</td>
<td>-0.273</td>
<td>-0.167</td>
<td>-0.070</td>
</tr>
<tr>
<td>Tip $\delta X$</td>
<td>-0.643</td>
<td>-0.012</td>
<td>0.360</td>
<td>0.437</td>
<td>0.303</td>
<td>0.112</td>
</tr>
<tr>
<td>Tip $\delta Y$</td>
<td>0.5519</td>
<td>0.491</td>
<td>0.279</td>
<td>0.067</td>
<td>0.030</td>
<td>0.48e-6</td>
</tr>
</tbody>
</table>

From the above table it can be seen that the error is reduced as $\alpha$ is increased, which is explained by the fact that the length of the cantilever is less as alpha in increased.

Finite Element Analysis for $\alpha = 0^\circ$ was conducted on a part to confirm the analytical results. The displacement results are shown in Figure 3.11. The maximum displacement at the tip was 0.5175 mm, and the analytical result gives a result of $\sqrt{(\delta X)^2 + (\delta Y)^2} = 0.5633$ mm, which is on the same order of magnitude and an error of less than 10%, matching closely with the analytical results.
Concept b: Spherical arm

The characterization of the curved beam, especially one where the radius of curvature is small compared to the dimensions of the cross section, is less straightforward than the previous concept as the effects of the internal normal and shear forces must be considered. As an approximation for the worst case scenario, the displacement for the beam of the following geometry in Figure 3.12 was found using Roark’s Formulas for Stress and Strain. [13]

\[ F_y \]
\[ x \]
\[ y \]

Figure 3.12: Concept b force diagram for analytical analysis.

Castigiliano’s second theorem says that deviation at the tip of the above configuration is

\[ \delta_y = \frac{\partial U}{\partial F_x}, \delta_x = \frac{\partial U}{\partial F_y}, \theta = \frac{\partial U}{\partial M_0} \]  \hspace{1cm} (7)

As a function of \( \phi \), the internal moment and forces are

\[ M_\phi = F_y R \sin \phi + F_x R(1 - \cos \phi) \]
\[ V_\phi = F_y \cos \phi + F_x \sin \phi \]  \hspace{1cm} (8)
\[ N_\phi = -F_x \cos \phi + F_y \sin \phi \]

The energy of the thick beam is

\[ U = \int \frac{M_\phi^2}{2AEe} d\phi + \int \frac{V_\phi^2 R}{2AG} d\phi + \int \frac{N_\phi^2 R}{2AE} d\phi - \int \frac{M_\phi N_\phi}{AE} d\phi \]  \hspace{1cm} (9)
Equations 7-9 are solved, for $\varphi = \pi/2$ to be

$$
\delta_y = \frac{(\pi/4)F_y R^3 + 0.5F_y R^3 + 0.5R(\pi F_y / 2 + F_x)[2f(1+v)-1]}{EAeR} + \frac{0.5F_y R[2f(1+v)-1]}{AE}
$$

$$
\delta_x = \frac{0.5F_y R^3 + (3\pi/4 - 2)F_x R^3 + 0.5F_y R[2f(1+v)-1] + (\pi/4)F_y R[2f(1+v)+8/\pi - 1]}{EAeR} + \frac{0.5F_y R[2f(1+v)-1]}{AE}
$$

$$
\theta = \frac{F_x R^2 + (\pi/2 - 1)F_x R^2 + F_x - F_y}{EAeR} + \frac{F_x - F_y}{AE}
$$

where $f = 1.2$ is a factor that depends on the form of the cross section of the beam and $c$ is the centroid distance. For a solid rectangular cross section, $c$ is half of the thickness of the beam. From this analysis, for a beam with a curve radius $R = 35$ mm and all other parameters as described in the introduction to this section, the maximum displacements in the structure for when the force is vertical at the tip are $\delta_x = 0.3160$ mm, $\delta_y = -0.4927$ mm, $\theta = -0.0178$ radians, which is a total error of 0.5853 mm. This leads to an error at the tip of the probe of 1.7 mm in the x-direction and 0.475 mm in the y-direction. FEA was performed both with a model with the same geometry as the analytical model, shown in Figure 3.13, as well as with a shortened curve that is more like what the final design would be after taking into consideration the height of the coil, seen in Figure 3.14. The maximum displacement in FEA for the full quarter circle is 0.5447 mm, which again shows a good correspondence with the analytical value. For the geometry that considers the height of the coil, the displacement is less than half what was found analytically.
Concept c: Cartesian bridge

