Computer Integrated Surgery II

Group 6 – RCM Calibration

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Final Report

Abstract

The Revolving Needle Driver (RND) surgical robot at the Johns Hopkins URobotics Laboratory shown in figure 1 has some unquantified error. We seek to fix the isocenter of this robot's Remote Center of Motion (RCM) and improve needle targeting. This will be done by first correcting some mechanical parameters, then optimizing the kinematic model. To observe the robot reliably, we must also develop a procedure for taking better measurements with the Polaris optical tracking system. To quantify the accuracy and precision of the Polaris, we use a Computer Numerically Controlled (CNC) milling machine as a positioning reference.

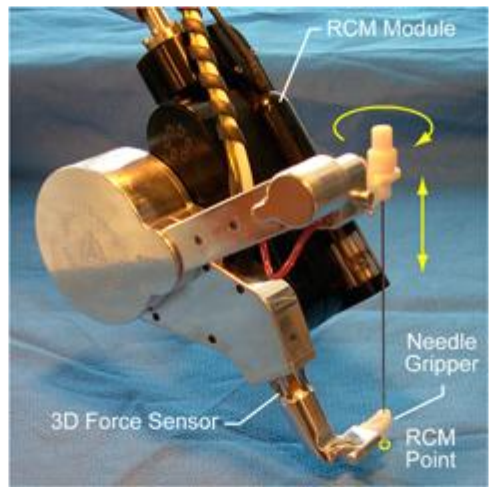

Figure 1 - RND features

Background

The pivoting of a tool about an entry point is common in modern surgical procedures. It is natural that surgical robots also be given the ability to pivot about a remote center of motion (RCM). By placing the RCM at the entry point in the patient, surgeons are able to obtain a very wide range of motion from a very small incision, which minimizes collateral tissue damage, blood loss, recovery time, scarring and infection. Several mechanisms have been proposed to achieve accurate targeting while maintaining a stationary RCM point. Mechanically (daVinci) and virtually constrained (Boctor 2004) RCM modules have had success in laparoscopic surgery, but for more dexterous applications higher targeting accuracy is required.

To develop a more accurate robot, its motion must be well-observed in 3 dimensions. A major component of this project will deal with error quantification of the Polaris optical tracking system. Once an ideal procedure for taking measurements is established, we will proceed with the RCM error quantification and correction. This procedure is very relevant to the medical community, as the use of this type of stereoscopic tracker is widespread.

The use of a CNC machine as a reference for optical tracker calibration has not been explored previously. Combined with a large sample size, we will eliminate more variance in Polaris readings and describe tracker accuracy with more confidence.

By correcting the motion of the RND robot both mechanically and kinematically, insight is gained into interaction between the physical and mathematical models. Systems identification will follow a grey-box procedure (Sjoberg 1995) in which some parameters are known, but others must be estimated. We will use knowledge from mechanical correction of the RCM isocenter and axes to inform the kinematic model optimization and improve targeting.

The goal for this project is to quantify and correct the RND RCM. By tracking the tool tip very accurately, we will be able to determine what level of accuracy to expect using the RCM module, and learn how to build more precise and accurate RCM's in the future.

Problem

The RND robot is not very accurate. Initial tests estimate the norm accuracy error above 3mm average over the robot workspace. Ideally, the RCM point is fixed at the intersection of two perpendicular rotation axes. This is the assumption that the kinematic model uses, taking the Euler angles and needle depth to estimate the needle tip position in a reference frame fixed at the RCM point. This idealized geometry is illustrated in figure 2. The two rotational axes shown are Rx and Rz, rotations about the X and Z axes. In practice, the RCM axes do not intersect nor are they perpendicular to one another. Since any error in the location of the RCM will cause even more errors to propagate along the linkage of the robot, a small displacement in the location of the RCM could lead to a very large displacement in the tip of the attached surgical device.

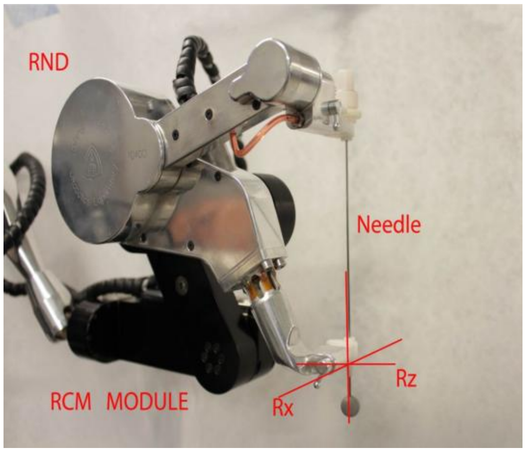

Figure 2 - RND robot showing ideal rotation axes and needle path

The solution to this problem is investigated in 3 parts. First, error quantification is performed on the Polaris tracker and an improved measurement procedure is found. Second, the RND robot is observed and adjusted mechanically to improve the location and alignment of the RCM axes. Third, the kinematic model is optimized to improve needle targeting.

