Tool Tracking for Periacetabular Osteotomy using CamC

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Project Report

Computer Integrated Surgery II

Dr. Russell Taylor

Spring 2018

Johns Hopkins University, Baltimore, MD

May.11, 2018

Contents

Abstract

Periacetabular osteotomy (PAO) is an orthopedic surgery that reorients the acetabulum of patients suffering from developmental dysplasia of the hip (DDH) in order to provide a better femoral coverage. Tracking is used to keep note of how the fragment is cut and the locations of vessels and arteries that need to be avoided which is difficult otherwise due to the limited visibility. Previous tracking methods involve multiple 2D X-ray images which are harmful to both patients and the surgeon, as well as time-consuming [1]. In this project, a tool tracking pipeline using an RGBD camera is proposed. Point cloud data obtained from the RGBD camera on CAMC is first segmented using mixture of Gaussian background subtraction algorithm, color segmentation and RANSAC to reject outliers. Then the sample consensus prerejective pose estimation algorithm is used to do the initial alignment followed by ICP for final fine alignment. By the end, the variation of the tracked position from the true position did not reach more than 11 mm length-wise and 2 mm width wise.

Introduction

Periacetabular osteotomy (PAO) is a surgery that realigns the misaligned hip. It is used to treat congenital or developmental dysplasia of the hip (DDH). People suffering from DDH typically have reduced femoral head coverage with the hip [2]. PAO surgery can improve femoral coverage and relieve joint pain by realigning the acetabular fragment. However, PAO is suggested to have a steep learning curve. Surgeons need to perform the realignment without introducing further complications. Overcorrection can lead to femoroacetabular impingement and reduced range of motion. Therefore, intraoperative feedback is crucial during the surgery. This leads to multiple X-rays during the surgery which will increase the X-ray exposure and longer operation time [2].

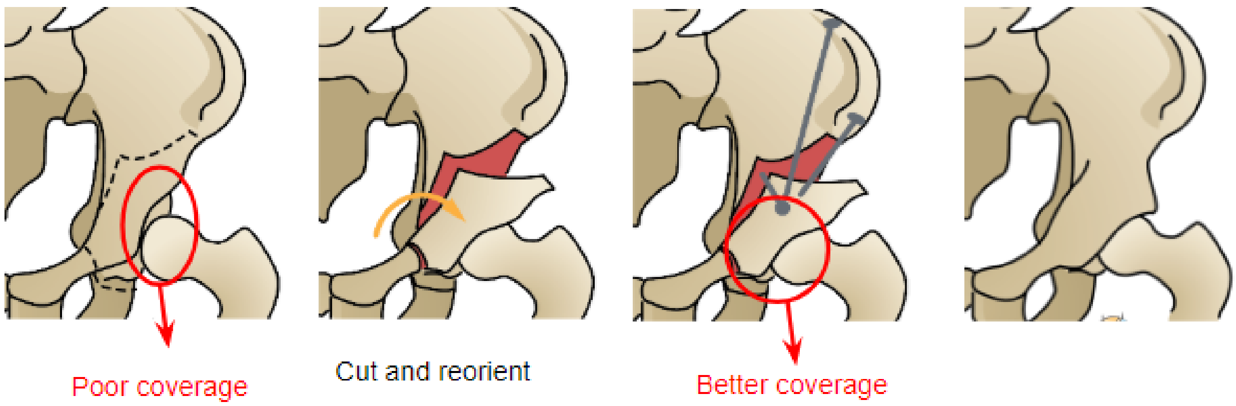

Figure 1. In PAO, the acetabulum is repositioned to increase coverage of the femoral head [3]

Several studies have proposed that computer-aided surgery for PAO has a number of potential benefits, including a better visualization for fragment and tools[4,5]. With the help of RGBD camera and 3D fragment tracking methods, it will be more effective to identify the intraoperative position of the fragment as well as reduce the number of X-ray shots [2].