The Cartesian bridge concept is one where a beam is supported on both ends and the probe holder can be moved along the horizontal track. Again a worst case analysis is performed. It is expected to be more stable as the bar is supported at both ends. Figure 3.15 below shows a diagram with the loading for the worst case deformation.
The deformation of the beam fully supported at both ends as shown in Figure 3.16 below was found. This should be a good approximation of the deformation, as it is assumed that the compression of the two supports that act in parallel will be a second order effect. The deformation is described in Equation 3.12.

\[ \delta_y = \frac{-F_y w^3}{192EI} \]  

(12)

From this analysis of a beam 90 mm long, a displacement downwards of 0.0551 mm is calculated, which is an order of magnitude stiffer than the individual arms concepts. FEA analysis (Figure 3.17) also shows good correspondence to the analytical result, providing a result of 0.0542 mm.
Figure 3.17: FEA displacement results of the Cartesian bridge concept.

**Concept d: Spherical bridge**

The spherical bridge concept was not characterized analytically, but FEA was performed. The base of this structure is also cut off like the spherical arm concept b that took into account the height of the coil, as seen in Figure 3.18. The maximum displacement of the structure is 0.005977 mm, which is much less than all the other concepts.

Figure 3.18 FEA displacement results of the spherical bridge concept.
Analysis Results

The maximum displacements at the probe holder found from both modes of analysis are listed in Table 3.9.

<table>
<thead>
<tr>
<th></th>
<th>Analytical (mm)</th>
<th>FEA (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cartesian arm</td>
<td>0.5633</td>
<td>0.5175</td>
</tr>
<tr>
<td>Spherical arm</td>
<td>0.5853</td>
<td>0.2366 / 0.5447</td>
</tr>
<tr>
<td>Cartesian bridge</td>
<td>0.0556</td>
<td>0.0542</td>
</tr>
<tr>
<td>Spherical bridge</td>
<td>--</td>
<td>0.00597</td>
</tr>
</tbody>
</table>

From these results, especially the FEA results, it is found that the shorter Spherical concepts which are more like what would be built and have similar proportions to the Cartesian concepts are stiffer than the straight beams, as well that the bridge concepts are much stiffer than individual arms. The highest Von Mises stress found in FEA in any model was around 6 MPa, which is well below the yield strength of plastic (60 MPa).

Error from constraints

There will also be inherent errors from parts that are able to move relative to each other. For a well designed machine system, these bearing errors are generally on the same order of magnitude as that from the structural stiffness of the part. In the spherical cases, there are two bearings, one along the base track and one along the support track, that will need to be constrained when locking the device in position to guide the probe and could contribute error. In the Cartesian concepts, the probe holder swings freely, and there is an opening at the entry point that acts as a constraint for the angle. In order to accommodate any angulation, the opening would have to be made wider, so positions close to vertical would not be constrained exactly enough as the probe can swing about the pivot point on the device. This is illustrated below in the following Figure 3.19. Thus there are three additional points of error in the Cartesian system, one from the base bearing, one from positioning the track along the correct horizontal position, as well as an additional error from the possible lack of constraint at the entry point.
Opening at entry point will create an error in the Cartesian concepts as angles close to vertical would not be constrained. The bold rectangle represents the width of a hole that allows the probe to pass through at an angle, but this constraint is too wide to constrain the vertical probe represented by dashed rectangle, which would only be properly constrained if the width was that of the dotted lines.

### 3.7 Concept Selection

Error considerations along with other parameters were factored into the following Pugh chart in Table 3.10 to help decide which concept to move forward on with detailed design.

**Table 3.10: Pugh chart for concept selection**

<table>
<thead>
<tr>
<th></th>
<th>Spherical arm</th>
<th>Cartesian arm</th>
<th>Spherical bridge</th>
<th>Cartesian bridge</th>
</tr>
</thead>
<tbody>
<tr>
<td>Novelty</td>
<td>+</td>
<td>+</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Time for procedure</td>
<td>+</td>
<td>+</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Error from forces</td>
<td>-</td>
<td>--</td>
<td>++</td>
<td>+</td>
</tr>
<tr>
<td>Constraint accuracy</td>
<td>0</td>
<td>-</td>
<td>0</td>
<td>-</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>+1</strong></td>
<td><strong>-1</strong></td>
<td><strong>+1</strong></td>
<td><strong>-1</strong></td>
</tr>
</tbody>
</table>

From the Pugh Chart, the spherical arm concept was chosen to do detailed design on. It has additional novelty as well as saving valuable time. It should be noted that the other 3 concepts are still viable options for further development.
4 Detailed Design