Approach

1. Polaris Tracker Accuracy Quantification

The manufacturer of the Polaris tracker states that the device has an error of 0.3mm, which is assumed to be a maximum norm error. For many applications this is sufficient. For the observation of a robotic end-effector, we would like the most accurate measurements possible to correct and calibrate the robot's motion. We must quantify the accuracy and precision of the Polaris optical tracker and develop protocol for better measurements. This prerequisite to RCM error quantification is more broadly relevant to the medical community due to the proliferation of similar optical tracking systems. In order to determine the capabilities of the tracker, we will use a highly accurate CNC machine to move the markers in a reference frame. The relative accuracy of the CNC is about 2 microns (0.002mm).

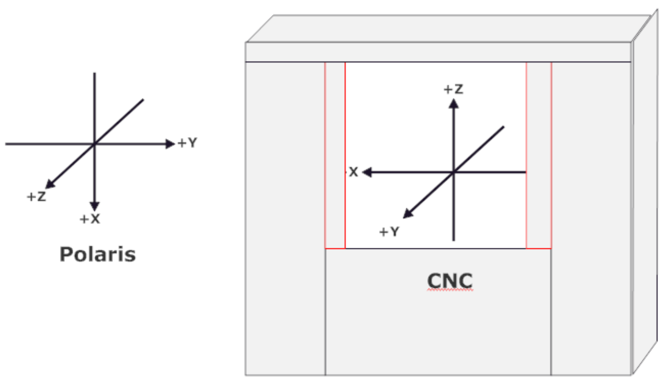

Figure 3 - Coordinate system definitions for Polaris observed and CNC reference coordinates

The Polaris coordinate system is displayed with the CNC machine in figure 3. Three CNC axis translations simulate the movement of a single marker observed by a stationary tracker. Preliminary tests in 1D and 2D were taken with the Polaris mounted on a tripod, and the marker attached to the XY table of the Haas VF-2 CNC machine. For 3D tests, the tracker was mounted in the CNC XY table to observe a marker placed in the spindle as shown in figure 4.

Interaction

For comparison between the two coordinate systems, marker position must be obtained from the Polaris and CNC. Both are connected to a computer through serial RS-232 ports using serial-to-USB converters. When the CNC is moved to a new location, a G102 command

Figure 4 - Polaris 3D test setup

transmits the current CNC coordinates of the marker to the computer. A C++ program is waiting for their arrival, and triggers the Polaris to start taking samples. After recording, the Polaris samples and CNC coordinates are written to separate text files. Then the CNC, which has been paused during this time, may move to a new location.

Data Processing

Data processing is done in MATLAB. After importing the text files, we can obtain the standard definition of sample precision as the diameter of a sphere enclosing all sample points. Sample means are computed to give the Polaris coordinates at each CNC location. With these coordinates, we now have point clouds in both CNC and Polaris space. We perform a point-cloud registration using Arun’s method. This aligns the CNC points to the Polaris coordinate system. The CNC data is used as a gold-standard for evaluating the Polaris. The difference between a CNC reference point and its observed Polaris coordinates is the accuracy of the Polaris tracker at that location. These point accuracies are averaged to provide a global accuracy over the observed volume. Their range is regarded as the global precision.

Experimental Procedure

First we verify the tracker volume geometry. This is idealized as two cameras angled towards each other at approximately 8˚ (measured value) from the horizontal. Their field-of-view (FOV) centerlines meet at a Z distance of -1742mm based on this angle. To get the FOV width, a marker is moved towards the tracker until it can no longer be seen. This limit occurs around Z = -820mm. With these two distances and the assumption that the FOV is symmetrical (pyramid-shaped), we calculate the region in which both cameras are able to see the marker. This volume overlaps the ‘calibrated volume’ stated in the Polaris manual, which is shown in figure 5.

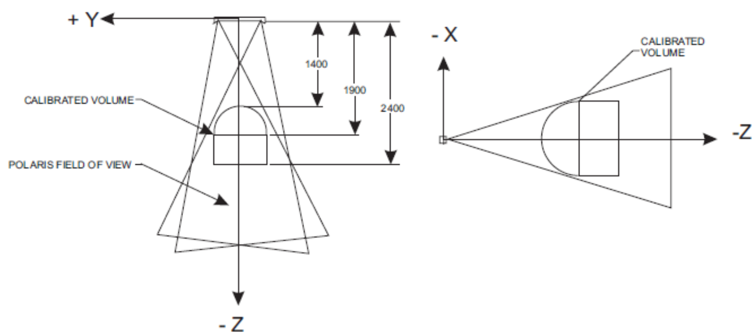

Figure 5 - Tracker geometry as stated in NDI Manual, units in mm.

