Group 9: Ultrasound Needle Detection Using Mobile Imaging

Technical Summary

Background:

Tool tracking is very useful for helping surgeons locate tools intraoperatively. The tracking of tools becomes even more useful when they are inside the patient's body, where the surgeon cannot see the exact location of the tool with their naked eye. In situations where surgeons need to use needles to access parts inside the body close to sensitive parts, locating tools become a necessity in order to prevent accidental punctures to sensitive organs. Current methods for intraoperative tracking of surgical tools include electromagnetic tracking-based and ultrasound-image based ones. Current methods for using electromagnetic tracking-based approaches require integration of extra hardware in the surgical suite. The have proved to be not especially accurate. Methods of intraoperative tracking using ultrasound imaging technology offers more accuracy, but require the entire needle to be within the plane of the ultrasound image. Keeping the needle in the plane of the ultrasound image is tedious and cumbersome for the surgeon. Without extra hardware, this task also becomes very difficult and time consuming.

Problem:

The use of ultrasound is common practice for intraoperative tracking of needles in the patient's body. With conventional b-mode ultrasound, the needle needs to be in the plane of the ultrasound image because the ultrasound 2-D ultrasound image does not distinguish the needle shaft from the tip when out of plane. Some groups have tried to solve the out of plane case problems of ultrasound imaging based intraoperative needle tracking by combining the approach with electromagnetic tracking based methods. These approaches, however, add to the cost since the extra equipment for electromagnetic tracking based hardware would also need to be purchased. Other groups have attempted resolve the same issue with 3-D ultrasound imaging hardware or stereo vision and projection. These approaches require extra hardware which also add to the total cost. We set out to implement a low cost solution using ultrasound and a mounted smartphone with camera to track a needle intraoperatively.

Approach:

In order to allow for tracking of the needle tip even when out of the ultrasound (US) image plane, the solution uses needle with an active piezoelectro (PZT) element attached at the tip. The ultrasound transducer is switched to listen only mode. It listens to the synchronized pulses from the PZT element. The data that the ultrasound transducer collects are the transducer element that is closest to the PZT element and the distance from the PZT element to the closest transducer element. This data gives a subset of locations where the PZT element may be. This subset of locations forms a semicircular arc that intersects with the ultrasound image plane perpendicularly. In order to find the location of the PZT element within this subset, a conventional image from a smartphone camera attached to the ultrasound transducer is acquired. This smartphone image captures the external portion of the needle. From this image, the plane that the needle lies on can be determined in the camera coordinates. The arc in ultrasound coordinates and the plane in camera coordinates must then be transformed into the same coordinate system using a pre-computed ultrasound calibration. After the arc and the plane are brought into the same coordinate system, their intersection is then determined. A single intersection point can be extracted, thus determining the position of the PZT element, which is also the needle tip.

Workflow:

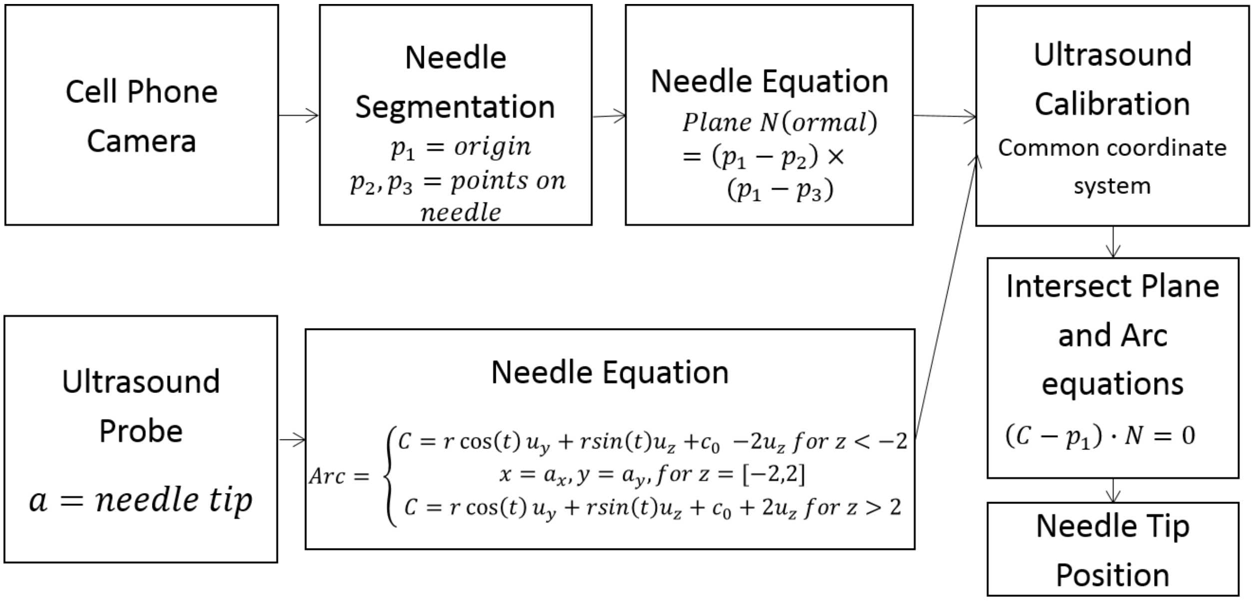

Figure 1: The workflow diagram of the method detailing the equations obtained or used in each part.

As stated above, the two information needed are the arc and the plane whose intersection is the needle tip position. In order to obtain the plane, an image is captured using the smartphone attached to the ultrasound probe. The needle is then segmented from the image, which will be described in further detail below, to obtain two pixels along the needle. In order to bring these pixels into needle coordinates, a camera calibration is performed, and these pixels are transformed into the camera coordinate system. Although the depth information is not available, these points will still be along the plane desired by our method. Finally, using these two points from the needle, as well as the origin of the camera coordinates, we can obtain an equation for the plane the needle lies on.

In order to obtain the arc, we find the position “a” of the PZT element detected by the ultrasound. We can use the information of this point to model the arc as a piece-wise function: two semicircles with a linear portion in between connecting them. The linear portion accounts for the elevational depth of the ultrasound probe, while the semicircle represents the subset of locations the needle tip may actually be.

The final step is to intersect these two equations. However, because they are in different coordinate systems, an ultrasound calibration is performed, and the plane equation is transformed into the ultrasound coordinate space. Then the plane and arc equations are intersected to obtain the needle tip position.

Camera Image segmentation Function:
The camera captures an image of the external portion of the needle. The needle is filtered out for the background in the image to give a grey-scale intensity image. The image is then converted to a binary black and white image. The edge detector built into Matlab is used to extract the edges from the image using the Prewitt method. The resulting edge image is then put through the standard Hough Transform and the peaks in the Hough Transform found. The peaks in the Hough Transform gives the lines found. There are more lines than the two edges of the needle shaft. Some lines are from reflection off the needle shaft. Short lines are filtered out as noise. The longest line detected is assumed to be on one of

the edges of the needle. In order to determine the other edge, all the lines are averaged (slope, intersects with one boundary of the image). Using this information, the other edge is found by searching through the lines to find a line that has an intersection with the boundary of the image that is greater than longest line's intersect plus its distance from the average intersect or less than longest line's intersect minus its distance from the average intersect. Once the second edge is determined, the two are averaged to give the line that should be at the center of the needle. This line segment's endpoints are then output.