4.1 CAD of Device

Figure 4.1 shows a solid model of the device. There are essentially three components: The base, the arm, and the probe holder. The arm is made from two parts for manufacturing purposes, and it is free to slide along the circular base, with a thumb screw to tighten and lock the arm in place. The probe holder is allowed to slide along the curved arm and is also tightened by a thumb screw, allowing probes to be directed towards a remote center of rotation a distance of 10 mm below the bottom of the base to account for the thickness of the coil. In the imagined workflow, after these two degrees of freedom are set, the probe is then inserted through a guide in the probe holder to the desired depth. After insertion of the probe, the probe holder can be easily unclasped from around the probe so that the arm can be reposition for the insertion of another probe and to reduce injury in case of unexpected patient motion. Two concepts for the probe gripping and releasing mechanism were explored and prototyped.

Figure 4.1: Solid model of device. Two tracks allow for orientation of the needle in two angles.
4.2 Structural Design

Many geometric arrangements were considered when designing the detailed structure. This device is unique from other devices out in the market in that it will sit on a plane above the skin and thus the insertion point. The design was started by considering a curved beam that had a central radius of 35 mm, to make sure that the needle holder would not take up more than 4 cm of space. However, because of the coil, the base of the curve will have to be offset upwards to maintain the angulation from the entry point. A diagram of this is shown below in Figure 4.2. This limits the range of angulation that can be achieved, but it was also important that the device did not take up too much axial distance of the needle so that deeper lesions could be targeted with current probes. Also, the needle itself cannot be positioned in the arm and is to be positioned on the side of the arm. The arm part must be offset in order to accommodate the needle always in line with the center of the circle and rotation about the entry point. (Figure 4.2(b))

Because the base is offset, the radius of the base has to be considered. The radius that the device must rotate about on is now \( b.r. = \sqrt{R^2 - h^2} \). In our design, we consider the inner radius \( R \) of the beam to be 30 mm. The offset \( h \), which included the base of the arm is taken to be 18 mm. Now our arm has an inner travel radius \( b.r. \) of 24 mm.

The arm was also offset such that the probe is held 2 mm off of the side of the arm. This creates torsional stresses in the beam so the cross beam cannot be too thin. The bearing for the arm travels on the track and rotates about the entry point.

Figure 4.2: Diagrams of offset of (a) the base and (b) the arm.
4.3 Bearing Design

The device is required to be precise while being low cost. This calls for kinematic constraints, where there is exactly 1 constraint for each degree of freedom to be controlled. Each rigid body has 6 degrees of freedom. In this case, there is to be two moving parts. Each part must translate along a track, so any design should contain 2 translational constraints and 3 rotational constraints, in order to leave one translating degree of freedom along the track. Friction from a lock or screw would provide the 6\textsuperscript{th} constraint.

There must be 5 constraints total, such as shown in Figure 4.3 below. Four constraints on a curved surface will constrain rotation about x and z as well as translating along the x and z directions. Adding an additional constraint on a lever far from the center of those constraints will support the load and keep it from rotating about the y axis. It is important to note that the constraints are acting in both positive and negative x and z directions, which balance each other and keep it properly constrained. For example, if we were to imagine that the 4 forces on top of the shape were to be rotated 90° clockwise about the y axis of the cylinder, there would be no force acting in the positive x direction and the track would be free to move in that axis and not be properly constrained.

![Figure 4.3: Force acting on the arm and kinematic constraint that could support this load.](image)

The constraint design can be reworked to have 4 contact points in a V groove shown in Figure 4.4 that would be easier to mount. If the force $F$ in the previous Figure 4.3 were directed upwards, it is likely for the 4 constraints on top to lift off. In the V groove
design, the fifth constraint was brought more line with the center of the 4 constraints to prevent rotation even if there were an upward force on the arm.

![Diagram of constraints and on a track that allows for movement along length of the track.](image)

Figure 4.4: Diagram of constraints and on a track that allows for movement along length of the track.

To make these contact constraints, spherical surfaces on flat surfaces were used. The spheres create a tangent point contact with the flat. For V grooves which have slanted flat surfaces, geometry was required to find the width of the groove given the clearance between the base and the carriage that moves on the spherical surfaces. Figure 4.5 shows parameters that are used to find the proper width and spacing that would allow a part on the spheres to sit square over a V groove.

![Parameters to find proper groove width to ensure clearance between two parts.](image)

Figure 4.5: Parameters to find proper groove width to ensure clearance between two parts.