We want to determine an appropriate number of Polaris sample readings. We take 2000 samples at a single point. The cumulative average will converge upon the best possible Polaris measurement. These subset averages are referenced to the 2000 point average. With this information, we choose 500 samples for the rest of the tests.

Due to the stereo camera arrangement, the dimension most affecting tracker measurement is the Z direction. Therefore these sample size tests are repeated along the

Polaris Z axis. Starting in the ‘sweet spot’, around Z = -1742mm, and moving to the edge of the Polaris field of view, 2000 samples are taken at every 100mm. Suitable convergence occurs near 500 samples; this is the number of readings taken for the rest of the study.

After choosing an appropriate sample size, we want to know where in the tracker volume to read. A pyramid of points is constructed according to the tracker volume geometry previously found. This set of predefined marker points includes 91 locations in a pyramid shape with 6 square point arrays growing away from the tracker, chosen to be as close as possible to the tracker. Performing a point-cloud registration on observed set, we obtain values for global accuracy and global precision against the CNC reference. To show the gains in accuracy for points closer to the tracker, point-cloud registration is performed on the first 15 points and used to calculate the closest point accuracy with corresponding sample precision.

We learn from observing the tracker that the best place in the tracker to read is as close as possible to the tracker source. Measurements should be taken in the Polaris XY plane to eliminate the large errors in the Z-direction. Procedures gained from this section will be applied to obtain better measurements of our robot-of-interest.

2. RCM Error Correction

Using the Polaris tracker, the RCM module will be observed in order to quantify errors in the current state of construction. A single passive marker is placed at the needle tip to watch the motion of the robot end effector. With this marker attached, the robot will be moved to different orientations and needle depths, with the Polaris taking measurements at each location. After performing these readings, we will have to two RCM axis locations relative to the needle tip in tracker space.

RCM Test

The Polaris tracker is attached to a tripod close to the RND robot. The RND is angled at 45˚ with respect to the tracker XY plane. This ensures that the projected area onto the XY plane is the same for both axes. The initial position for all tests is at Rx = -30˚, Rz = 0˚, and Ty = -100mm. This aligns the rotation axes and needle path with the XYZ world frame at the RCM. The first test rotates about the X-axis from -30˚ to 30˚. Then the Z-axis is rotated from 0˚ to 50˚. These angles are the limits of the RND workspace. Polaris takes 500 samples every 5˚. The needle is then moved from -100mm to -40mm, taking samples every 10mm.

Data Analysis

The data is analyzed in MATLAB. Inputs are 3 text files with the Polaris readings for Rx (rotation about X), Rz (rotation about Z), and Ty (needle depth). The arcs obtained from Rx and Rz are each projected onto a plane, and a circle is fit to the points. The vector which passes through the center of this circle and is normal to the plane is the observed RCM axis. An estimation of the needle path is found by a linear fit to the Ty data. The needle path should be aligned with the robot Y-axis when Rx is at -30˚. With the RCM X-axis, Z-axis, and needle path, we can determine several important parameters. First the minimum distance between the 2 rotation axes is computed. We can assume the RCM isocenter is located at the midpoint of this vector. The angle between the axes is also known. The first application of these values will be to correct the RCM mechanically.

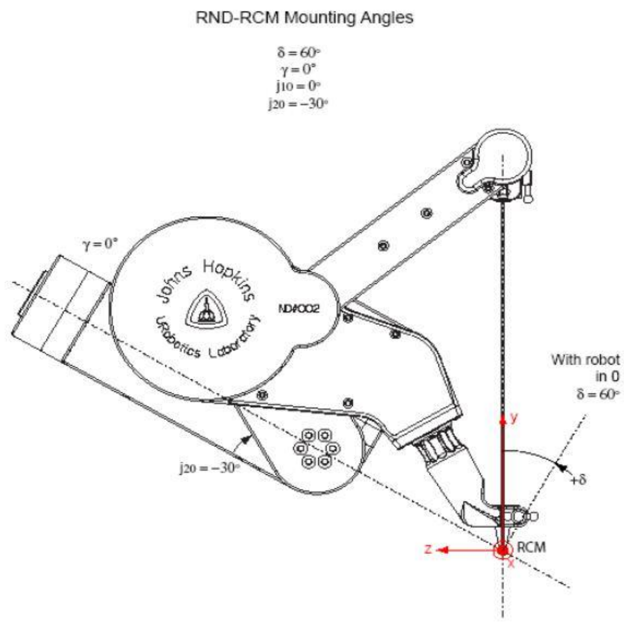

Figure 6 - RCM configuration

Mechanical Adjustment

Several adjustments can be easily made to the RND robot, starting with the zero configuration from the CAD model (figure 6). We are able to adjust the Y offset angle (β) angle, as seen in figure 7. This will also move the needle path in the X direction along an arc, closer to Rz. We are also able to put a shim in the same joint near the base, which will affect the X offset angle (α), as illustrated in figure 8. This will also move Rx in the Y direction along an arc, closer to Rz. The location of these adjustments is seen in figure 8. Lastly, we adjust the RND driver attached at the end of the RCM module, which will rotate in the needle in the YZ plane to be aligned with robot Y.

