CIS 2 Molly O'Brien
Final Report 5/11/17

Introduction

Physiological hand tremor has been measured to be 38 μm in retinal microsurgery [1]. The frequency of hand tremor can vary between 4-9 Hz [2] Hand tremor poses a risk to the patient in microsurgery because the surgeon must navigate through and operate on sub-millimeter structures. Surgical robots help remove hand tremor. At Johns Hopkins, the Galen Steady-Hand Robot has been developed for microsurgery in the head and neck with sub-millimeter precision [3]. Steady-Hand Robots (SHR) are cooperative systems where the robot and the surgeon both hold the tool. The surgeon pushes on the tool, the robot reads the force applied and moves in the desired direction.

To compute the hand tremor from a surgical video the tool must be tracked. The 3D trajectory of the tool can be transformed in the frequency domain and the motion above the tremor threshold isolated. There are many publications on tracking tools with and without markers. Bouarfa et al [4] developed method for tool tracking with color markers. The authors paint the shafts of laparoscopic tools different colors and compute color histograms for each marker color. These color histograms are used to find the probability each pixel in an image is a marker. The CAMshift algorithm is used to find the most likely marker positions in the image.

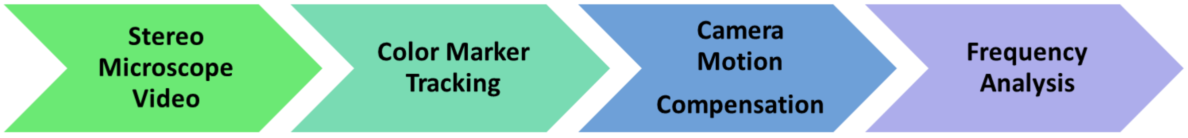
Problem

We want to compare the magnitude and frequency of tremor in manual and robot-assisted surgery. In many microsurgical applications, surgical site is observed through a stereo microscope which is not rigid and can move during procedures. We propose an algorithm that can accurately track color markers on surgical tools and in the background, compensate for microscope motion, and perform frequency analysis on the tool trajectories. This algorithm is used to compare suturing task performed manually and with the Galen robot.

Methods

Our algorithm performs frequency analysis on tool motion observed through a calibrated stereomicroscope. The microscope was calibrated using OpenCV functions.

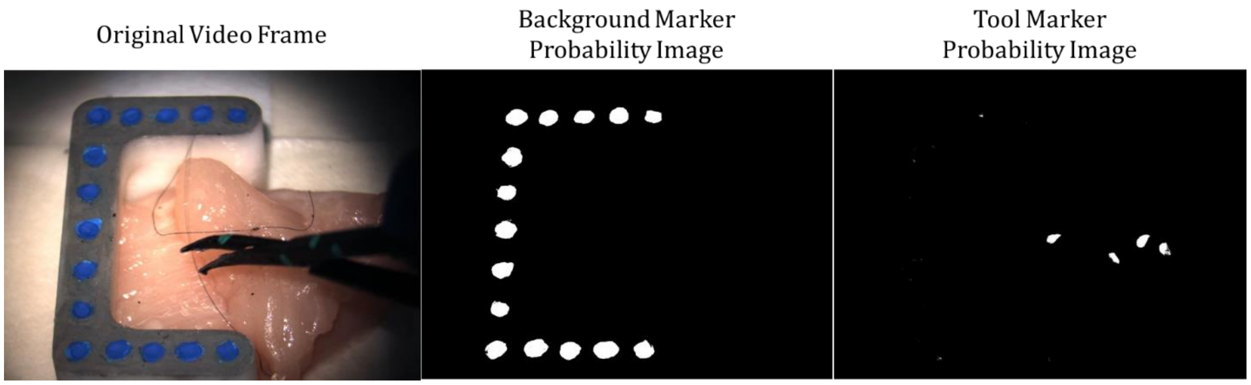
Algorithm Pipeline:



<u>Color Marker Tracking</u>

We need to track the tool motion and microscope motion. In our experimental setup the background is stationary; therefore, apparent background movement in the microscope video corresponds to the microscope movement.

Blue color markers were painted on the background, and green color markers were painted on the surgical tools. The surgical tools used have multiple green markers so they can be tracked from many different angles. The color markers were manually segmented in several images (between 1 and 7) from the experimental videos. Color histograms were created using the Hue and Saturation values from the segmented marker pixels. A Gaussian mixture model (GMM) was used to compute the probability a pixel with a given hue and saturation was from a color marker. Two separate GMMs were created for detecting background and tool markers. The number of modes of the GMM (3 or 4) and the channel with marker detections were tuned manually for each experimental video.