The project proposed and implemented a tool tracking method which could be used to update the preplanned fracture line and assist surgeons to align the bone fragment more accurately intraoperatively using RGBD and less X-ray data.

Project Goal

The goal of this project was to write a program that would be able to track the osteotom with respect to the pelvis during the PAO using the data from an RGBD camera mounted on a camC arm. This would allow for reduced x-ray exposure during surgery and would also decrease operation time[2]. The tool tracking would allow the surgeon to better keep track of where they are cutting by improving the low visibility during surgery. The improved visibility will help both preoperatively as well as intraoperatively by being able to line up the tool with the planned orientation so that the fragment can come out closer to the desired shape.

Technical Approach

Camera augmented mobile C-arm (CAMC)

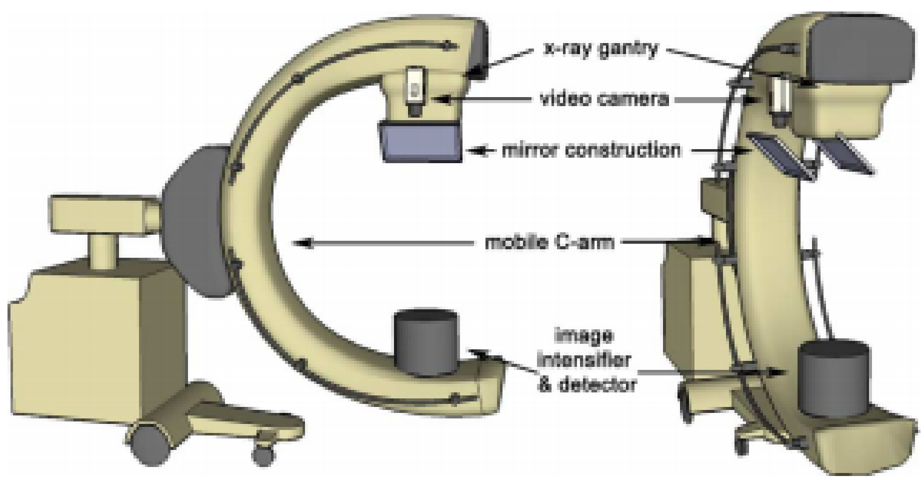

Figure 2. The setup of camera augmented mobile C-arm (CAMC). A RGBD camera is attached on the C-arm [6]

Camera augmented mobile C-arm, or CAMC, is equipped with an optical camera in addition to traditional C-arm [6]. With the help of the extra camera, the surgeon is able to achieve the same surgical outcome with reduced amount of X-ray images. In our project, we are going to use the RGBD camera that is fixed on the C-arm to track the chisel used in PAO.

Segmentation

In order to track the tool, the first objective is to segment the tool from its surroundings. Initially, we tried to segment the tool using distance in a way that we would get the depth value of each pixel, and if it was out of the range of the threshold, it would be counted as background. Next we tried using OpenCV's Mixture of Gaussian background subtraction. This type of background subtraction compares the current frame to the previous frames, and if the pixel is within the same color threshold, it is considered background. This subtraction is good for non-static backgrounds, because if something moves, it will eventually fade out if still for a long enough period of time [7]. However, if the tool is stationary for a period, it will start to fade as well.

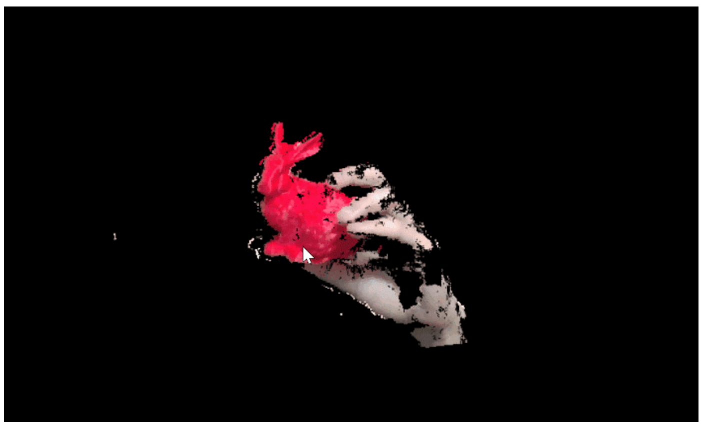

Figure 3. Background subtraction by mixture of Gaussian

We then decided to do a combination of color segmentation and plane segmentation.