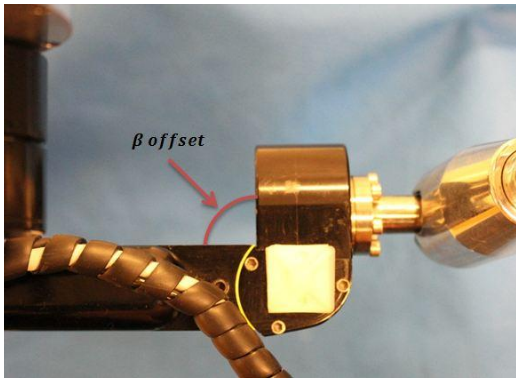

Figure 7 - Adjusting β will help the needle path intersect Rz.

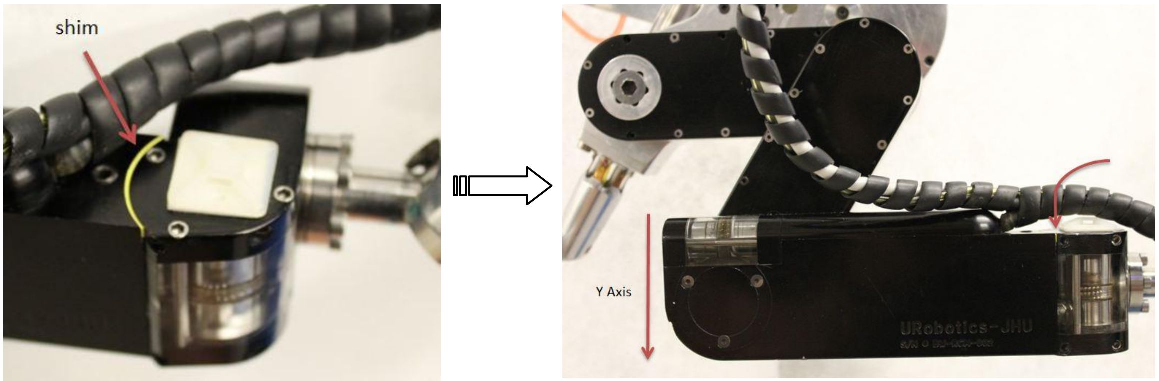

Figure 8 - The shim pushes Rx down to meet Rz.

With these three adjustments we bring the RCM axes closer together and nearly perpendicular. Then the RCM test is repeated and new adjustments must be made. This process is iterated until we converge upon the best possible physical adjustment of the RND robot. From here, further improvements may be made in targeting within the robot workspace by adjusting the kinematic model. The parameters found in this step will be very useful in the optimization of this model.

3. Kinematic Parameter Identification/Optimization Based on Polaris Measurements

Once physical adjustments have been made and the RCM more closely resembles the idealized Euler angle model, improvements in needle targeting can be made by adjusting parameters in the forward kinematics. The parameters which will be adjusted include α and β angles as described above, as well as the needle depth offset.

Targeting Test

To test the targeting ability of the RND robot, a pyramid of points is constructed near the boundaries of its workspace. The angles and depths input to the robot driver program are also input to a MATLAB script which uses 3 rotations (Euler angle formulation) along with 1 translation (needle depth d) to describe the position of the needle tip with respect to the world reference frame, which is fixed at the RCM location. The observed needle tip locations are compared with the idealized model to obtain a measure of targeting accuracy.

Model Generation

The current kinematic model uses 2 rotations and 1 translation to map the needle tip to world coordinates. The transformation is as follows:

$$R_x(\theta_x)=\begin{pmatrix}1 & 0 & 0 & 0\\ 0 & \cos\theta_x & -\sin\theta_x & 0\\ 0 & \sin\theta_x & \cos\theta_x & 0\\ 0 & 0 & 0 & 1\end{pmatrix}$$

$$R_z(-\theta_z)=\begin{pmatrix}\cos-\theta_z & -\sin-\theta_z & 0 & 0\\ \sin-\theta_z & \cos-\theta_z & 0 & 0\\ 0 & 0 & 1 & 0\\ 0 & 0 & 0 & 1\end{pmatrix}$$

$$T_y(d)=\begin{pmatrix}0 & 0 & 0 & 0\\ 0 & 0 & 0 & -d\\ 0 & 0 & 1 & 0\\ 0 & 0 & 0 & 1\end{pmatrix}$$

$$T_{ideal} = R_x(\theta_x)\cdot\ R_z(-\theta_z)\cdot T_y(d)$$

The homogeneous transformation is fed the same rotation angles and needle depths which the RND robot has used in the targeting test. The transformation maps these inputs to XYZ coordinates in the world frame, which originates at the ideal RCM isocenter. This point cloud is aligned with the observed XYZ coordinates from the Polaris optical tracker via point-cloud registration (Arun's method). There is some error between these ideal and observed coordinates. The next step is to add parameters to the model which will improve the fit to observed data.

