THE COLLEGE OF ENGINEERING
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Frameless Stereotactic Navigation

Final Report
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Abstract

Stereotactic navigation is a method used in medical procedures to determine the location of an instrument relative to the patient. Dr. Nathaniel Brooks, a neurosurgeon at the UW Hospital, believes that a more affordable and portable version of computerized stereotactic navigation could be created to increase the availability of this technology for a wider range of procedures. Reducing the cost of stereotactic navigation would allow less invasive procedures, including pain reduction therapies and spinal injections, to justify the use of the technology. The goal then is to create a frameless computerized stereotactic navigation system using inexpensive commercial products while maintaining a high level of accuracy. In order to attain the most affordable design, existing tracking packages, such as the Xbox Kinect and Wii motion sensors, were evaluated. After concluding their insufficient accuracy, alternative software and products were evaluated. Exploring possible avenues for cameras, from industrial grade to webcams, it was decided that the final design chosen would incorporate two HD Logitech C920 webcams as the image-capturing components. These cameras were chosen due to their high accuracy and relatively low cost and bulk. Webcams were also favorable in the coding of the system due to the use of a universal serial bus, USB, which allowed for accelerated data analysis on a standard operating system with C++. These cameras are used in conjunction with a central computer and marker array in order to establish 3D coordinates in relation to a patient's imaging results, allowing the real time tracking of a surgeon's invasive tooling.

Problem Motivation

Computerized stereotactic navigation is a system that aids in the precision of certain surgeries, such as neurosurgeries on the brain or spine, which require very accurate measurements. Typical stereotactic navigation systems are extremely bulky and can cost upwards of $250,000, according to our client. Due to the system's high cost, it is only available for use in more invasive procedures, such as brain surgery, which require extreme precision. The size of the system also limits its presence to select operating rooms, where it can only be used for high risk patients. Our goal is to create a much less expensive and more portable stereotactic navigation system using commercially available 3D object tracking hardware and software. By decreasing the cost and improving the portability and flexibility of such systems, the technology could be used in less invasive surgeries and even extend to other fields. Specifically, spinal injection procedures could benefit greatly from this system by reducing the patient's radiation exposure caused by excess fluoroscopy imaging. Operations outside of neural medicine, such as root canals and nasal reconstruction, could also be improved if this technology were readily available. The system designed in this course will track a tool, specifically a spinal needle, and project its position *in-vivo* in real time. In order to display the tool location, its position will be superimposed onto the patient's X-ray images which are visible to the surgeon. This system could be expanded upon later to incorporate other tooling.

Client Description

The client for this project is Dr. Nathaniel Brooks. He is a neurosurgeon at the UW Hospital who specializes in spinal surgeries. He believes this design would be helpful in a wide range of procedures, from spinal injection pain intervention to precise injection of treatments, which do not normally have access to the expensive equipment used in computerized frameless stereotactic navigation.

Background

Stereotactic Navigation is a computerized tracking system that allows surgeons to track a tool in real time in order to make very precise and accurate movements in higher risk surgeries. By using markers placed on the patient and the tool being tracked, the system can triangulate the position of the tool in relation to the patient. The position is then overlaid onto a set of X-ray images taken before the procedure to give the operator a three dimensional view of where in the patient the tool is. This allows the user to accurately and precisely navigate to the proper areas in higher risk surgeries such as brain or spinal surgery where very precise measurements are key.

The main concept behind stereotactic navigation involves the use of triangulation in order to establish a 3D location. The components for triangulation consist of two cameras and an object in their overlapping field of vision. By finding the angle between the object and each camera, as well as knowing the distance between the two cameras (baseline), a relative position can be calculated using the law of sines. An example of this can be seen in Figure 1. Therefore, an object's spatial location can be found by utilizing the two cameras.

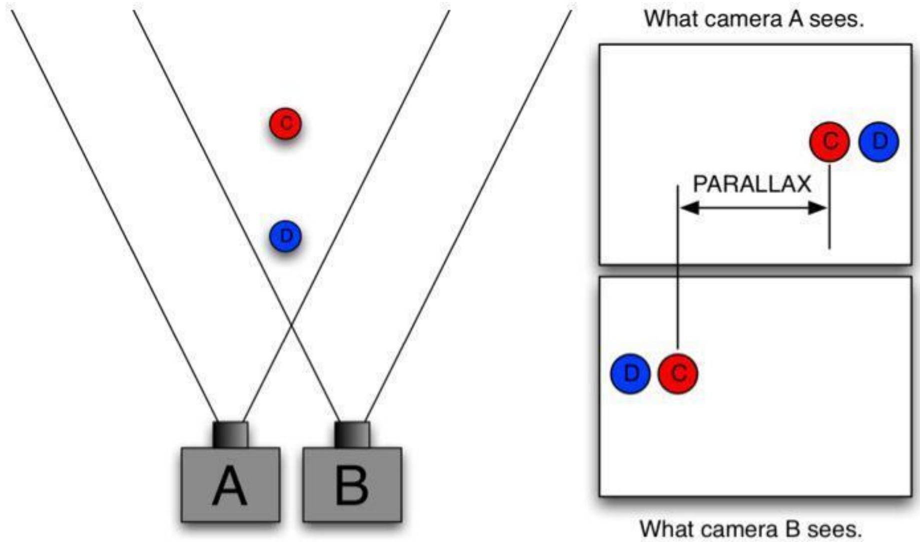


Figure1: The process of triangulation, using cameras A and B in order to locate objects C and D. [1]

This theory is utilized differently in various stereotactic navigation devices. Some products utilize two high definition (HD) infrared (IR) cameras to track IR spectra by either *active* or *passive* navigation. An *active* IR detection system bounces infrared light off of an object and collects the reflected light, while a *passive* IR detection system only collects the infrared light that is emitted by the object or reflected from other sources. [1] Other products use HD visible wavelength cameras to track visual markers, which are identifiable due to their colors or their level of luminescence.

Current stereotactic navigation systems, such as Medtronic's *StealthStation S7 Surgical Navigation System*, are typical only available to be used on more expensive surgeries do to their high costs, with the StealthStation itself costing $1,100,970. A typical spinal and cervical case using the StealthStation would cost an average of $28,262 to the patient. [2] However, if the technology were to be made more affordable, it could be used on a greater array of spinal procedures, including typical epidural steroid injections, with inpatient procedures costing about $150 per procedure and outpatient procedures costing about $330 per procedure. [3]

Using stereotactic navigation techniques during spinal injections could also reduce the patient's exposure to radiation. Currently in a spinal injection procedure, the spinal needle is navigated within the patient using fluoroscopy, which uses X-rays to create a real-time image of the needle location. If a stereotactic navigation system were used, the patient would only be exposed to X-rays during a final fluoroscopy location check, significantly reducing total exposure time.

The technology behind stereotactic navigation can technically be utilized for any type of surgical operation; however, the difficulty of creating a reliable frame of reference for the system is the primary challenge. For consistent tracking, bone landmarks must be mapped and reference points must use bone regions with a constant spatial relationship to the organs surrounding them. [4] Only in this way can superposition of a patient's imaging results be achieved. Due to this limiting factor, along with the cost to design and develop a reliable reference arc which mounts to bone, stereotactic navigation technology has been largely limited to brain and spinal surgeries. Additionally, stereotactic navigation has been used in breast biopsies and in the removal of tissue.

Due to its need for a consistent bone and skin interaction, stereotactic navigation has also begun to be used in transfacial operations. One example is its use in minimally invasive transnasal nasopharyngectomy. This surgery is typically used in the operation of Nasopharyngeal cancer, which causes the growth of malignant tissue on the nasopharynx located on the top of the palate near the back of the nasal cavity. The technology allowed the surgeons to perform the surgery without severing carotid arteries, and allowed for a safer and less expensive surgery with a shorter healing period compared to previous open transnasal operations. [5] This technology has also facilitated new experimentation with deep brain tissue innervation, which has been incremental in many recent breakthroughs in the treatment of several neurologically damaging disorders.