For the color segmentation, we found the RGB range for the color of the object we want to segment under various light condition and collect the pixels that fall within that range.

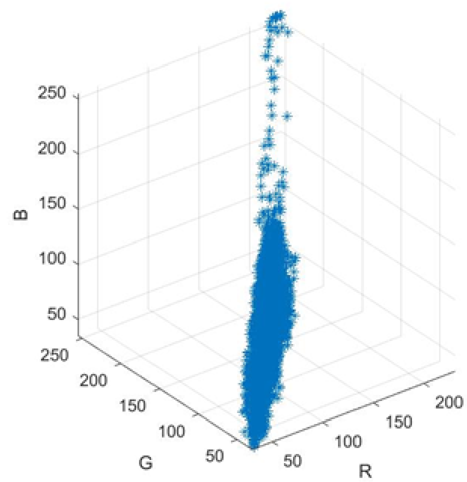

Figure 4. Distribution of the osteotom's color in RGB space

The plane segmentation uses random sample consensus (RANSAC) to find out the plane containing the largest amount of points [8]. In our project, the detected plane could be assumed to be the operation table. Therefore, all the points on and under the plane could be treated as background and subtracted out accordingly. However, due to the nature of the surgery, there aren't many points on a single plane due to the operating table contains the patient covered in cloth. We finally decided on doing a combination of color and background segmentation which allows for a more accurate segmentation of just the tool, even though the amount of points available dwindles when the tool is stationary.

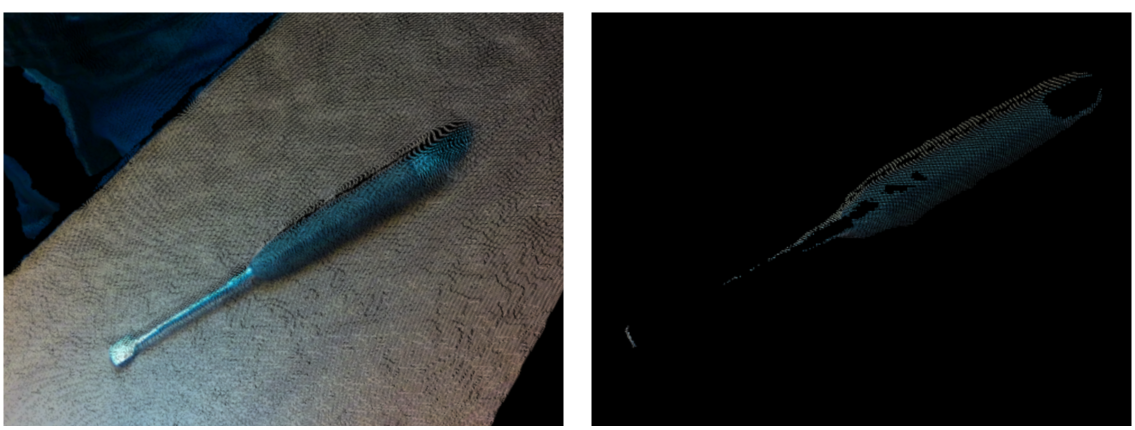

Figure 5. Comparison of the point cloud before and after plane segmentation.