Parameter Identification

The three parameters previously mentioned, α, β, and needle depth offset, will affect the forward kinematics as illustrated by the combined homogenous transformation written below:

$$R_x(\theta_x-\alpha)=\begin{pmatrix}1 & 0 & 0 & 0\\ 0 & \cos(\theta_x-\alpha) & -\sin(\theta_x-\alpha) & 0\\ 0 & \sin(\theta_x-\alpha) & \cos(\theta_x-\alpha) & 0\\ 0 & 0 & 0 & 1\end{pmatrix}$$

$$R_y(-\beta)=\begin{pmatrix}\cos-\beta & 0 & \sin-\beta & 0\\ 0 & 1 & 0 & 0\\ -\sin-\beta & 0 & \cos-\beta & 0\\ 0 & 0 & 0 & 1\end{pmatrix}$$

$$R_z(-\theta_z)=\begin{pmatrix}\cos-\theta_z & -\sin-\theta_z & 0 & 0\\ \sin-\theta_z & \cos-\theta_z & 0 & 0\\ 0 & 0 & 1 & 0\\ 0 & 0 & 0 & 1\end{pmatrix}$$

$$T_y(d + offset) = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & (-d + offset) \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

$$T_{parameters} = R_x(\theta_x - \alpha) \cdot R_y(-\beta) \cdot\ R_z(-\theta_z) \cdot T_y(d)$$

Additional terms are required for β, the angular offset about Y. α is subtracted from the Rx angle, and the needle depth offset is added to all d values. These parameters were chosen because of their correspondence to prior mechanical adjustments.

Estimates for these values are obtained from the RCM tests. Offset angle α is calculated from the angle between observed Rz and needle path. β is calculated from the angle between Rx and Rz axes. Needle depth is the difference between commanded depth and observed distance from RCM point. Offset angles are small, on the order of a single degree. The needle depth offset is more wildly incorrect, with preliminary estimates at 25mm.

Optimization

These initial offset parameters are fed into a minimization algorithm (built-in MATLAB function fminsearch) which uses the Nelder-Mead simplex (direct search) method to find the parameter values which lower the accuracy error. The accuracy error is the mean of the Euclidean distance between points generated by the kinematic model and the observed Polaris coordinates.

Results

Polaris

It is possible to achieve better measurements with the Polaris optical tracker than previously thought. We will recommend the number of samples and where to observe inside the tracker volume.

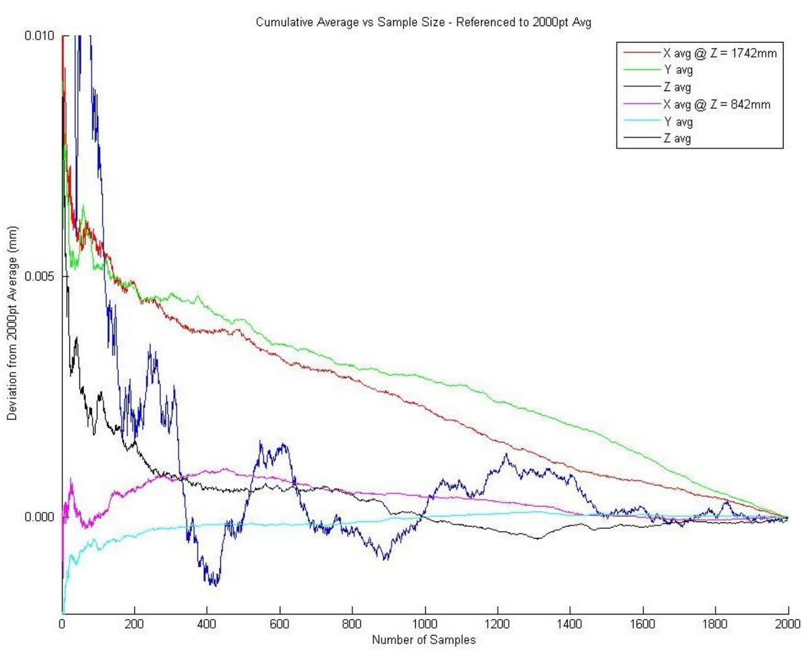

Figure 9 - Effect of sample size on cumulative average

Figure 9 shows the cumulative average of samples acquired successively at the same static location of the marker plotted in the XYZ Polaris directions. As expected, these show that the cumulative average provides a more stable measurement with increasing sample size. For Z-distances closer to the tracker, the cumulative average converges faster for all three Polaris coordinates (XYZ), and is more stable in the Z-direction.