Current Devices

Stereotactic navigation is widely used today in order to limit the invasiveness of surgeries and aid in precision targeting. Companies such as Brainlab and Medtronic currently produce a variety of devices on the market. These devices utilize the tracking methods mentioned, including infrared (IR) and Red/Greed/Blue (RGB) spectra tracking. However, at the UW Hospital these devices can cost upwards of $250,000. [3] In most general procedures, the cost of using the equipment would be too expensive, limiting the number of procedures able to use the machine. In addition, current modules can be large and heavy, as seen in Figure 2, and as a result are usually restricted to operating rooms alone. These limitations make it difficult to transport the technology between rooms, preventing full use of the technology.

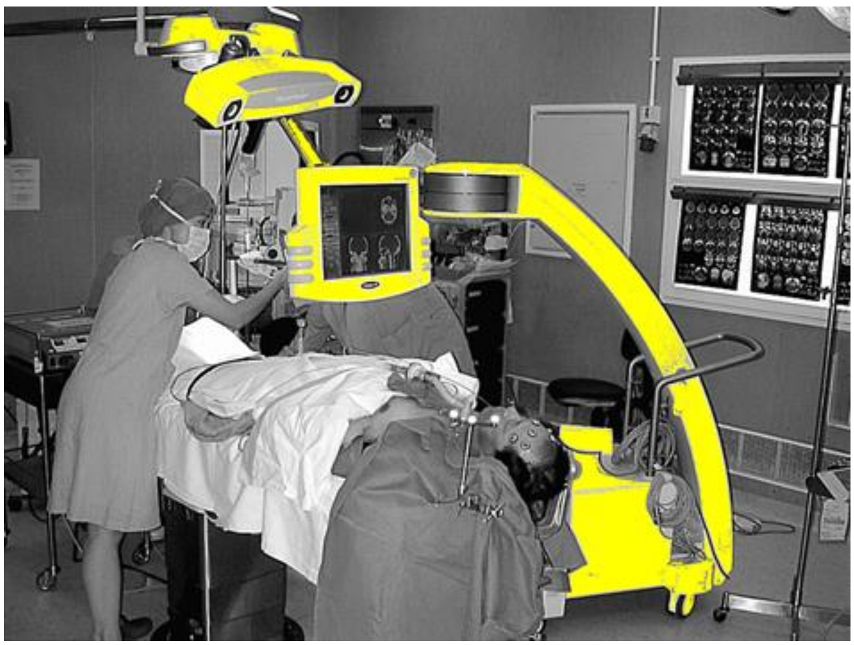


Figure 2: The complete computerized stereotactic navigation system is highlighted in yellow, demonstrating the size and operating conditions of current systems. [5]

Design Alternatives

Stand

The first component of the design to be determined was the base of the design. How the design and its components will be transported and housed within the hospital was vital to establish before the size constraints of the remaining components could be determined.

Specifications

All stands must be designed with the work environment in mind. These bases must perform in the surgery room and as a result must be made with sanitation in mind. The stands or system setups must be capable of handling chemo-wipe cleaning. The materials used must also be hypoallergenic and capable of handling the stresses of constant transportation and use. The base must be able to support the system's cameras at a height between 1.2 – 1.8 m from the ground, and be sturdy enough to avoid accidental tipping. Obviously, the transportation of the stand must also be a priority, and it must either have a wheelbase well under the width of a standard doorframe (0.75 m) or, if carried, weigh less than 7.5 kg.

Design 1: Altered IV Stand

The first stand design considered would utilize a standard IV stand which would be customized to support both our camera array and on board computer seen in Figure 3. Using an IV stand as our base would be beneficial due to the broad range of options on the market, and the fact that all IV stands must already be hospital approved for safety. IV stand designs can vary significantly, but the primary difference between products is the effective base radius and the number of legs, which typically ranges from 150 mm to 170 mm and 4-6 legs respectively. [6] However, the higher the quality, the greater the cost. To fit our budget and design constraints, the Blickman Chrome IV Stand was our stand of choice. The Blickman incorporates five casters with rubberized wheels, a two-hook IV bag orientation, a ship weight of 5.89 kg, and an extendable height between 1.33 – 2.38 meters. At $118, it is also one of the least expensive IV stand options in the 5-caster IV stand market, and offers a 610 mm base diameter. [7] The IV stands primary weakness, however, is its stability. To maximize safety, all components attached to the stand must lie within its base area. This limitation could hinder the use of the stand as our attachment point for our computing components.

Figure 3: On the left is an image of the Blickman 5-legged Chrome IV stand. The image on the right is a concept draft of how the finished customized IV stand would look. [7]

Design 2: Tripod

The second stand design considered would utilize a camera tripod in order to support the system's camera array. The tripod considered for our design was the Grainger Aluminum Laser tripod with ¼-20 bolt attachment and an adjustable height of 0.69 – 1.52 meters. This tripod fit well within our budget, costing $95.35. It is also relatively lightweight, with a shipping weight of 3.92 kg. [8] A tripod design's strength is in its stability. Accidental bumps or shifting would be very unlikely to result in tipping, due to the tripods large base span. However, the tripods stability positively correlates with its weight and bulk, which must be considered when designing a portable system. Tripods also become exceedingly expensive as the maximum adjustable height gets larger. The tripod evaluated is shown in Figure 4.

Figure 4: Shown is the Grainger Aluminum Laser tripod with ¼-20 camera mount. The tripod's camera head can be tilted with an accuracy up to one degree. [8]

Design 3: IV Stand Clamp

The final stand design considered utilized the local IV stands existing in the hospital itself. Rather than building a transportable base out of commercial products, the IV clamp will mount the camera array to IV stands present during the time of surgery, reducing clutter and the number of wheel bases in the room at the time. Our camera array would be attached to the stand via a Nootle ¼-20 Quick Release Pipe Clamp, which is shown in Figure 5. The Nootle clamp is capable of clamping onto poles up to 3.81 cm in diameter (1.5") and has the capability to adjust its angle at the neck. [9] Utilizing local objects as a base would result in an extremely light and portable design for the camera array, however, reliable clamping ensuring no shifting of the cameras throughout the operation is crucial. It is also important to be certain that no damage or residue is left onto the clamped surfaces once the array is removed.

Figure 5: On the left is the Nootle ¼-20 Quick Release Pipe Clamp [1]. On the right is a concept of how the camera array attached to a typical IV stand via the Nootle would appear. [9]

Camera Stand Design Matrix

Criteria (Weight)	Design 1: IV Stand 		Design 2: Tripod 		Design 3: IV Stand Clamp 	
Cost (30)	2	12	3	18	5	30
Height/Weight (25)	4	20	3	15	5	25
Stability (25)	3	15	5	25	2	10
Ease of Manufacture (10)	3	6	4	8	5	10
Ease of Use (10)	5	10	4	8	4	8
Total (100)	63		74		83	

Table 1: The Design Matrix evaluates the ability of each stand design alternative to follow the given criteria on a scale from one to five, with five being the best score and one being the worst. The categories and weights were chosen based on their importance to the design and client requirements. The total score for each design is shown at the bottom as a value out of a total of 100 possible points.

Cost

In keeping with our design criteria, the stand cost was weighted the most in this design matrix. Maintaining a balanced function to cost comparison was the biggest concern in our choosing of the ideal stand design. All three designs fell reasonably within our budget, but after consideration, the attachable IV stand clamp would be the most cost effective. Aside from component material costs, the primary component, the Nootle pipe clamp costs a mere $15.98, which is meager compared to our tripod which would cost $95.35 and our IV stand which would cost $118.

Height/Weight

One of the second highest weighted sections of our design matrix is the relative height/weight ratio of the stand. In order to design an optimally transportable system, the relative weight and size of the stand must be kept relatively low while maintaining the height requirements for tracking. In this section, the IV stand beats the tripod. By dividing the stand's max height by its weight, we can see that the tripod has a height/weight ratio of 0.38 while the IV stand has a ratio of 0.41. The tripod simply cannot achieve the same height as the IV stand without excessively adding to its weight. However, the attachable IV stand clamp wins in this area with an effective ratio of 21.64. Weighing only 110 grams and being able to attach to local IV stands means that the stand clamp has the same effective maximum height as the IV stand at a fraction of the weight.