Pose Estimation

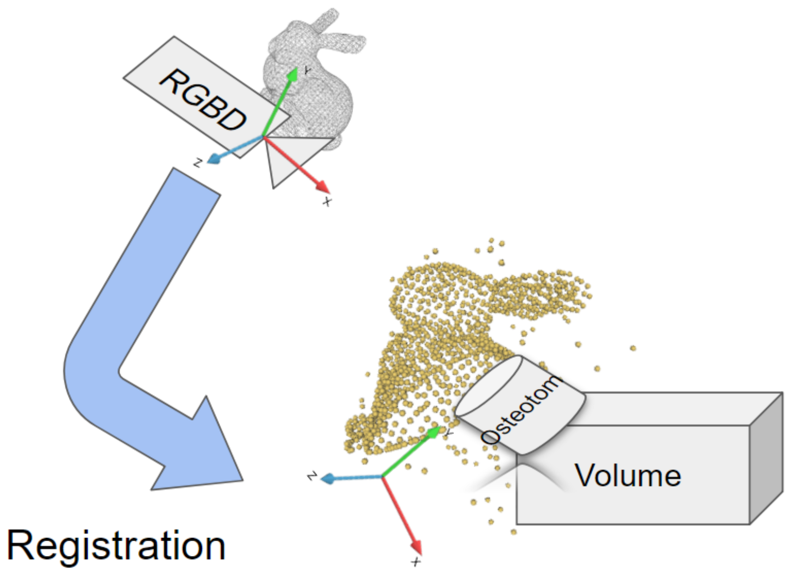

Figure 6. Schematics of registration process

Once the point cloud is segmented, the next step is to find out the orientation of the tool. This is done by initial alignment between the real time point cloud and CAD model followed by iterative closest point (ICP) [9]. ICP is an algorithm that iterates through a set of points comparing each point to a point in a separate set of points in a different frame of reference so that the points of the two sets can be paired together. It is a local method commonly used for fine alignment. To get a good pose estimation result from ICP, a good initialization is highly desired. In this project, sample consensus prerejective alignment method is chosen [10]. This method is chosen because it is robust to clutter and occlusions as instead of trying to minimize the fit error, the RANSAC prerejective routine tries to maximize the inlier rate. Fast Point Feature Histograms (FPFH) [11,12] descriptor is used as point descriptor.

Self pose correction

Considering the fact that the shape of chisel is approximately cylindrical, it is highly possible that the initial estimated pose is pointing to the opposite direction as is shown in the Figure 7. Thus, the ICP would be trapped in the local minimum.