Original Video Frame
Background Marker Probability Image
Tool Marker Probability Image
Fig 1: frame from microscope video, background marker probability image, tool marker probability image

For each frame in the microscope video a background marker probability image and a tool probability image were created. The tool markers were detected using an MSER blob detector on the probability images. We matched the tool marker points detected in the left image to nearby markers detected in the right image. If there was no nearby marker point detected in the opposite image the detected marker was ignored.

The background markers were detected by matching a background marker template to the current frame. A left and right template were used to match to the left and right videos. The templates were cropped marker probability images with all 15 markers visible. The centers of the markers in the template image were detected using an MSER blob detector. A simple greedy search was used to match the blobs in the left template and the right template.

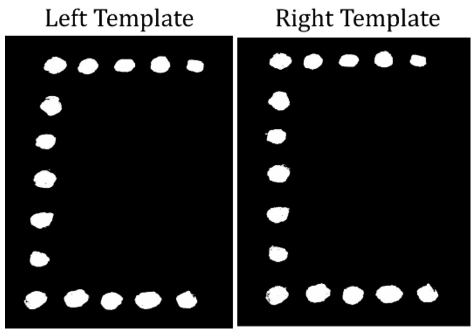


Fig 2: left background template, right background template

For each video frame, the algorithm found the best translation and rotation the templates to match the background probability image. The marker points detected in the images were rotated and translated by the best transform found. These points were taken as the background marker image detection points. This allowed positions for all 15 background markers to be found in every video frame, even if some markers were occluded. Once the tool and background markers were detected and matched in the left and right images, the 3D marker locations were triangulated.

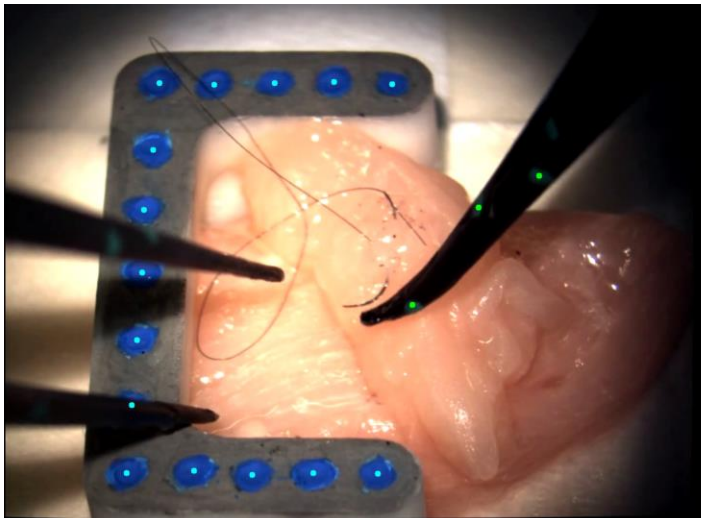


Fig. 3: Video frame with marker and tool detections

Camera Motion Compensation

The background in the experimental video was stationary. Any apparent background motion in the video was microscope motion. The camera motion compensation module found the rigid transform from the triangulated 3D background points in each frame to the background points in the first frame. This transform was applied to the detected tool points in each frame to remove the effects of camera motion. The Procrustes algorithm [5] was used to find initial guesses for the transforms T_{initial}. Bundle adjustment was applied on a shifting window of 80 frames to find the optimal transform from each frame to the first frame.

N: number of frames in the video

$$T_{initial} = [T_{00}, T_{10}, \dots T_{(N-1)0}]$$

The homogeneous transform T_{i0} aligns the background marker points in frame i to the points in frame 0. T_{i0} can expressed as 3 Rodrigues angles and a translation.

$$T_{i0} = \begin{bmatrix} & x \\ R & y \\ & z \\ 0 & 1 \end{bmatrix}$$

$$rod_x, rod_y, rod_z = Rodrigues(R)$$

The vector P_{i0} is used to parameterize T_{i0}.

$$P_{i0} = 1\ x\ 6\ vector$$

$$P_{i0} = [rod_x, rod_y, rod_z, x, y, z]$$

$P_{initial}$ is a vector with the transformations for all N video frames.

$$P_{initial}: 1\ x\ 6N\ vector$$

$$P_{initial} = [P_{00}, P_{10}, \dots P_{(N-1)0}]$$

$$points_i : 3D\ triangulated\ points\ of\ background\ markers\ in\ frame\ i$$

The goal is the minimize error the error: $\min(T_{i0} * points_i - points_0)$

sumError is the sum of Euclidean distances between the rotated points in frame i and points in frame 0:

$$sumError_i = \sum_{j=1}^{15} dist(points_0[j], T_{i0} * points_i[j])$$

The translational error in frame i:

$$t_i = mean(T_{i0} * points_i) - mean(points_0)$$

The rotational error in frame i:

- Find rotation between the T_{i0}*$points_i$ and $points_0$ using Procrustes algorithm [5]

$$\Delta R_i: rotation\ between\ T_{i0} * points_i\ and\ points_0$$

The Rodrigues angles of deltaR are the rotational errors of T_{i0}

$$\Delta R_{xi}, \Delta R_{yi}, \Delta R_{zi} = Rodrigues(\Delta R_i)$$

Return the error of each parameter scaled by the overall distance between the points in the point cloud:

$$Error_i = [sumError_i * \Delta R_{xi}, sumError_i * \Delta R_{yi}, sumError_i * \Delta R_{zi}, sumError_i * t_{xi}, sumError_i * t_{yi}, sumError_i * t_{zi}]$$

$$Error: 1\ x\ 6N\ vector$$

$$Error = [Error_0, Error_1, \dots Error_{N-1}]$$

Bundle adjustment finds the vector P that minimizes the vector Error.

Frequency Analysis

The DFT of the stabilized tool trajectory was used to analyze the hand tremor. Three 1-dimensional DFTs were taken of the x-coordinates, y-coordinates, and z-coordinates of the trajectory. The 3 DFTs were summed to get the maximum possible movement at each frequency. Physiological hand tremor is between 4-9Hz [2]. The microscope video is recorded at 30 fps so we can recover motion frequencies up to 15 Hz. A lowpass filter was applied to the frequency results to isolate the tremulous motion above 5 Hz.

Experiments

To test the marker detection and frequency analysis, stereo microscope video was recorded of a novice suturing a chicken breast manually and with the Galen robot. To get stable background fiducials, a chicken holder was 3D printed and painted (see figure 4).

To test the camera motion compensation, a stereo microscope video was recorded of the background marker moving along a grid with known side lengths. The movement between the stabilized 3D points and the original triangulated 3D points was compared to the known movement of the background marker.

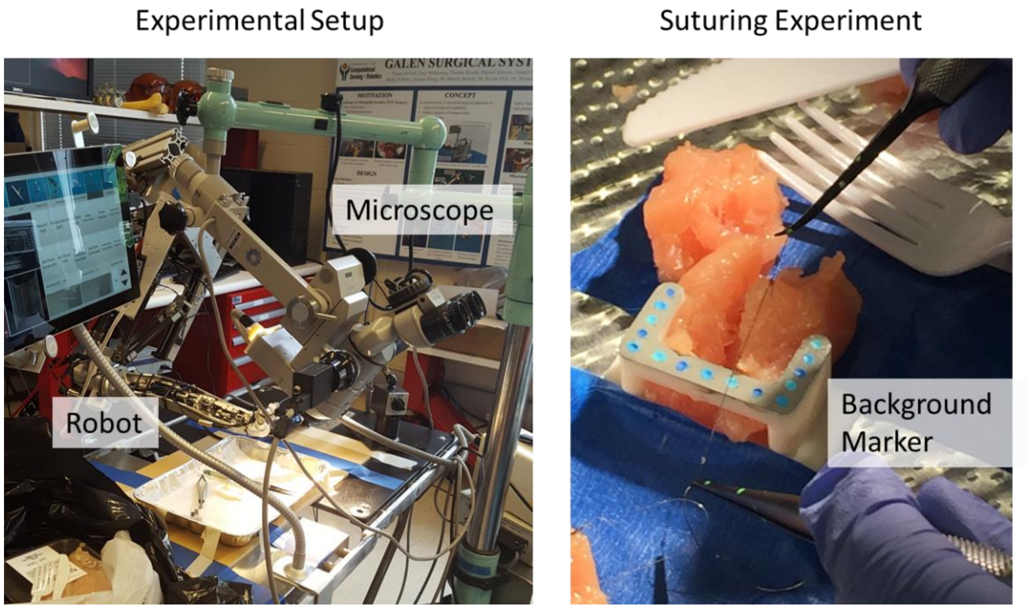


Fig. 4: Lab setup with robot and microscope. Background marker being used in suturing experiment.

Results

<u>Triangulation Accuracy</u>

Fig 5 shows the 3D background marker positions triangulated from a frame in the suturing_manual_05-04-17-1 video sequence. The ground truth distances between the markers were measured using digital calipers.