Stability

Stability was also weighted as the second most important characteristic for the stand. The safety and reliability of the system largely rely on the stability of its stand. However, it was not given the most weighted position due to the system's capability to frequently auto-calibrate, lowering the importance of the stands ability to remain still. In this category, the tripod takes the highest score though. While its lower max height compared to the IV stand is a weakness in some aspects, it makes the tripod more stable overall. Also, with a wider base area and effective base radius than the IV stand, the tripod is more resistant to tipping on multiple levels. The IV stand received a significantly lower score as a result of its greater height and smaller base, and the fact that most of its bearing weight would be supported at a higher elevation than the tripod, making it more prone to tipping if bumped. The IV stand clamp received the lowest score, because it inherently has all of the weaknesses of IV stand stability, but also must rely on the pipe clamp holding properly to avoid shifting.

Ease of Manufacture

The ease of manufacture was also considered in our stand design decision as one of the lowest weighted design criteria. The ease of manufacturing was more of a short term comparison, weighing how successfully our team could successfully prototype each design in our project timeline. In this area, the IV stand received the lowest. It would require the greatest amount of effort to retrofit the device to properly support our camera array, and would ultimately cost the most in materials out of the three designs. The tripod came in second in this area. While the tripod itself would not require the same amount of effort to customize as the IV stand, changes would have to be made in order to increase its maximum achievable height. The IV stand clamp won in this area do to its simple design. While each of the other designs would require customization of the stand on top of designing a camera array mount, the IV clamp would only require the effort to design the mount. The Nootle pipe clamp itself would require no customization.

Ease of Use

The operator's ease of use was also considered in the final design of the system's stand. This section was one of the lowest weighted sections of the design criteria, primarily due to the importance of the function of the product, and secondly because all three of the proposed stands are simple to use. In this section, the IV stand clamp and the tripod received the same score, mostly due to the requirement that for both designs the operator must assemble the components and is personally responsible for the proper setup of the camera array. The customized IV stand came in first in this section as disassembly is not required. The IV stand can be wheeled into the room it is needed in, and would already be prepared, placing no responsibility on the practitioner to properly set up the device.

Image Tracking Needle Attachment

Specifications

In order to guide the design of the needle tracking attachment, a set of requirements was created. The most important criterion was that the attachment to the spinal needle should not interfere with the surgeon's operations. The attachment must also be easy to use and attach to the needle without any extra tools required. Another concern that was taken into account is that there is a second removable needle component within the main needle that is removed once the needle is placed within the patient. The marker attachment cannot interfere with the removal of the inner needle once it has been attached to the spinal needle. Finally, the attachment must be easy to track to ensure the highest possible accuracy.

Design 1: Layered Discs

The first needle reference marker design would involve using an attachment at the end of the needle that would consist of several different colored stripes for the cameras to track, shown in Figure 6. The attachment would be a simple clip that slides on over the back of the needle and clamps on using two small dimples which are present on the removable head of each needle. The major benefit of this design is that it is extremely small and is unlikely to disturb the clinician or affect his performance. Once the needle is inserted into the patient the inner needle can be pulled out with the clip still attached to it. Another advantage of this design is that it is easy to manufacture. Since the design consists of only the prong shaped clamp and the cylindrical portion with strips around the perimeter the 3D modeling and printing of it would be quick and inexpensive.

Figure 6: The Layered Disk needle attachment design

The layered disk design, however, comes with its negatives too. The major downside is in how the attachment is tracked. The program tracks colored markers by finding the center of area of the given color. Given the shape of the stripes, the center of area may appear in different locations based on how it was oriented. A sphere, on the other hand, would appear in the same location regardless of its orientation.

Design 2: Tripod Marker

The second design utilized three balls in a shape of a triangle attached to the needle component of the spinal needle via a ring clamp. The Tripod design works by using three spheres in a triangular formation, equidistant from the needle, to create three distinguishable points for tracking Figure 7.

The advantage of the Tripod Marker is that it can track the rotation of the needle along its length. When the clinician holds the needle in his or her hand and spins it around the center of the needle, the tracking system would be able to tell how it was rotated since there are three trackers. Also, since spherical objects appear the same to the cameras at any orientation, it is fairly easy to determine the center of area of each spherical marker.

Several drawbacks prevented this design from being used in the final product. The size of the attachment presents an ergonomic problem for the surgeon; their hand would have to grab around the attachment so it doesn't block the trackers. Also for tracking purposes, the camera system would not be able to tell if the needle was upside down or not because there is no directionality to the plane created by the three tracking markers. The last downside to this design is that it does not allow the inner needle to be removed without extra work. Since the attachment clamps around the entire needle and not just the removable plastic end portion, it would need to be removed before the inner needle can slide out.

Figure 7: The Tripod attachment design

Design 3: Distal Series Tracker Rod

The final design that was considered was the distal rod attachment with the markers in a series. This design utilizes two tracking spheres of different colors that are centered along the axis of the needle. The distal series tracker attachment can be seen in Figure 8. Since the center of each ball is in-line with the needle axis, simple vector math can be used to calculate the needle tip location based on the locations of the two independently identifiable spheres.

Figure 8: The Distal Series Tracker Rod attachment design

Out of the three needle tracking design, the Distal Series method requires the fewest location markers. As a result, the calculations needed to predict the needle tip location are minimal. As with the Tripod arrangement design, this option uses spherical tracking markers.

The main fault of the design is the reduced amount of comfortability holding the needle due to the size of the tracking spheres. The spheres must be large enough for the camera system to track from at least two meters away, resulting in a rod long enough to space out the spheres. If the clinician holds the needle just below the attachment site or holds the attachment as one would a hypodermic needle with the thumb on the back of the attachment, then this should not create much of a problem.

Needle Attachment Design Matrix

Criteria (Weight)	Design 1: Layered Disks 		Design 2: Tripod Marker 		Design 3: Distal Rod 	
Tracking Reliability (30)	1	6	4	24	5	30
Size/Weight (30)	5	30	2	12	4	24
Cost(25)	5	25	1	5	3	15
Ease of Manufacture (15)	5	15	1	3	4	12
Total (100)	76		44		81	

Table 2: The design matrix for the spinal needle marker attachment. Each category carries a weight which is then rated from one (the lowest) to five in terms of the design's ability to complete the category

Tracking Reliability:

Tracking reliability refers to how easily the system is able to track the attachment. This is the heaviest weighted category because if the system is unable to track the needle attachment then it is impossible to determine the location of the needle. The layered disks scored a one because the geometry of its markers depends on the orientation. The tripod marker scored a four because the balls allow the center of each tracker to be found easily, but is awkward to hold and requires more calculation than the distal rod. The distal rod won because it the easiest to track and is the simplest to hold with the ball trackers.

Size/Weight:

The size and weight is the second most important category. The attachment needs to be lightweight to make the needle easy to handle. If the attachment is too heavy it makes fine movements hard to perform and can hinder the use of the needle. The layered disk scored a five because it is the smallest and lightest design. The Distal rod design beat the tripod because it uses fewer balls making it slightly smaller and lighter.

Cost:

Cost carries a weight of 25 because the attachment is meant to be thrown away after one use, requiring the attachment to be inexpensive. The tripod design is the most expensive since it is the largest and the most complicated arrangement, making it hard to fabricate and raising the cost. The distal rod scored a three because it is simple and requires a minimal amount of materials. The layered disk scored a five because consists of only a cylinder with colored rings making it the simplest of the designs.

Ease of Manufacture:

The final and lowest weighted category is the ease of manufacturing because the main concern is accuracy and precision rather than manufacturing. The tripod design scored the lowest as it is the most complicated and therefore difficult to fabricate. The distal rod scored a four because it fairly easy to make apart from the attachment mechanism. The layered disk scored a five because a cylinder with two prongs at one end is very easy to construct compared to the other designs.

Camera

All of the designs that were considered shared the same general physical setup. In each design, the cameras would be built into the stand design that was chosen in the previous design section. The cameras would additionally be separated by a set distance to maximize the accuracy of the triangulation calculations. Attached to both the patient and surgical tools would be markers that would be tracked by the cameras for triangulation. Since all of the designs use the same physical setup, it is now possible to discuss the different types of cameras used to track the patient and the tools. A more detailed list of design requirements can be found in the Appendix under the Product Design Specifications.