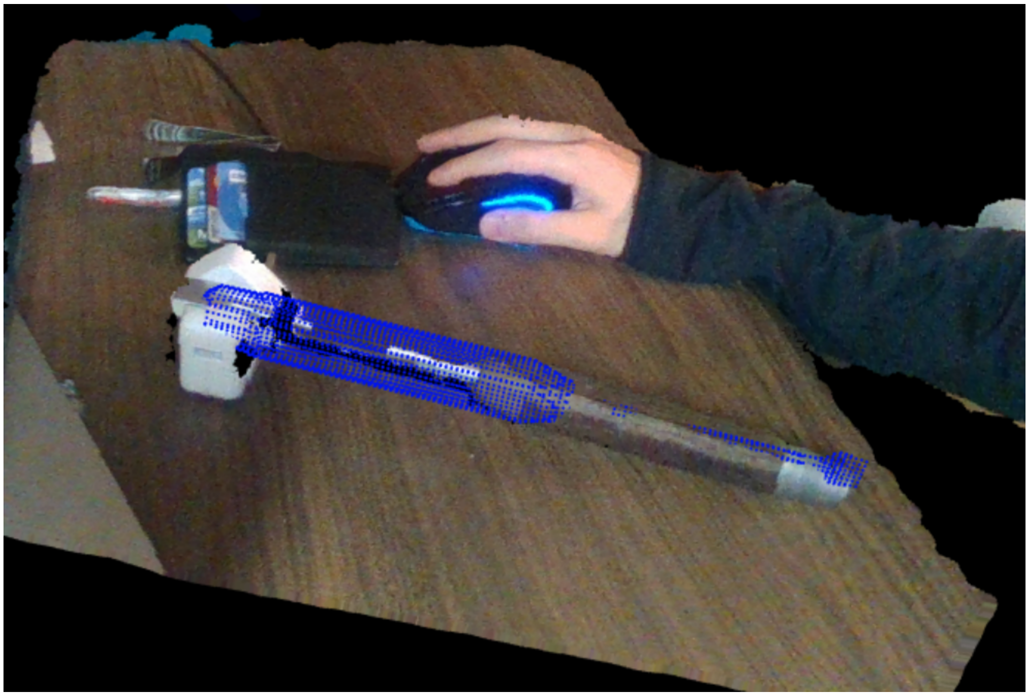

Figure 7. Pose estimation falls into local minimum of opposite direction

To overcome this issue and increase the robustness of our algorithm, we made the assumption that the tool tip is always pointing downwards to the operation table. The direction of the tool tip could be easily calculated by checking the sign of the dot product between the normal vector of the operation table (obtained in plane segmentation) and length axis of the current estimated pose. The checking is done after small iterations of ICP. Once the estimated pose is found with tool tip pointing upward, it will be flipped down before proceeding the remaining ICP iterations.

Tool Tracking

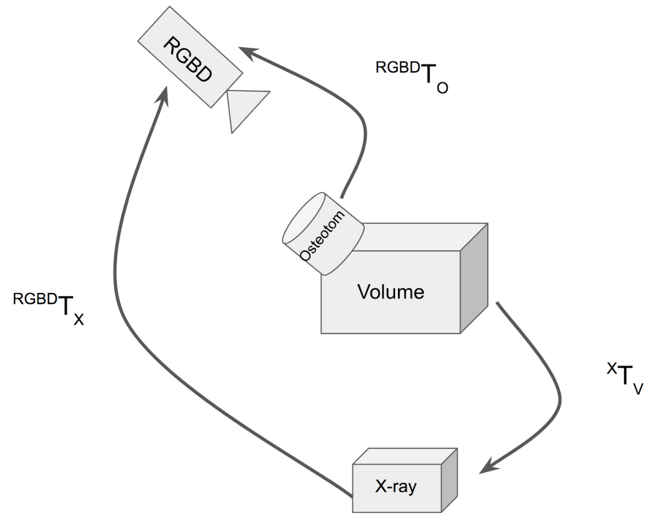

Figure 8. Schematics of the transformation chain for tracking the tool with respect to the pelvis

To find out the relationship between the osteotom and the volume, we need to complete the transformation chain above from volume to the osteotom.

$$^{V}T_{O} = {^{X}T_{V}}^{-1} * {^{RGBD}T_{X}}^{-1} * {^{RGBD}T_{O}}$$

The transformation from RGBD camera to the osteotom ($^{RGBD}T_O$) is found by pose estimation method which has been discussed above. As both X-ray and RGBD camera is fixed on the C-arm during the operation, $^{RGBD}T_X$ is a constant which can be find by calibration. The relationship between the X-ray and the volume ($^{X}T_V$) is obtained from existing 3D/2D registration of pre-op. CT intra-op. X-ray [13].