Equation 13 was used to find the distance that would allow a clearance of .3 mm between the track lip and the bottom surface of the carriage that rides over it. The signs of \(d\) and \(h\) depend on whether or not the ledge should be higher or lower than the radius center. If it is lower, as in Figure 4.5, then \(d\) and \(h\) are negative.

\[
x + d = \frac{R}{\sin \theta} + \frac{h}{\tan \theta}
\]  

(13)
Taking in those geometry considerations, the ball and groove designs were made. The fifth contact in both cases was designed as a ball on a flat surface. Cross sections of the models can be seen in Figure 4.6. In the bearing that goes on the base, the bearing will have to be snapped on, where as in the needle holder, that piece can be slid over the arm.

![Figure 4.6: Cross sectional views of the bearing designs used in the arm as well as the probe holder carriage.](image)

In order to properly preload the bearings, as well as to provide a clamping force to lock the bearings in place, thumbscrews were chosen. Thumbscrews are simple, intuitive to use, and do the job with just one part. Threads on the part away from the head allow for that half to move as a lead screw, effectively preloading the bearing, or more to lock the piece in place.

Saint-Venant’s principle is also an important design consideration. To ensure accuracy, the bearing support length $d$ must be greater than $1/3$ of the length from the bearing to action arm $l$, and it is illustrated below in Figure 4.7.

![Figure 4.7: Saint-Venant’s Principle: $l$ must be less than three times $d$. a. Schematic of the top view. b. schematic of side view of device.](image)
In the top view, \( l = 29 \) mm, and \( d = 10 \) mm to satisfy Saint-Venant’s Principle. From the side view, \( l = 34 \) mm, and \( d = 11 \) mm, which almost satisfies Saint-Venant’s Principle. A wider \( d \) was not convenient because the carriage would be bigger and take up valuable room on the arm, limiting the range of motion.

Finite element analysis was performed to ensure that the parts not would break. First FEA was conducted to make sure stress from preloading via the thumbscrew does not exceed the yield stress. The material is acrylic, and a 1 N force was applied to the hole that is to be threaded in both the probe holder (Figure 4.8) as well as the arm carriage (Figure 4.9). The maximum Von Mises stresses were found to be 5.3 MPa and 1.2 MPa respectively, which are well below the yield stress of acrylic (207 MPa) and even below the yield stresses of weaker plastics such as Nylon which has a yield stress of 60 MPa.

Figure 4.8: FEA stress results of the probe holder carriage.
FEA was also used to confirm that the arm base would not break in the process of snapping the piece onto the base. From Figure 4.10 below, we see in (a) that the von Mises stress is 3 MPa when the displacement at the nub is 0.11 mm (b). If the material behaves linearly, then in order to split apart the required 1 mm, the part will see 30 MPa. This still gives us at least a factor of safety of 2 for some weaker plastics such as nylon.
4.4 Release Mechanism Design

There must be a release mechanism designed to easily allow the needle to move freely after insertion, both to prevent injury in case of patient movement, as well as to reposition the probe holder carriage to place an additional probe. Another functional requirement is that the mechanism must not come off of the carriage itself to minimize the risk of losing or misplacing an extra part.
A number of different release mechanisms were considered such as those based on cam locks and screw locks. However, as the parts are to be made out of plastic, another approach was to use a plastic snap mechanism that use the compliance of plastic as a spring in order to hold pieces together. Such an approach is prevalent in many plastic consumer products.

Two concepts were designed as presented in Figure 4.11. One concept has a hinge and latch much like many plastic snap pieces (a), and another with just a cover to act as a spring (b).

(a) & (b)

Figure 4.11: Two different methods of needle release mechanisms that were developed. (a) The snap concept. (b) The compliant spring version.

4.5 Design for Manufacturing

These parts are intended to be made for mass production through injection molding, and preferably for injection molding via a single pull. Windows were put in the back of the bearings to allow for a single pull to make the features. The whole arm piece could not be made by pulling both the arm and its carriage bearing at once. Thus, the arm was split into two pieces with two 2-56 screws connecting them. The screws are reversely oriented in consideration of access to holes. Both parts can now be injection molded with a single pull, although each piece also now has holes that must be drilled and tapped in a separate step.
Figure 4.12: The arm part after considerations for manufacturing were made consisting of 2 pieces and screws.

Parts were also designed with similar feature thicknesses to ensure equal cooling time throughout the piece. As the model is seen in Figure 4.11, the probe holder carriage could not be injection molded via a 2 mold system. Additional windows could be added to the bottom side of the carriage to allow access to form the spherical features, or more advanced injection molding techniques could be used.
5 Prototyping and Evaluation

The device was prototyped using stereolithography of an ABS-like resin by Vaupell Rapid Solutions. Plastic screws were used to assemble the pieces together and provide correct preload. A final assembly is seen in Figure 5.1.