Specifications

When deciding on the best camera option, there were a few design criteria that had to be considered. The camera needed to be able to stream in real time to provide constant feedback to the user. The camera also needed to be able to acquire an image with a resolution of at least 720p, preferably 1080p which is true high definition. The high resolution is needed to obtain the accuracy of tracking of three to five millimeters required for the project; the more pixels there are, the finer the resolution will be. To be able to capture this movement of the user’s tools, the cameras need to be able to capture footage at a minimum of 20 frames per second (FPS). This frame rate would be preferable so that the clinician would not have to wait between frames to see how their tool moved. The final criterion for the camera is that it needs to fit into the budget. The camera should be inexpensive enough that it would allow us to buy two of the same model and have room in the budget to still buy the other necessary.

Design 1: Wii Remote

The first camera that was looked at was the Wii remote, as seen in Figure 9. The Wii remote works by passively reading infrared (IR) light in a room to recognize objects present. It also has the ability to perform object tracking of up to four objects due to an internal processor. [10] In order for the Wii remote to work in this project, the setup would require an infrared lamp to increase accuracy. There would be one Wii remote placed on either side of the IR lamp on the adjustable arm which can be seen in Figure 10.

Figure 9: Multiple views of the hand-held Wii Remote are shown. The location of the IR sensor can be seen in the topmost view. [11]

The major benefit of the Wii remotes design is that it only costs $25 for each remote, making the total camera array for this design cost $50, which is well within the budget. [10] Another great advantage of the Wii remote is that there is a large online community of developers who have created software for using the Wii remote for purposes outside of gaming. This would allow for easier program development when trying to perform triangulation and tracking calculations. Additionally, the Wii remote supports a high resolution of 1024x768 pixels at 30 frames per second. It connects to the computer through Bluetooth, which allows for an upload speed of 24 megabytes per second. [10] In terms of the accuracy of the Wii remote, it can track a difference in position of one millimeter from one meter away. Unfortunately, this is too close in proximity to the patient than what the general setup for the system would normally be; ideally the system would be at the base of the operating table, which is about one to two meters away from the operating site. The Wii remote meets the requirement for cost, but just barely meets it for accuracy.

Figure 10: The Wii remotes require an IR lamp to increase accuracy. The entire setup, including the central computer and display unit, is shown. One Wii remote is placed on either side of the IR lamp at the top of the apparatus.

Design 2: HD Camera

The second design possibility involves the use of HD cameras. Several options were researched, including the Replay XD1080 HD Video Camera, as depicted in Figure 11, and the Logitech C920 HD Webcam, as shown in Figure 12.

The Replay XD1080 camera is meant to be used for action videos like skiing or biking, so it is small and light. The camera itself is only 28 mm in diameter and 93 mm in length with a weight of 85 grams, making it easy to fit onto the adjustable arm that will serve as its base. The camera is simple to use as it only has two physical buttons, one for recording and one to switch settings, requiring no programming to adjust setting. The Replay XD1080 can capture video at 1080p at 30 frames per second or 720p at 60 frames per second. [12] This will allow for high accuracy while tracking over distances of less than one millimeter, meeting our requirement. It also has the ability to live stream through an HDMI connection at a rate of 480 megabits per second making the video input into the computer almost instantaneous. [12] However, there is no software development community for this camera, so a significant amount of software will have to be developed by the team with limited aid from external sources. The Replay XD1080 HD Camera would meet the design requirement for accuracy while staying within the budget.

Figure 11: The Replay XD1080 consists of a lightweight, simple design. [13]

Figure 12: The Logitech C920 comes with an adaptable computer mount. [14]

The Logitech C920 is a high-definition webcam capable of streaming and recording 1080p video via a Hi-Speed USB 2.0 connection. The camera has a built-in universal tripod clip which will allow for easy attachment to the mounting unit. It is comparable in size to the Replay XD1080, and has a weight of 165g. There is a large online community of open source software development for video acquisition and manipulation using webcams connected via USB, so the team would likely have a significant amount of help in developing the required software. The Logitech C920 is also fairly inexpensive, costing only $79.99. [15]

It was determined that the Logitech C920 would be the better HD camera choice because it provides full HD video acquisition while maintaining a low cost. Because two cameras would be required for determining depth, the setup shown in Figure 13, the Replay XD1080 option would cost the team $600 total, while the Logitech C920 would only cost about $160. In addition, the USB connection for the Logitech C920 provides a more universal and easier to control computer connection than the HDMI in the Replay XD1080.

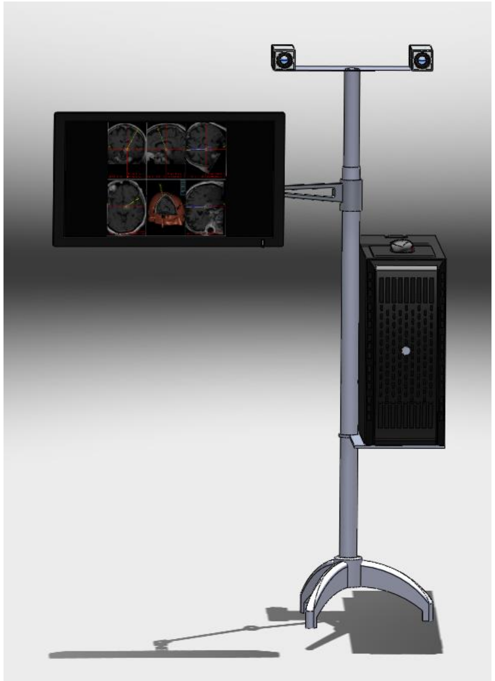


Figure 13: The combination of the two HD cameras provides enough information to determine the 3D location of an object.

Design 3: Bumblebee2

The final design that was brought up for consideration utilized the Bumblebee2 by Point Grey. This camera actually consists of two separate cameras in one box, seen in Figure 14. The Bumblebee2 comes with software for the cameras that already has the ability to triangulate positions in 3D space. The cameras work at 1032 x 776 pixels at 20 frames per second, giving a high quality picture that allows for a tracking accuracy well within a distance of one millimeter. Another benefit of the Bumblebee2 is that it comes with a kit for software development, making it easy to program the computer for video analysis and tracking. There is also free software development help through Point Grey. [16] This camera has also been proven to be reliable and accurate as it has been used by Google in prototypes of their automated-driverless cars.

Figure 14:   The Bumblebee2 contains two cameras and can accurately determine 3D location without the need for another optical input. [16]

The major downside to this design is that the basic Bumblebee2 unit costs $1895. [16] This cost is outside of the budget for the project and would require an increase in budget overall, not even including other component costs of the design. The Bumblebee2 makes the project much more feasible by providing a prefabricated software kit and hardware, but it is outside the budget of this project. The complete setup incorporating the Bumblebee2 is shown in Figure 15.

Figure 15: The spacing between the two cameras in the Bumblebee2 is predetermined. That and its internal processor aids in accurate 3D point tracking.

Camera Design Matrix

In order to evaluate each of the three designs, a design matrix was constructed. Each design alternative was evaluated on the criteria of accuracy and reliability, cost, program elegance, size and portability, ease of use, and safety. The complete scoring breakdown for each design alternative can be seen in Table 3. The HD camera design scored the highest overall, and therefore will be design which we pursue.

Criteria (Weight)	Design 1: Wii Remote 		Design 2: HD Camera 		Design 3: Bumblebee 2 	
Accuracy and Reliability (30)	4	24	4	24	5	30
Cost (20)	5	20	4	16	1	4
Program Elegance (15)	3	9	3	9	4	12
Size and Portability (15)	4	12	5	15	4	12
Ease of Use (10)	3	6	4	8	4	8
Safety (10)	3	6	4	8	4	8
Total (100)	77		80		74	

Table 3: The Design Matrix evaluates the ability of each design alternative to follow the given criteria on a scale from one to five. The categories and weights were chosen based on their importance to the design and client requirements. The total score for each design is shown at the bottom as a value out of a total of 100 possible points.