Path updating

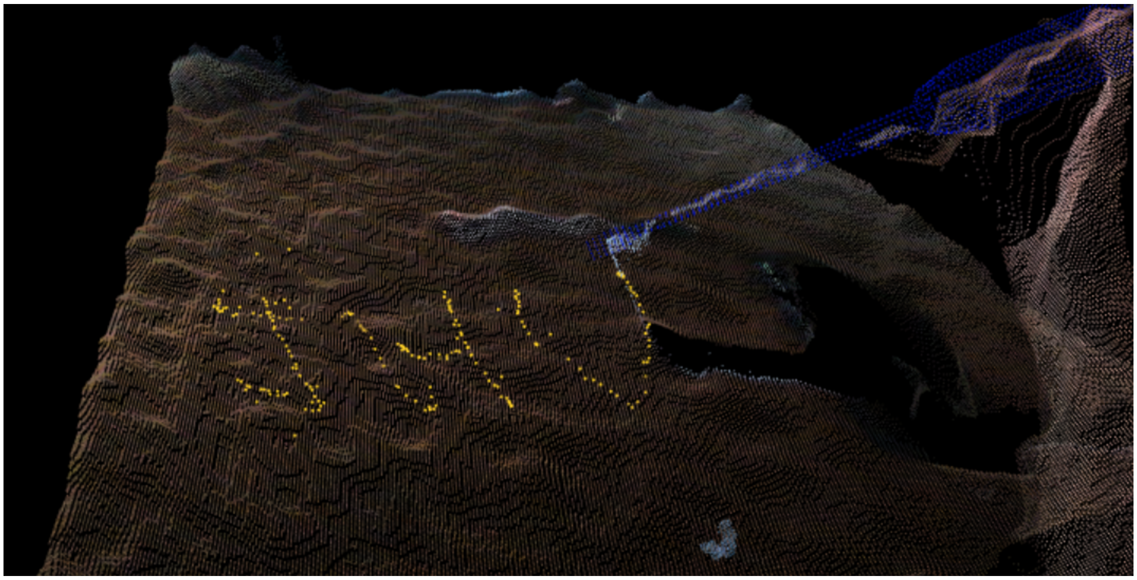

Figure 9. Hold the tool and move the tooltip following the path of “JHU”

In order to update the preoperative plan, we visualize the path of tooltip according to the result of pose estimation. As the CAD model of the tool is assumed to be known, the local coordinate of the tool tip can be obtained from the CAD model and no pivot calibration is required. As the tool is moved by hand following the “preoperative” plan of character “JHU” written on a paper, the path of estimated tooltip is shown on the table, indicating the actual cutting line.

Results

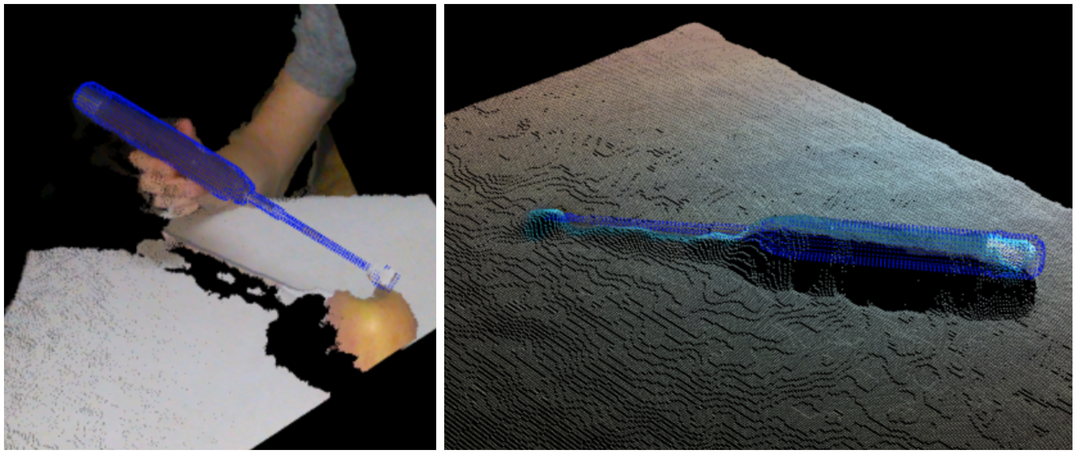

Figure 10. Tool under tracking. Blue shade indicates the tracking result

Using the proposed pipeline, the tool is able to be tracked smoothly in real time at around 40 fps. (Tested on Intel 7600U under single thread) To test the accuracy of our algorithm, we fixed the tool at two different poses and randomly recorded ten pose estimation by our algorithm of each pose and calculated their corresponding error and covariance. The true pose is obtained by doing the segmentation and initial alignment manually on the original point cloud data, followed by ICP for fine alignment in CloudCompare Software. When the chisel is kept stationary the corresponding measurement errors are shown in the following table:

	Average tool tip error (mm)	Covariance matrix of tool tip in camera coordinate (mm^2)
Pose 1	3.0	0.1576 0.0851 -0.0228 0.0851 0.1450 -0.0792 -0.0228 -0.0792 0.1890
Pose 2	3.1	0.0177 -0.0050 0.0157 -0.0050 0.0132 -0.0113 0.0157 -0.0113 0.0324

In addition to testing the error when the tool is stationary, we conducted another experiment testing the deviation of the estimated tool tip from the ground truth when the tool is moving. In this experiment, we moved the tool with its tip fixed on the table. The estimated position of the tool tip is visualized as yellow dots as is shown in the picture below.

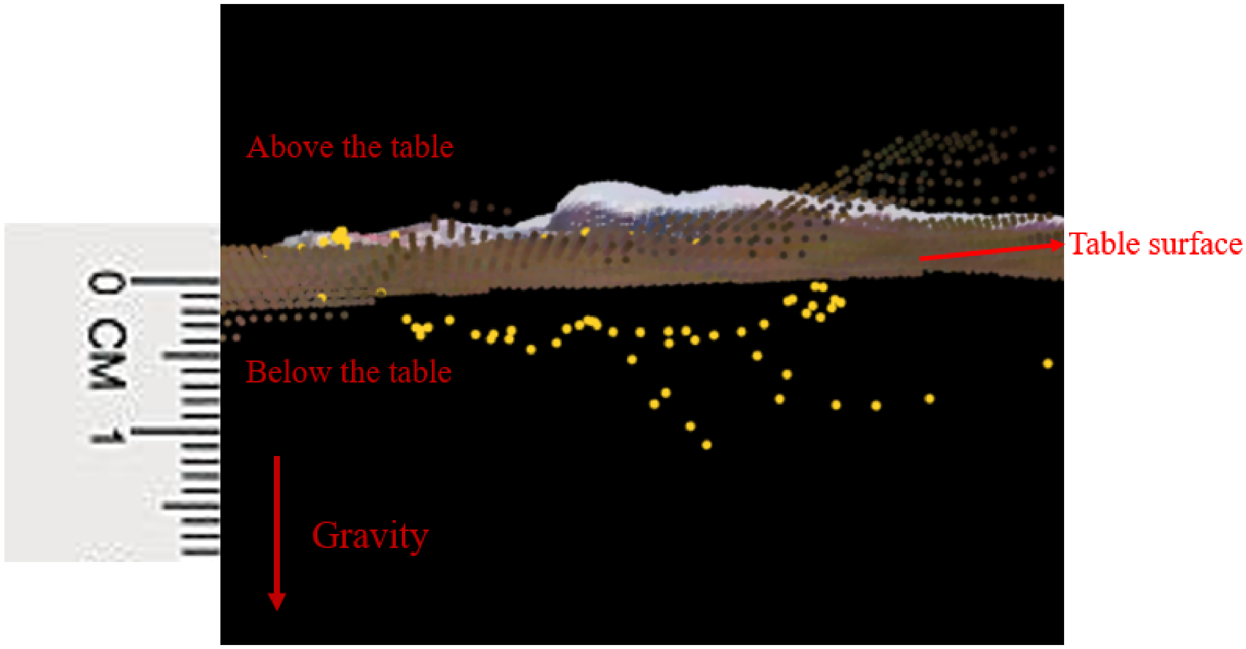

Figure 11. Sectional view of the table when the tool tip is moving on the surface of table. Yellow dots indicate the estimated tooltip position of each frame

Not surprisingly, the error of the tooltip when the tool is moving is much larger than that when the tool is kept still. While all the yellow dots should be within the surface of table ideally, the point with largest deviation is around 11 mm from the surface along the direction perpendicular to the surface of the table. On the other hand, 83.8% points' deviation from the ground truth are within 5 mm along the normal of the surface.