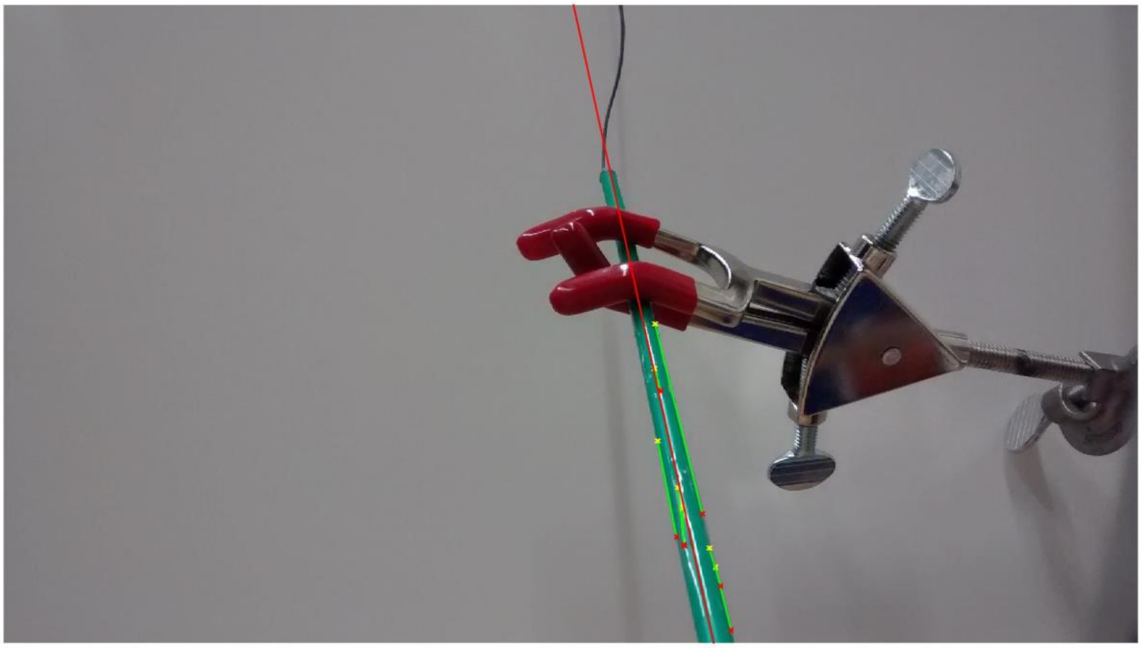

Figure 2: Sample result of planeSegmentation.m function (above). The red line is the line segment determined to be the center of the needle. The green line segments are the detected edges after filtering out edges shorter than 50 pixels.

Mathematical Approach:

Ultrasound coordinate system convention:

The lateral direction (along the probe) is the x-axis, the axial direction (depth of the US plane) is the y-axis, and the elevational direction is the z-axis (where z = 0 is the US plane).

Plane Equation

A plane can be described as a point on the plane and a vector normal to the plane. From the three points we have obtained from the needle segmentation and camera calibration we can compute the normal to the plane:

$$N(ormal) = (p_1 - p_2) \times (p_1 - p_3)$$

Where

$$p_1 = origin$$

$$p_2,\, p_3 = points\ on\ the\ needle$$

Arc Equation

The arc is modeled as a piecewise function with 3 components: 2 semicircles and 1 linear portion in between. The semicircular portions are two halves of a circle which lies perpendicular to the ultrasound plane,

$$C = r\cos(t)\,u_y + r sin(t) u_z + c_0$$

Where

$$a = PZT\ element\ location\ detected\ by\ ultrasound$$

$$c_0 = center\ of\ the\ circle\ given\ by\ [a_x, 0, 0]$$

$$r = radius\ of\ the\ circle\ given\ by\ |a_y|$$

$$u_y, u_z = unit\ vectors\ in\ y\ and\ z\ directions$$

Because the ultrasound probe has some elevational depth, there is a linear portion in between the two semicircles. This equation is simply a line segment with x and y values that of "a", and z value from -2 to 2 (because the ultrasound probe elevation is 4mm). The final equation is therefore:

$$Arc = \begin{cases} C = r\cos(t)\,u_y + r sin(t) u_z + c_0\ - 2u_z\ for\ z < -2 \\ x = a_x,\ y = a_y,\ for\ z = [-2,2] \\ C = r\cos(t)\,u_y + r sin(t) u_z + c_0 + 2u_z\ for\ z > 2 \end{cases}$$

Intersection

Finally, the intersection of the two equations is found. This is done by solving the following condition:

$$(C - p_1) \cdot N = 0$$

$$\left(r\cos(t)\,u_y + r sin(t) u_z + c_0 - p_1\right) \cdot N = 0$$

And then substituting the value of t back into the equation of the arc:

$$C = r\cos(t)\,u_y + r sin(t) u_z + c_0$$

The condition

$$(C - p_1)$$

Represents all lines that intersect both the plane and the circle. However, while the point is guaranteed to be on the circle, it isn't necessary in the same plane as the plane equation. In order to make sure this is the case, the line above must also be coplanar to the plane equation, i.e. the dot product of the plane normal and the line must be zero. Solving this equation results in two values for t, and therefore 2 values for the intersection. However we can reject the point that lies outside of the body, i.e. y < 0, which results in the single point of intersection, the position of the needle tip.

The equation is solved analytically using Matlab.

Experimental set up:
For the experiment, an active PZT element was attached at the end of a simulated needle that was composed of multiple straws taped together. The simulated needle was held by a three-pronged holder that was attached to a solid stage with ability to precisely control 3 axis of movement. The ultrasound transducer was set up to listen for the synchronized output of the PZT element. Another three-pronged holder that was attached to another solid stage also with ability to precisely control three axis of movement held the ultrasound transducer. The phantom used for the experiment was a container of tap water. The smartphone was attached to the ultrasound transducer with two pieces of Lego blocks in a way to point the camera at the external portion of the needle.
During the experiment, the ultrasound transducer was moved at measured intervals of (4mm) along the 3 orthogonal directions to collect the data for various in and out of plane ultrasound data. The needle was then moved and the ultrasound transducer movements repeated for difference poses of the needle.