Table 1 (µm)	**X**	**Y**	**Z**	**Norm**
Global Accuracy	15	35	190	195
Global Precision	13	53	404	408
Closest Point Accuracy	24	0	5	55
Closest Point Precision	16	2	75	76

Table 1 shows the global precision and accuracy over this set. The similar factory-stated value of global accuracy norm is 350µm. The table also lists the data for points closest to the scanner. Accuracy and precision improve as the measured volume moves closer to the tracker. The Z-direction continues to dominate the norm error. Another source of error may be vibration of the tracker during sample readings. During initial tests, vibration of the Polaris while mounted on the CNC XY table was a large contributor to error in the vertical direction (Polaris X). While later tests mitigated this vibration, it is still a concern. We followed the NDI-recommended warm-up time of 20 minutes at room temperature. The optical passive marker was likely unaffected by metallic field disturbances, unlike an electromagnetic tracker. Parallax error was also not considered. When using a passive marker, it is advisable to leave ambient light undisturbed. It is helpful to turn lights off.

The method of point-cloud registration will minimize the error between the two sets of coordinates. As a result of this minimization, points in the weighted center of the point cloud typically have lower accuracy errors, while points on the boundaries of the cloud may have higher errors. Combining this error distribution with the non-uniform error distribution inherent in the optical tracking system may compound errors at the extremes of the observed volume.

The precision and accuracy of the Polaris tracker can be improved if measurements are taken statically and averaged. The measurement performance deteriorates in the depth (Z) direction from the scanner. If possible, measurements should be taken closer to the scanner and/or preferentially using the frontal plane (XY). In ideal conditions the Polaris may provide extremely accurate and precise measurements. Optical trackers using similar stereo camera arrangements may also benefit from these protocol suggestions.

RCM Calibration

To correct the RCM mechanically, we observe the initial test results shown in figure 10 and corresponding numerical values, shown in table 2. With some knowledge of link parameters, these values will help bring the RCM axes closer together and ensure that the needle path passes through the RCM point. We adjust the parameters mentioned above and repeat the test. The results show a significant improvement in system-model correspondence for the RND and Euler angle formulation.

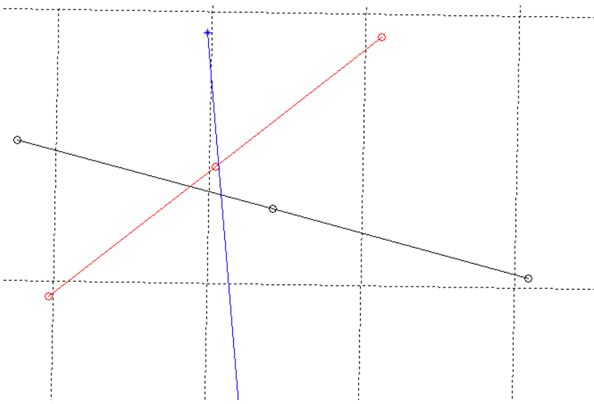

Figure 11 - RCM Axes and needle path visualization

Rx = red, Rz = black, Needle path = blue.

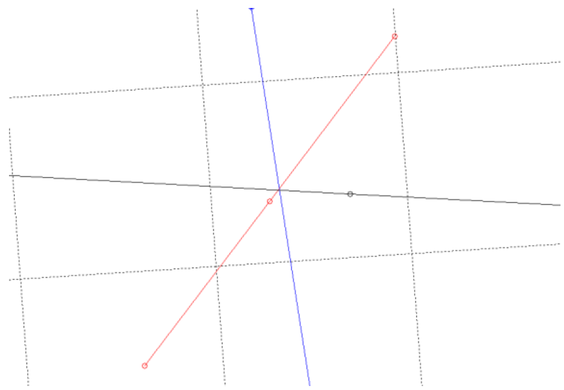

Figure 10 - RCM Axes visualization after correction

Table 2 (mm) Distance Between:	Rx - Rz	Rx – Needle path	Rz – Needle path
Before Correction	3.18	3.16	1.28
After Correction	0.6	0.77	0.43

The axes are now more closely aligned. As seen in figure 11, the minimum distance between all axes is smaller. In the ideal model, they intersect, so there will still be some error as a result of the remaining imperfection. We mitigate some of this error in targeting with the kinematic parameter optimization.

Several factors make it impossible to perfectly align all axes. The needle (like most needles) is not straight, as seen in figure 12. It is difficult to quantify our mechanical adjustments due to the unique geometry of the RCM module. There is some error inherent in the Polaris tracker.

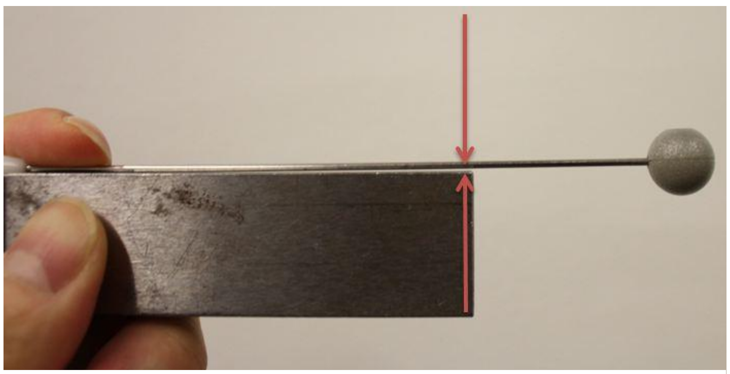

Figure 12 - A bent needle will affect the observed needle path.