Accuracy and Reliability

In accordance with our problem statement and the directed use of our design, accuracy was our most heavily weighted factor in our design comparison. According to our client, the measurements and estimations of tool location in-vivo by our system must be accurate to at least one millimeter. At roughly a one-meter distance from the patient, this level of accuracy was attainable by each of the camera systems proposed, with the Wii remote at an accuracy of 1mm and both the HD cameras and Bumblebee2 system at an accuracy of >1mm. However, due to its existing infrastructure and software design, it was determined that the tested and verified Bumblebee2 design would provide the highest degree of accuracy.

In terms of reliability we wanted the design to be able to be used extensively with no issue about the system turning off. Each design has the ability to run off an outlet, meaning that a battery life is not an issue. Since all of the systems have the ability to run indefinitely there was not a large concern when it came to reliability for this category and more focused on the accuracy of the design.

Cost

The cost of the device plays a very important role in the design process. One of the main reasons for this design is so that we can create an affordable version of stereotactic navigation using less expensive hardware but still keeping it as accurate as possible. With cost playing such a large part in the final design, it was weighted as 20 in our design matrix to show how imperative it is that the final device be low in cost. The Wii remotes received the highest score for they were the least expensive option of the three. The Bumblebee2 earned the lowest mark because it is completely outside of the current budget and would cause for an increase in funding.

Program Elegance

A large concern with the undertaking of this design was program complexity and elegance. Excluding the Bumblebee2 design, the systems utilizing HD cameras and Wii remotes would each require a significant amount of software design, requiring greater effort determining the most efficient language and coding practice, although there does exist independently produced code for the Wii remotes for tracking. The Bumblebee2 design was excluded from the previous statement due to the fact that the product is pre-programmed to auto calibrate itself and comes included with a programming package. This means that their coding has been tested and backed by the funding of the established Grey Point Industries. For this reason, it received the highest rating in this category.

Size and Portability

Along with the cost and accuracy of the design, it is also of utmost importance that the design be collapsible and light enough to be transported between rooms and environments. The current products are plagued by this flaw, and are limited to being assembled in surgical rooms. A smaller design would provide a larger number of clinicians access to this technology to apply to a greater number of procedures. The Wii design needs an IR lamp which would cause for more setup and make it less portable. The Bumblebee2 camera system while relatively small is still larger than the two HD cameras combined. Due to its flexibility in size and compact design, the HD camera system scored highest in this category.

Ease of Use

While it is extremely important for the device to be accurate and cost effective, it is also important that it be streamlined and easy for a surgeon to use with as little effort as possible. Ease of use carries a weight of 10 on the design matrix. The ease of use category refers to the finished product’s ability to be controlled by the user. The weight of the category comes from the fact that while the device needs to be accurate and low in cost, it must also be simple and easy to use so that any person would be able to operate it. It may not have a weight as large as accuracy or cost, however simple operation is an important aspect in any interface-based system.

Ideally, the finished product will be robust and straightforward enough to eventually develop a tablet version to further simplify operation.

Safety

In this case, ‘safety’ is a more general concern for the well-being of the patient and the surgeon. This factor was ranked relatively low on our matrix due to the systems limited physical contact with the patient in question. The primary concerns of human safety in this project are covered by the reliability of the systems accuracy. This requires considerations as far as the sanitation procedures, production materials, and surgical practices are concerned. The use of hypoallergenic materials is required, and the ability of the practitioner to maintain the device must be considered in designing a device that can accommodate a safe, sanitized environment. The ability of each design to be incorporated with different materials was weighed, and the HD camera system was determined to be the safest due to the system’s ability to be customized to different environments.

Final Budget

Item	Quantity	Cost/Item	Total
Logitech C920 HD Webcam	2	$79.99	$159.90
Grifiti Nootle Clamp	1	$20.00	$20.00
Mounting Unit Materials	1	$17.50	$17.50
			$197.48

Table 4: The final cost of materials totaled less than $200, falling well within the team's budget.

The final cost of project materials came to $197.48. This amount was provided for the team via the UW Hospital, and the details can be found in Table 4. Some of the materials, such as the tracking markers, were purchased by individual team members and donated to the project. At mid-semester, the projected cost was close to $800, but the group was able to reduce this amount after choosing a different webcam and deciding not to purchase computer hardware for the final design. Given an initial budget of $1000, the team managed to develop a working prototype for a cost well within that amount.

Testing

Because accuracy and reliability are so important to the project, a significant amount of testing was required to evaluate the final design. Four separate tests were conducted on the system to measure its range, accuracy, light tolerance, and stability. Future testing, similar to the accuracy testing, would have to be carried out once the X-ray images were incorporated in the system to determine their effectiveness.

Range Test

The range test is a simple test to determine at what maximum and minimum distance that the device can operate. The setup of this test is shown in Figure 16. To perform this test, a tape measure was placed beginning at the cameras and extending outward. The tracker was then moved in increments of 0.15 m, or 0.5 ft. to determine at what ranges the tracker could be tracked reliably by both cameras. The minimum distance was determined to be 0.31 m (1 ft.) while the maximum was determined to be 2.438 m (8 ft.).

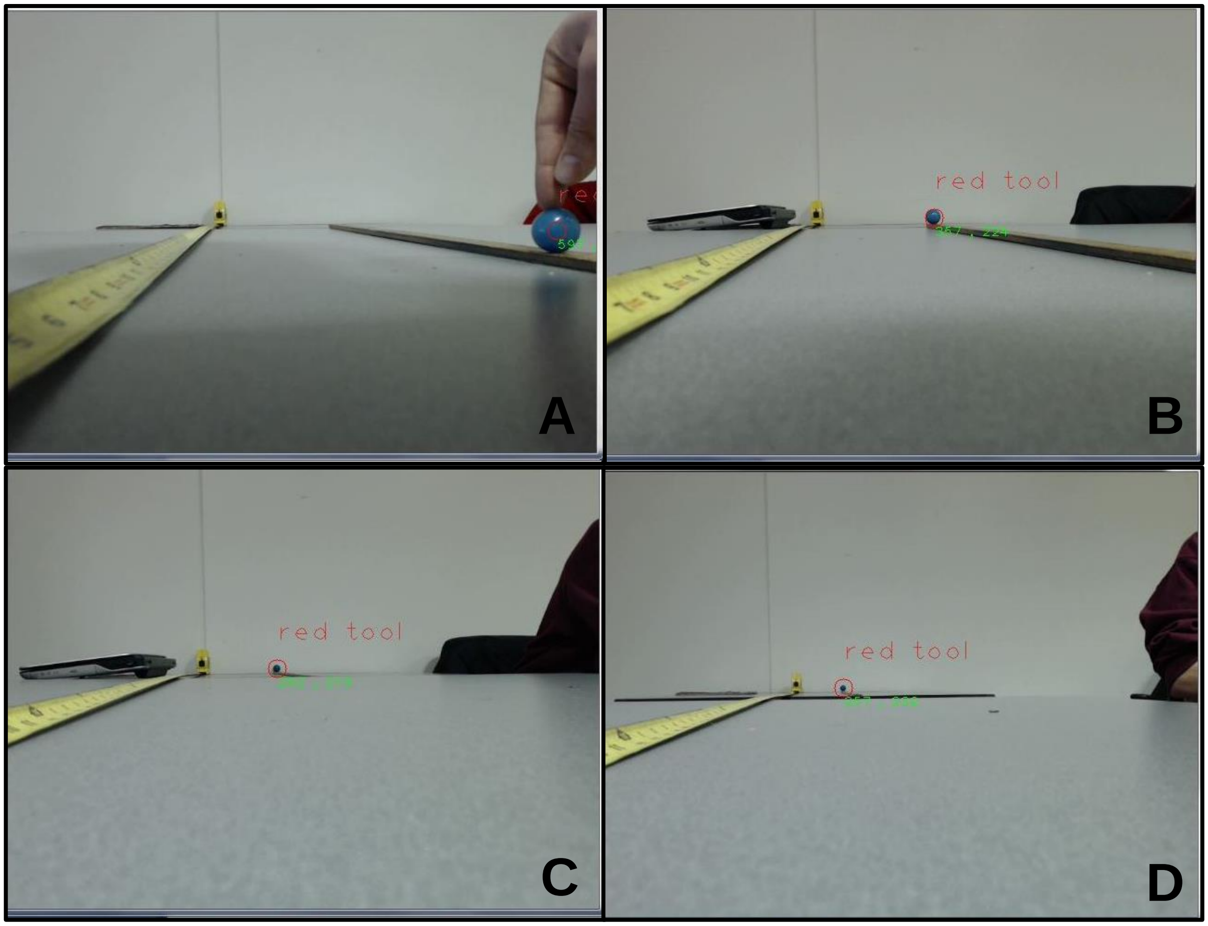
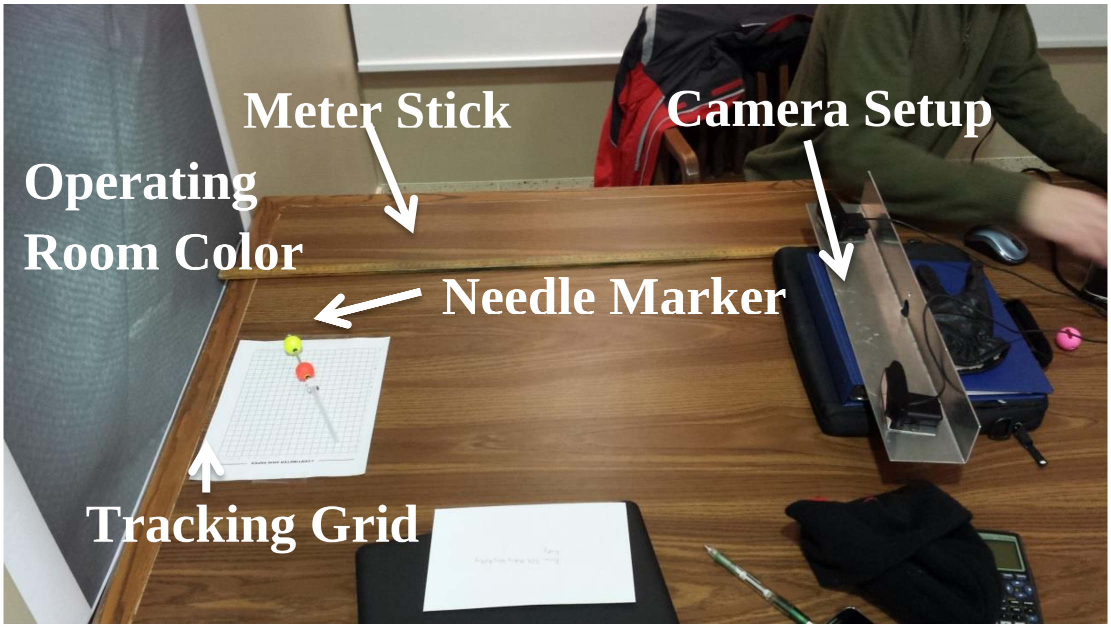