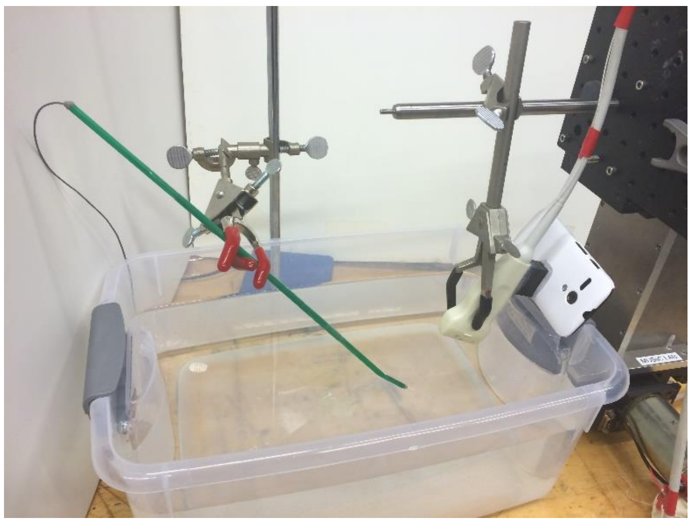

Figure 3: Picture of the setup with the "needle" on the left and the ultrasound probe and camera on the right.

Results:
Accuracy was determined from the how far computed points were out of plane compared to points that were experimentally placed in plane. 2 different poses of the needle were taken.

Accuracy	RMSE
Pose 1	0.6333 mm
Pose 2	0.1752 mm

Precision was determined by comparing the relative distance between two calculated points compared to the known distance of each step of movement (4mm). A total of 50 data points were used.

Precision	
RMSE	0.8608 mm
Std Dev.	0.8600 mm

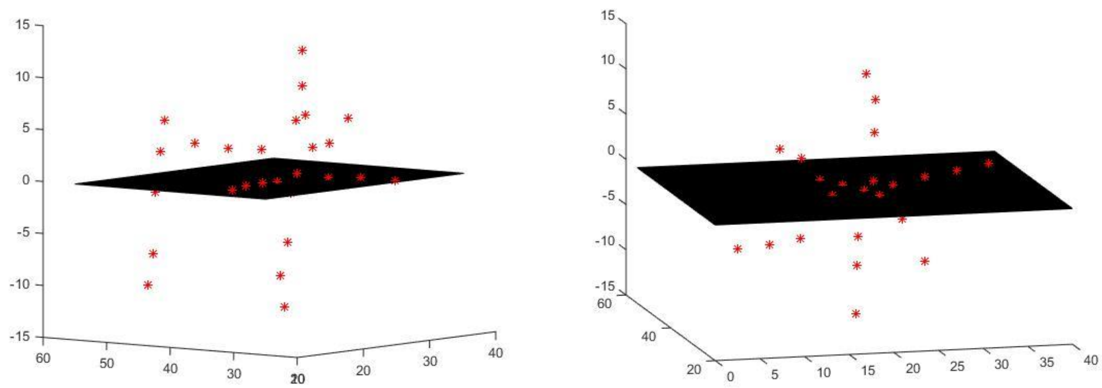

Figure 4: Positions of the needle tip on various movement of the ultrasound probe. The red dots represent the calculated needle tip position, and the black plane represents the ultrasound plane.

Sources of error:

Some sources of error may stem from our ground truth of the ultrasound in plane images being set by visual perception. We may not have chosen the absolute in plane image of the tool tip. In addition, there is probably slight flexing of our needle, as it is a hollow construct of straws. The weight added by the putty for adhering the active PZT element may have weighted down the straw. The segmentation of the needle may also create some error. This is because the edges are not perfectly defined. Since the resulting plane is from the average of the two edges chosen, the plane may not be perfect. A thicker needle may cause larger error. Since the camera does not have infinite number of pixels, the slope of the plane will also not be perfect. This will also introduce error. This means higher resolution images will give more actual results and less error. There is also some error from the camera and ultrasound calibration which was a pixel error of [.59 .23] for the camera and ~2mm for the ultrasound. Finally, the movement of each step was not perfect. This is because there is no way of perfectly turning a nob 2 turns for a perfect 4mm translation. This error may be up to 0.083mm error if assuming up to 15 degree offset.

Significance:
We have shown that this method is able to localize a needle tip both in-plane and out-of-plane positions to some degree of accuracy. This is advantageous to ultrasound only guidance methods which can only detect in-plane points, and also advantageous to electromagnetic tracking methods as it only requires any mobile device with a camera and an active source at the tool-tip to work.