Additionally, the rotation of the tool along its local length axis is hard to perceive because of its cylindrical shape. This is, however, not indicated in the above error metrics of the tool tip as the center of the tool tip is on its length axis whose position is invariant to rotational error along its length axis. Nevertheless, this difficulty has to be solved if we want to visualize the cutting plane and figuring out the exact shape of the acetabulum that is cut down on the pelvis.

Discussion

Our proposed project was a real-time tool tracking program for PAO by using an RGBD camera mounted on a C-arm. The tracking will allow for better alignment of the acetabular component during surgery while reducing the amount of radiation received and length of the surgery.

Although the combination of background and color segmentation allows for the passed point cloud to only include the osteotom, there are cases that occur when a small amount of points are passed to the ICP pose estimation portion. This is due to cases where the osteotom is stagnate for a long enough period of time to be considered background. With a smaller number of points, the accuracy of the pose estimation therefore suffers. A more accurate segmentation method would lessen the error in the pose estimation and improve tracking accuracy.

After the initialization of the tool tracking has occurred the variation of the tracked position from the true position did not reach more than 11 mm length-wise and 2 mm width wise. When the tool is more obscured, the error tends to lean more towards the extreme ends. However, when the tool is less obstructed, the tracking becomes more accurate. A way to keep the accuracy high in tracking is to use multiple RGBD cameras. This way, when one is obstructed, there will be another with a clearer view that can be used to estimate the pose.

Due to the cylindrical shape of the osteotom, a rotational degree of freedom is lost around the length axis. This occasionally results in the pose estimation of the tool to be rotated in a different way.

In terms of practical surgical use, this tool tracking can be reliable in the cases were the movement is at a moderate to slow pace. Currently, the tracking is not robust to fast movement, although that is normally not too much of an issue during orthopedic surgery. This can help surgeons visualize the path that their tool has cut, which will allow the bone fragment to be better tracked and moved to ensure optimal coverage of the femoral head.

Conclusion

In this project we wrote a program that can track an osteotom during a PAO using an RGBD camera mounted on a C-arm. This procedure, though not good a tracking abrupt motion can track the path of the tool intra-operatively. This can reduce the operation time as well as radiation exposure to the patient and surgeon as well as improving upon the visibility of the surgeon. Tracking can also allow the surgeon to better match their pre-operative plan intra-operatively.

Management Plan

During the course of the semester we had our code stored in a private bitbucket repository which allowed the code to be backed up while also allowing both of us to work on the code separately. We also had weekly meetings with our mentors in order to update them on our progress and to receive guidance as to what our next step on the project should be. The two of us would also have additional meetings in order to combine our code and update the other on our individual progress. In terms of dividing up the workload, Billy was in charge of the segmentation while Wenhao was in charge of the pose estimation. However, both people contributed to each part.

Deliverables

The deliverables that resulted from this project are C++ source code and documentation that can both segment a chisel and use that data to estimate the pose and orient the CAD model to match that pose and from there, track the path of the chisel. Due to a loss of a team member early on, we were not able to obtain our original maximum deliverable of investigating the plan approach and collecting data on how it works together with the x-ray during the surgery.

Future Work

In the future, machine learning can be used to improve upon our current segmentation method. This way the segmentation could better account for factors such as lighting or tools blending in with the environment. Additionally, the original maximum deliverable of combining the tool tracking with the planned approach can be achieved which will allow for the tool to be better aligned with the planned orientation both preoperatively and intraoperatively. The tool tracking can also be implemented into pre-existing works on fragment tracking. This is because tracking the tool path will help determine the shape of the cut made on the bone, and, therefore, make a more accurate estimate of the fragment.

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