Figure 16: Images of range testing at A: 0.30 m (1 ft), B: 0.91 m (3 ft), C: 2.29 m (7.5 ft), and D: 2.59 m (8.5 ft).

Accuracy Test

To determine the accuracy of the device, an 18 cm by 18 cm grid of 1 cm squares was placed at a known distance from the cameras. The needle tip was then placed at different locations on the grid and the output of the program was acquired. Because the actual x, y and z coordinates (with the origin centered at the left camera) were known, we were able to calculate how close the measured location was to the actual location. Figure 17 depicts this setup. This test was performed in the x-z plane, as well as the x-y plane. At 64.5 cm away from the device the average distance from the calculated point to the actual point was 1.50 cm. At a distance of 82.5 cm the average distance from the calculated point to the actual point was 3.97 cm.



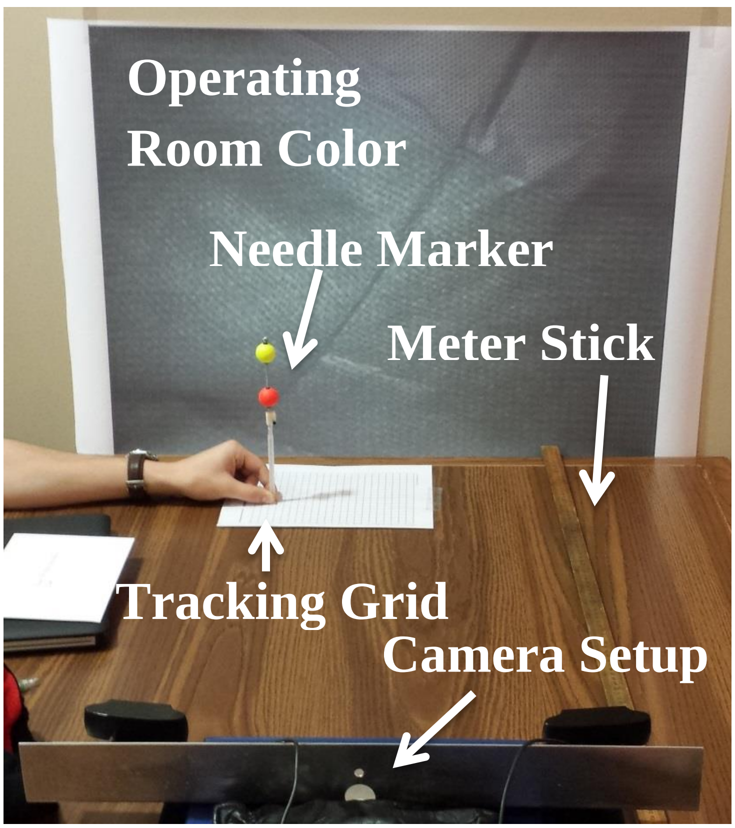


Figure 17: Accuracy test setup detail. The camera tracks the needle marker on a grid at a set distance. The measured position is then compared to the actual position in order to determine accuracy. To simulate real conditions, a background of colors conventionally found in an operating room was used to contrast the marker.

Shadow Test

Since the system uses the Hue/Saturation/Value (HSV) system to track markers, shadows can affect its ability to track. Shadow testing was necessary in order to determine the brightness threshold of the device. The shadow test consisted of holding a light obstructing board above the markers at the minimum and maximum tracking distances. The board was then slowly lowered until the device could no longer reliably track the marker. A picture was taken of the marker covered by the shadow and the luminescence of the marker at that point was determined. At a minimum distance of 0.31 m the marker was able to reliably track at 15 lumens, and at a maximum distance 2.44 m the marker was able to reliably track at 36 lumens. As a reference an image of a bright blue sky is set at about 116 lumens. The test is shown in Figure 18.