Kinematic Optimization

The initial parameter values are obtained from the best and most recent RCM calibration. These are used in the generation of expected target locations. Graphs showing the expected and observed target locations are shown in figure 13. After optimization, new parameter values are used and accuracy improves. Comparing the error vectors before and after optimization will show a small gain in accuracy, mainly due to the needle depth offset. This gain is quantified in table 3.

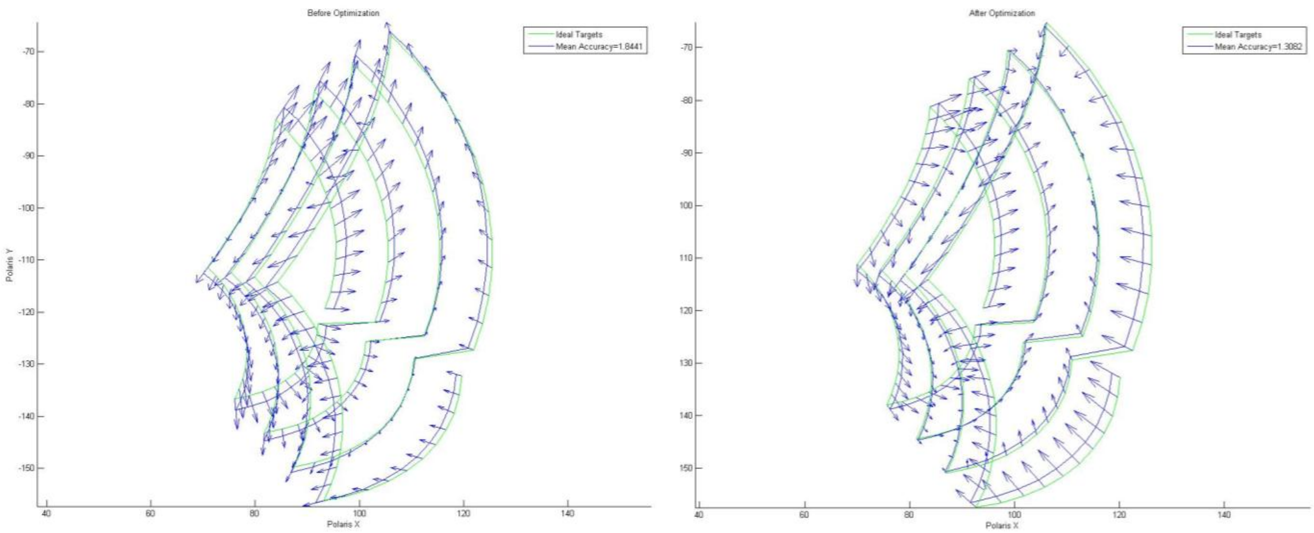

Figure 13 - Visualization of targeting errors before and after parameter optimization

Table 3	α (deg)	B (deg)	Needle Offset (mm)	Targeting Accuracy (mm)
Before Optimization	0	0	25	1.84
After Optimization	-0.06	0.12	22.34	1.3

A model with more parameters and more basis functions which accurately reflect the smaller components of the RND robot may provide better targeting accuracy. The construction of the RCM module is beyond our modeling knowledge currently, but could be investigated in the future.

Significance

The Polaris data is the most significant portion of this project. The use of stereoscopic cameras is prolific across the medical industry. When a system exhibits complex motion, there are few measurement methods which can match the optical tracker in terms of ease-of-use. As long as there is a line of sight to the required number of markers, the tracker will report values which are accurate enough for many applications. The optical tracker could be utilized for development and calibration of robotic systems requiring accuracy on the order of 10μm. By using an extremely accurate reference and taking many more samples than previous studies, we have lowered the limit for expected precision and accuracy.

The RCM is a common concept in medical robotics, so its mechanical and kinematic improvement is useful to others in the field. This specific RCM module is used frequently in the URobotics laboratory, so future calibration of robots using this module will be easier. It is also a good starting point for a more in-depth kinematic analysis of the RCM module which could provide greater gains in accuracy by modeling more link parameters.