![Photograph of prototyped instrument guide.](image)

When the parts first arrived, the appropriate holes had to be tapped, and the tracks needed sanding due to overbuild in the stereolithography process as the carriages could not slide along the tracks with reasonable force applied. Sanding eventually did allow the carriages to slide more easily along the tracks.

Tightening the thumb screws made the carriages not move along the tracks when pushed. After tightening, the probe holder carriage seemed to be stiff with no discernable movement in the pieces when trying to wiggle the carriage by hand. The carriage of the arm piece was less secure. Lifting up on the tip of the arm did cause the bearings to disengage a little, however this type of loading is not expected to occur during any procedures when accuracy is required. After the first assembly, the carriage of the arm was stable and was constrained properly. However, after snapping on and off the track a few times, there is now considerable play in that bearing, due to the wear of the plastic
when rubbed against itself. The arm carriage was subject to additional wear as the spherical nubs rubbed against the thick lip of the base as the assembly was forced on and off. Eventually, this wear along with the sanding made it so that not all 4 contact points in the V groove existed, allowing for considerable waggle of the carriage as rotation about the vertical axis is no longer fully constrained. This loss of contact is seen below in Figure 5.2

Figure 5.2: Wear has caused loss of contact between the bearing and track allowing for considerable waggle.

Despite this wear, the preload was able to hold a force pushing down on the arm. Testing should be performed to find the load expected and the proper amount of preload that would constrain the arm in the correct position.

Another premise of this device is that it has the ability to position multiple needles. Given the dimensions needed to ensure stability and accuracy, there is less of a possibility of having multiple arms on one base. There is however an ability for the holder to hold more than 1 probe on each arm, as shown in Figure 5.3.
Figure 5.3: Device with 2 probe holders on the arm.

The maximum angle of the device from vertical was measured to be approximately $35^\circ$, which is $10^\circ$ off from the targeted specification. As seen in Figure 5.3, it is also confirmed that the device does direct probes to one remote center of rotation below the base of the device. Another observation of the device is that it is very small, but the device is operable by nimble hands. Some features such as the thumbscrews could be made bigger to be more ergonomic, or switched for a different clamping mechanism. It is also possible that such a small device may be able to be mounted onto the patient directly, but then it would be harder to fulfill the ideal of having it integrated with a MRI coil for registration.

Both needle holding mechanisms were prototyped, and both concepts were able to firmly hold a needle in position. In the snap concept, the pin in the hole was toleranced incorrectly, and the pin had to be sanded down in order to fit in the hole. In the assembly process, the pin broke off, leaving only about a quarter of the pin left. With a quarter of the pin in the hole, the concept was still evaluated. The snap shut easily, and was very snug and held the needle in a position. Releasing the probe required some more force, but it was doable, although it may be easier than it should be because only a very small amount of pin was constraining the door. The one piece spring cover also held the needle in the position, but in the prototyped version the spring cover was too stiff to easily insert the probe directly, and there was no good way to release the probe. More optimization and testing should be done to find the correct compliance that would allow the cover to be easily opened. For the one piece concept, the probe holder carriage itself will have to be loosened before the grip on the needle can be released, whereas for the concept with a separate snap piece, it can be released without moving the entire carriage.
6 Conclusions and Future Work

The prototyped device is a proof of concept to the feasibility of an instrument guide for MRI guided interventions. The device worked for the most part as designed, and can be used to define two angles and hold a needle directed at the entry point. There are many next steps to be taken in order for this device to transfer into a successful probe guidance device.

First on the mechanical device itself, more wear resistant material should be used, and the optimal tolerancing for these types of bearings should be found to ensure that the bearings have a long life and remain kinematically active and so that sanding is not required. Further testing may be done to see how much the structural design could be optimized so arms and carriages can take up less space so there could be potentially more probe holders and a better resolution for how far apart the probes must go. Testing to find the proper preload that would allow for the carriage to be held in proper position should be conducted. Labels that mark the two angles also need to be added in order to tell what angles the probes are entering at. While the thumb screws enable the bearings to be preloaded, and the needle holding mechanism functioned accordingly, a more ergonomic design could also be beneficial to improve the usability of the system.

Aside from the mechanical device, the system should be incorporated with some imaging based software to track the location, and since the original intention was to place the device over a customized coil, the coupling system needs to be designed. Kinematic couplings provide excellent accuracy and should be used for attachment. Given the small size of the device, either the coil can be designed to have very small openings for these to go over, or the device itself could have wings that can expand over to the coil. It’s imagined that there are special features on the coil to aid in registration as well as coupling with this device. Possibilities for actuating this device can also be developed in the future.
References