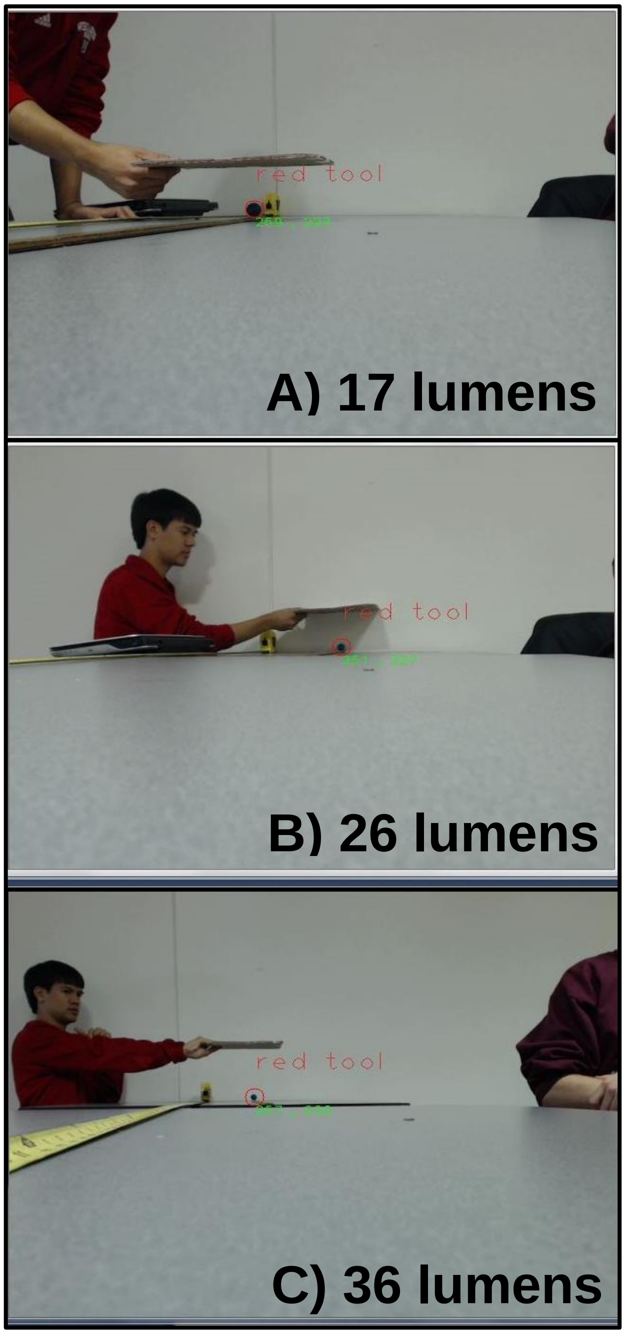


Figure 18: A series of images taken from shadow testing at A) 0.91 m (3 ft), B) 2.13 m (7 ft) and at C) 2.59 m (8.5 ft). The object is tracked at increasing intervals. As the distance from the camera increases, the lumen threshold decreases

Stability Test

The stability test was conducted by creating a free body diagram of the stand and device to determine at what point the stand would tip due to the weight of the device. In order for Drive Medical's 4-legged Economy IV pole with leg length of 0.21 meters (the least stable commercially available IV stand) to tip at the current prototype weight, the Nootle clamp would need to extend the device to 0.74 m away from the IV stand. The device currently sits 0.12 m away from the stand. A free body diagram is shown in Figure 19.

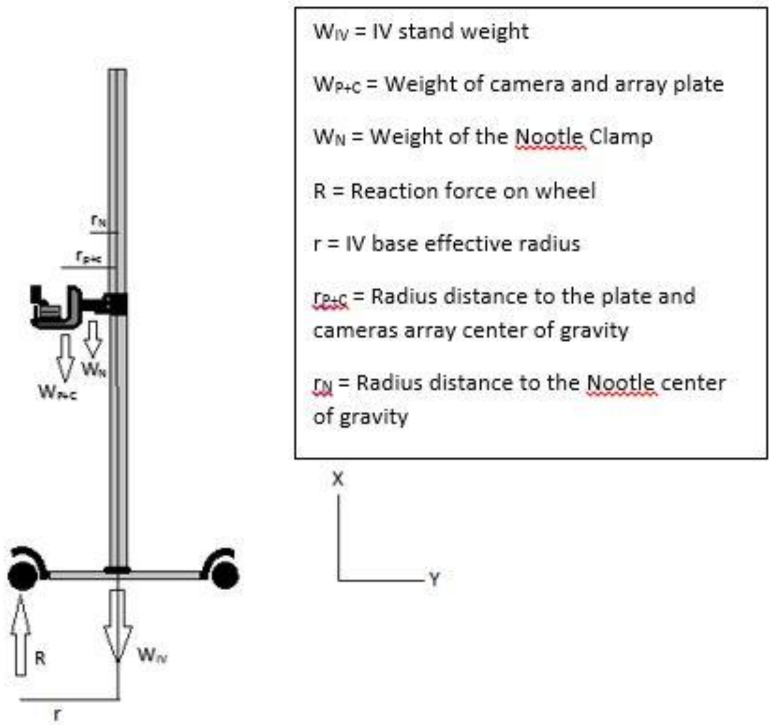


Figure 19: A free body diagram of the IV stand.

Results

Range

The range test concluded that the farthest the device can be from the tool being tracked is 2.438 m, or 8 ft. The design criteria states that the device needs to operate accurately at distances anywhere from one to two meters from the cameras, with our testing revealing the fulfillment of that requirement. The ideal distance from the tool to the device would be between 1.22 m and 1.83 m, or 4 ft. to 6 ft.

Shadow Testing

The shadow test showed that at maximum distance the cameras can still track the markers at about 36 lumens, while a bright image of a blue sky registers at 116 lumens. This means that the device should reliably work even if someone is casting a shadow on it. Ideally the device will still only be used in brightly lit rooms such as operating rooms, however the test shows that shadows cast by the user or others in the room should have a negligible effect on the reliability.

Stability Testing

From the stability testing, it can be concluded that the device has no risk for tipping over the IV stand. The moment arm needed to tip the IV is 0.74 m, while the current center of gravity resides at 0.12 m. This results in a safety factor of 5.94 for tipping. Therefore, the device can be safely attached to IV stands.

Accuracy Testing

The accuracy tests reveal much about the current capabilities of system. The x-axis is the most accurate only having a standard deviation of 0.23 cm. The-y axis is the next most accurate with 0.32 cm. Finally, the z-axis has the greatest deviation of 0.34 cm. One trend measured is that as depth (the z-axis) value increases, the rate of accuracy decreases. At a distance of 64.5cm, the measured coordinate points were off an average of 1.72%. At 82.5 cm, the percentage off increased to 4.08%. This results in a 266% decrease in accuracy over a distance of 18 cm. These findings show that consistency, as well as overall accuracy must be improved in order to make it a viable system.

Additionally, the x and z plane testing indicated that the camera was slightly shifted and unaligned with the coordinate grid. This is evidenced by the parallelogram shape of the camera view, instead of the actual rectangle (Figures 20 and 21). In order to compensate for angle shifting effects, a reference arc should be eventually be incorporated. This will increase the accuracy of the system by adjusting for camera orientation.

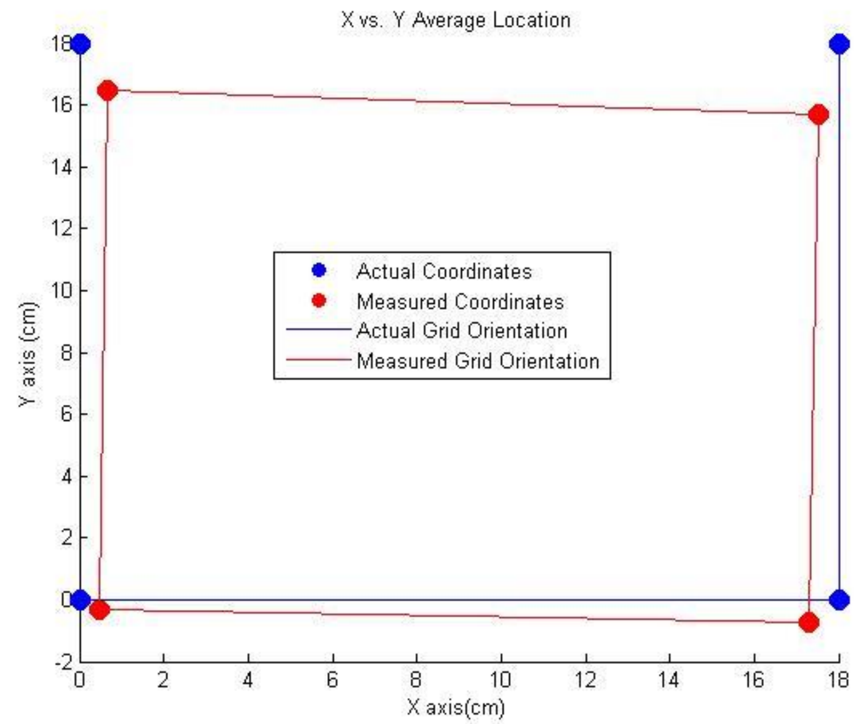


Figure 20: A graph of the actual and measured coordinates in the X and Y plane. The red parallelogram is representative of the camera angle shift.