Management Summary

Deliverables - Planned

- Minimum
  - Write a technical report on the accuracy and precision of the Polaris tracker
- Expected
  - Include in the technical report a comparison of multiple types of optical trackers
  - Quantify the RCM error of the RND robot
  - Mechanical dissection and analysis
- Maximum
  - RCM fixed based upon mechanical construction corrections
  - Simplified systems identification (one or two parameters)
  - Develop a new, more accurate kinematic model for the robot

We have accomplished all our deliverables except for one. We did not look at different types of optical trackers. Initially there was a possibility of borrowing a different tracker from the LCSR at JHU, but due to limited availability this was abandoned. There was also not enough time to develop separate control programs for the capture of data from other tracker manufacturers. The data obtained for the Polaris optical tracker was sufficient to generalize optimal procedures for stereoscopic optical trackers. The mechanical dissection was necessary to replace a pin inside the RND driver. During this dissection we learned much about how the robot operates. The more accurate kinematic model is a result of the identification and optimization of the parameters previously discussed.

Project timeline – actual

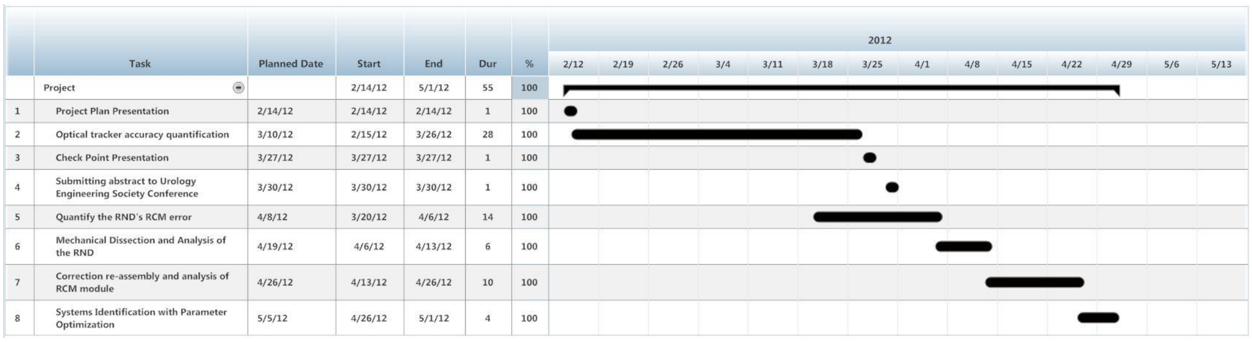

Figure 14. Gantt chart showing actual project progress.

Assigned Responsibilities

- Alex
    - RCM/RND error analysis
    - RND robot dissection, correction and reconstruction
    - Kinematic Optimization
    - Documentation and Web maintenance
- Changhan
    - CNC control and programming
    - RCM/RND error analysis
    - Mechanical RCM Correction
    - Kinematic Modeling and Optimization
- Ryan
    - Optical tracker error analysis
    - Serial port communications for optical tracker and CNC
    - Mechanical RCM Correction
    - Targeting test + Kinematic Optimization

Lessons Learned

We have learned much about the operation of the Polaris tracker, specifically a procedure for obtaining better measurements. We learned basic CNC commands and safety protocol. Now we know more about the inner workings of the RCM module which is common in robots at the URobotics laboratory.

Future Work

More tests are needed to confirm the gains in accuracy and precision which result from our improved protocol, as this level of accuracy has not been attained previously. The use of more types of trackers would verify the results for other stereoscopic models.

The kinematic optimization improved targeting results; however, the model is a simplification of the actual situation. A more detailed model which incorporates more of the actual link parameters in the robot could not only have more physical insight into the origins of error in the system, but also help to correct it by adjusting new parameters. The scope of this project allowed a limited kinematic adjustment, but future models could be developed alongside the design of new RCM modules.

Technical Appendix:

At the time of this writing, all our code and data is available through the following link:

https://www.dropbox.com/s/sfve3dj5v9gcfkt/DATA_Copy.zip

This contains the following items by folder name:

"G-Code" – The G-Code used to control the CNC machines during the Polaris error quantification.

"Initial Tests" – The first tests for evaluating Polaris accuracy and corresponding code and figures used in analysis.

"PROGRAM" – The C++ program used to communicate between CNC and Polaris

"RCM Tests" – The RCM error quantification and targeting tests as well as relevant MATLAB code for analysis and figures.

"Tests XXXX" – Polaris accuracy tests for different geometries, including analysis code and some figures.

References

- Evaluating Remote Center of Motion for Minimally Invasive Surgical Robots by Computer Vision, JT Wilson IEEE/ASME 2010
- Comparing Accuracies of a RFID-based and an Optical Tracking System for Medical Navigation Purposes, M. Broll 2011

- Virtual Remote Center of Motion control for needle-placement robots, M. Boctor 2004
- Comparative tracking error analysis of five different optical tracking systems, Rasool Khadem, 2000
- AcuBot: A Robot for Radiological Interventions, D. Stoianovici IEEE 2003
- Accuracy assessment and interpretation for optical tracking Systems, Andrew D Wiles, Medical Imaging 2004
- Jonas Sjoberg - Nonlinear Black-box modeling in system identification – a unified overview, 1995