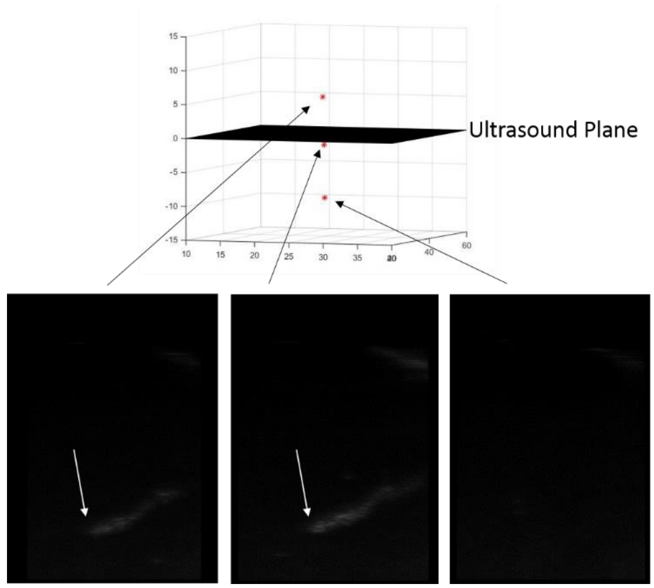

Figure 5: Below are the inverted B-mode image in 3 different positions of the probe. The left and center images are on either side of the ultrasound plane, and the right image shows a position where the ultrasound alone is too far away to see the needle. Above are the positions of the needle in the corresponding B-mode images (indicated by the arrow) calculated by our method.

Notice in Figure 5 that the left and center images are very similar, and there is no way to differentiate which side of the ultrasound probe the needle is on. However, above, we see the corresponding locations of the needle by our method, which clearly differentiate the 3 positions.

Future steps on this work will involve a real-time, mobile app based implementation of this system, as well as testing in more realistic phantoms using a tool more similar to that used in actual surgery.

Management Summary

Phillip implemented the approach in Matlab, ran the camera calibration, and analyzed and visualized the results. Bofeng wrote the needle segmentation function, created the “tool”, and created the animation to help visualize the approach. Both members were present during the ultrasound calibration and the experiment to collect data.

The minimum and expected deliverables were accomplished. These were an offline method of localizing the needle-tip and the analysis and validation of these results, respectively. The method source code is available on Dropbox on a link on the wiki, and the results of the analysis of this method was shown above. However, the maximum deliverable, a real-time implementation of this method was not achieved. We were also unable to test the results in more realistic phantoms.

Future steps on this work will involve a real-time, mobile app based implementation of this system, as well as testing in more realistic phantoms using a tool more similar to that used in actual surgery. As this was only a proof of concept, more testing will be required to see if this method will be viable in a clinical setting. Specific steps on the real-time system will be to integrate reading the ultrasound data points, as well as capturing images from the phone camera automatically into the system.

Lessons learned from a technical aspect were Image segmentation, simplifying solutions to tasks, animation skills, and putting much of what we learned from CIS I into practical implementation, including camera and ultrasound calibration. From a management perspective, the importance of time management, or the troubles of the lack of time management, as well as the importance of being more strict on planning deadlines and meeting deadlines were emphasized from this experience.

Technical appendices

Source code can be found on a Dropbox link on the wiki or the following link.

Animation detailing the approach can be found on the wiki.

Animation of the results rotating in 3D space can be found on the wiki.

Caltech Camera Calibration Toolbox was used: http://www.vision.caltech.edu/bouguetj/calib_doc/

Important Files:

- Arcs.mat – The locations of the PZT element in ultrasound coordinates
- Camera_Calibration.mat – The results and matrices of the camera calibration
- CaptureFigVid – Records a rotating video of a 3D plot – Credits Dr. Alan Jennings
- Error.m – Calculates the RMSE of the results. Must be run after Needle_detection_autosegment.m
- ErrorStdev.m – Calculates the standard deviation of the results. Must be run after Needle_detection_autosegment.m
- Experiment1.jpg – Details the experimental position of points in needle pose 1
- Experiment2.jpg – Details the experimental position of points in needle pose 2
- Needle_detection_autosegment.m – Main driver file which runs through all data points and calculates their position
- planeSegmentation.m – Function which segments the needle.
    - Input: Image Name
    - Output: A 2x2 matrix containing two points on the needle:
        - `[x_pixel1, y_pixel1; x_pixel2, y_pixel2]`
- Ultrasound_Calibration.mat – The ultrasound calibration transformation matrix
- Results – Contains the results from our experiment
    - US_Needle_points_segmented.mat – contains the calculated positions of needle tip
- 02_CIS2_2015 – Contains the experimental raw data, i.e. camera images and ultrasound DAC data.