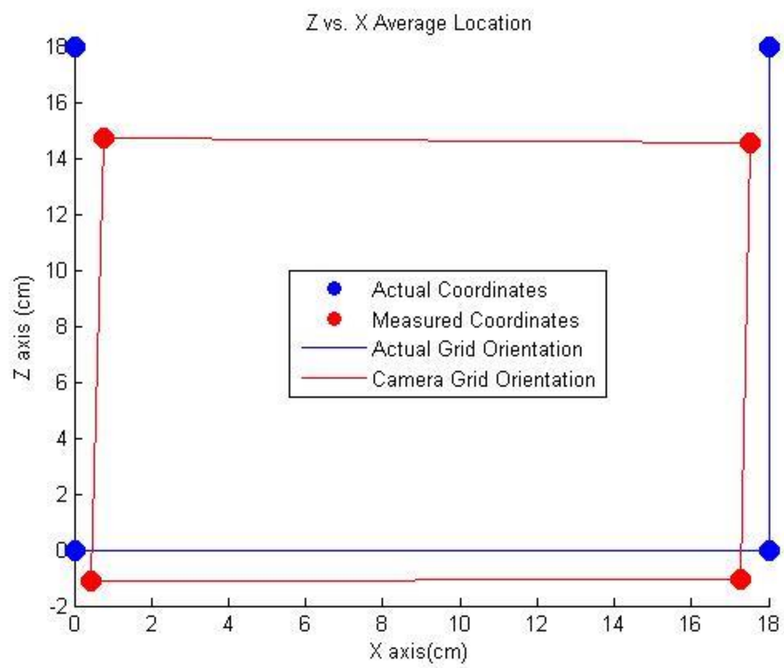


Figure 21: A graph of the actual and measured coordinates in the X and Z plane. The red parallelogram is representative of the camera angle shift.

Overall, precision of the system is fairly consistent, as each axis had a moderate standard deviation. However, the accuracy does not meet the requirement of 1 mm. The smallest measured accuracy of our system (1.5cm) is an order of magnitude greater than the acceptable threshold. Therefore, the accuracy of the system needs to be greatly improved before the system can be used.

Future Work

Timeline

Table 5 displays the intended dates of completion for major team objectives. The shaded boxes represent the predicted timeframe, with each "X" indicating progress or completion of the task on that date. At this time, the team has succeeded in being on time or ahead of the projected task schedule in all categories.

Tasks	September			October				November					Dec	
	13	20	27	4	11	18	25	1	8	15	22	29	6	13
Product Development														
Research	X	X	X	X	X									
Brainstorming	X	X	X	X	X									
Design Matrix			X	X										
Design Prototype					X	X	X	X	X					
Order Materials					X	X	X		X	X				
Fabricate Prototype								X	X	X	X	X		
Testing												X	X	
Meetings														
Advisor	X	X	X	X	X	X	X		X	X	X	X		
Client	X		X	X		X		X				X		X
Team	X	X	X	X	X	X		X	X	X	X	X	X	X
Deliverables														
Progress Reports	X	X	X	X	X	X	X	X	X	X	X		X	X
PDS	X	X			X									
Mid Semester PPT			X	X										
Mid Semester Report				X	X									
Final Report												X	X	X
Final Poster												X	X	X
Website Updates	X	X	X	X	X	X	X	X	X	X	X		X	X

Table 5: Displays the projected timeline for the group. Shaded boxes represent the intended timeframe for a task, and a check indicates that the task was worked on or completed.

Software Development and Physical Setup

Moving forward from this point will consist of a few different steps in both the software and hardware. One of the main improvements that needs to be made is in the display. The needle needs to be overlaid on X-ray scans taken before the procedure to allow the user to navigate in relation to an actual patient. This also means that a reference arc needs to be implemented. The reference arc would allow for higher accuracy as well as allow the device to be moved and the automatically calibrate based on the reference arc. Physically, the device also needs to be modified in a few ways. The camera tilt needs to be locked down so that even if bumped they will remain in the same position. It would also be optimal to reduce the size of the trackers so that they do not hinder the operator. The needle clamp also needs to be redesigned so that it can be attached to a wider range of needles. One final change that could be made is to attach a wireless data transmission device to remove the clutter of wires on the final product.

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Appendix

Frameless Stereotactic Navigation
Product Design Specifications
12/11/13

Group Members: Stephen Monette, Alex Yueh, Matthew Boyer, Jake Levin, Alex Nguyen

Function:
Computerized frameless stereotactic navigation is a system that allows for precise determination of location of tools and instruments relative to a patient during medical procedures. The system is commonly used in surgeries, such as brain or spine surgeries, which require a high level of accuracy in tool placement. Such systems are highly costly and are therefore less available for smaller, less invasive procedures, including interventional radiology and pain procedures. The goal of this project is to develop a stereotactic navigation device using inexpensive and readily-available components, such as HD cameras, which maintains a level of accuracy necessary for use in radiology and pain procedures.

Client requirements:

- Design must be accurate up to three to five millimeters
- Constructed using off the shelf software and hardware (i.e. Kinect, Wii motion software)
- Conformable with pre-existing x-ray prints taken of the patient to track tooling
- Final design should be lighter than 18 kg (39.6 lbs)
- Budget: $1000

Design requirements:

1. Physical and Operational Characteristics

a. *Performance requirements*: Device must be able to locate the surgeon's tools within three to five millimeters accuracy on the patient readouts. The stereotactic navigation system must also have a high refresh rate with a minimum of 20 FPS for data acquisition.

b. *Safety*: The end design must comply with medical standards in both sanitation and reliance. It must be able to handle sanitation cycles and be free of unnecessary faces, which facilitate bacterial growth. Any location identifying stickers/markers placed on the patients or tools must also be safe and free of any possible products that may affect the patient (I.E. latex-free, hypoallergenic materials). Stickers/markers must also comply with the data acquisition protocols used in the stereotactic system, i.e. discernible, high contrast colors. Errors in precision may not exceed three to five millimeters.

c. *Accuracy and Reliability*: The device must have an accuracy minimum of 3-5 mm, and it must maintain this level of accuracy while the system is anywhere between 1-1.5 m from the patient.

d. *Life in Service*: The life of the product should be 5 years, operating 5 times per week at most for 12 hours at a time.

e. *Shelf Life*: While in storage the device should be kept at normal room temperatures, the device will use power from the computer display.

f. *Operating Environment*: The device could come into contact with small amounts of water or other liquids found in operating rooms, such as blood. It should work at any climate and conditions acceptable for an operating room.

g. *Ergonomics*: The system should not interfere with the surgical process. The locators on the patient should provide minimal discomfort to the patient.

h. *Size*: The device should be able to accommodate maintaining a three dimensional visual field the size of 0.028 m^3 around the surgical site. The system will be designed in order to rest at the foot of the one meter high surgical table. The system will consist of a stand and a mount for the cameras. The entire system should be able to collapse down to a carrying case or rolling stand that occupies no more than 0.042 m^3, as specified by the client.

i. *Weight*: The system should be easily transportable between operating rooms with/without the use of a wheeled cart. The total collapsed system should weigh no more than 18 kg.

j. *Materials*: The portion of the device coming into contact with the patient should be easily cleaned or disposable and should not cause harm to the patient.

k. *Aesthetics, Appearance, and Finish*: Because it will be used in the clinical setting, the product must be easy to use, and the display must be easy to read. The system should not be distracting to the patient or surgeon. Focus should be kept on the utility of the design rather than the aesthetics.

2. Production Characteristics

a. *Quantity*: We are designing one system to be used on multiple subjects.

b. *Target Product Cost*: The target product cost is $750.

3. Miscellaneous

a. *Standards and Specifications*: If marketed, the product will require approval from the FDA.

b. *Customer*: The system should be able to track all movements and recognize the instruments being used while taking up minimal room and not interfering with the surgical procedures. The project should be easy to use and inexpensive.

c. *Patient-related concerns*: The information from the fluoroscopic x-rays should be accessed in the system and protected during the procedure, but afterwards discarded. All equipment must be able to be sterilized.

d. Competition: *Brainlab* and *Stealth* are some current models of this technology, but they are too expensive for smaller interventional radiology and pain procedures. Students at the University of Washington have developed a program for the Kinect, which maps the body so that when surgeons use robotic tools they can receive tactile feedback to aid them in navigation.