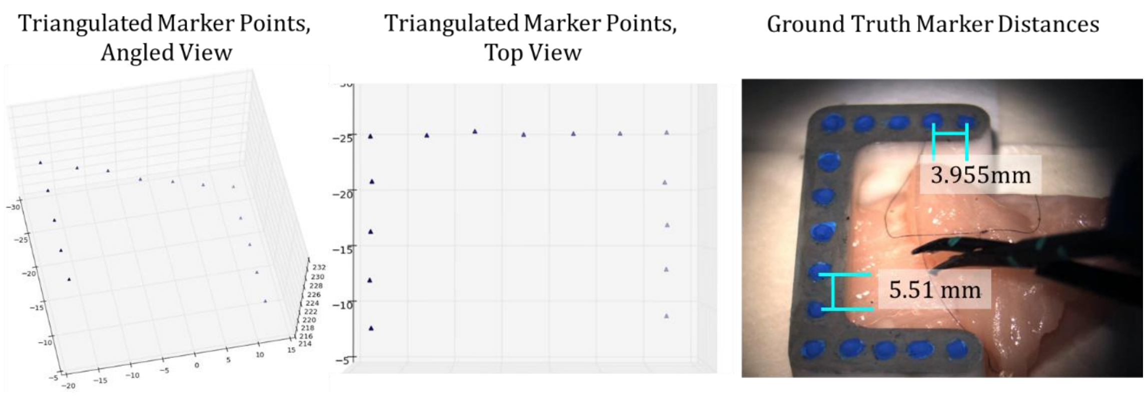


Fig 5: Background markers triangulated from suturing_manual_05-04-17-1 clip

The distance between all adjacent triangulated markers was computed(see figure 5 left and center). The ground truth distance between markers along the 2 shorter ends of the chicken holder is 3.955 mm. The ground truth distance between markers along the longer end of the chicken holder is 5.51 mm. The average distance in the triangulated chicken holder is 4.02 $\pm$ 0.22 mm along the short ends and 5.39 $\pm$ 0.24 mm along the shorter ends. The triangulation error was < 0.15mm. This shows that the 3D triangulated points are accurate.

Measured Marker Distances:

	Triangulated Distance	**True Distance**	**Error**
Short Side	4.02 $\pm$ 0.22 mm	3.955 mm	0.065 mm
Long Side	5.39 $\pm$ 0.24 mm	5.51 mm	0.13 mm

Camera Motion Compensation

To test the camera motion compensation, the background marker was moved a known distance in a stereo microscope video. The triangulated background points were stabilized. The translation between the stabilized points and the original points was compared to the known distance the marker was moved. The tracked translation is the average distance between each stabilized and original point on the background marker. The tracked movement is the norm of the tracked translation.

True Movement	**Tracked Movement**	**Error**
6.3 mm	6.804 mm	0.504 mm
12.6 mm	13.03 mm	0.430 mm
18.9 mm	20.33 mm	1.43 mm
25.2 mm	25.8247 mm	0.625 mm

Frequency Analysis

The tool markers were detected in each video frame. Markers near each other were grouped frame to frame to create tool trajectories. There were multiple green dots on both surgical tools. This led to multiple markers being detected in each frame and markers from both tools being detected together. This is problematic because the final trajectory could have the tool movement from one time counted in multiple trajectories and in the robot sequences there are a short trajectories detected from the manual tool in the left hand. An intermediate solution to this was to only analyze the longest trajectory in the video. This trajectory would not have multiple detections from the same frame or from different tools. As part of my future work I plan to implement a tool appearance model that can find the tool position and orientation given a subset of markers. The appearance model will let us detect the tool position and orientation consistently in every frame.

In the experimental video from 05-04 the background marker was not fixed rigidly to the table. The background points were not truly stable so I did not apply the motion compensation to the detected tool points. In this video, there was minimal camera motion so the frequency analysis is still meaningful. A lab mate, Radhika, designed a background marker tray that will rigidly hold the background marker in future experiments.

Without microscope motion compensation:

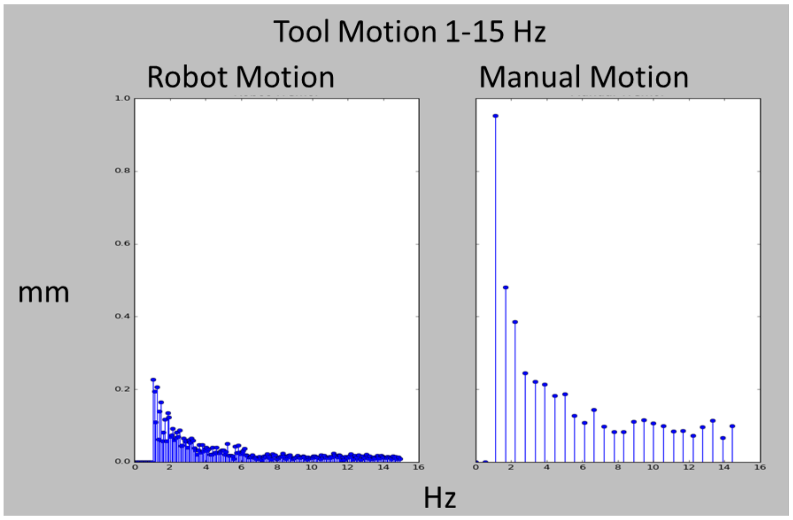


Fig 6: Tool motion from 1-15 Hz
Video: suturing_robot_05-04-17-1, suturing_manual_05-04-17-1

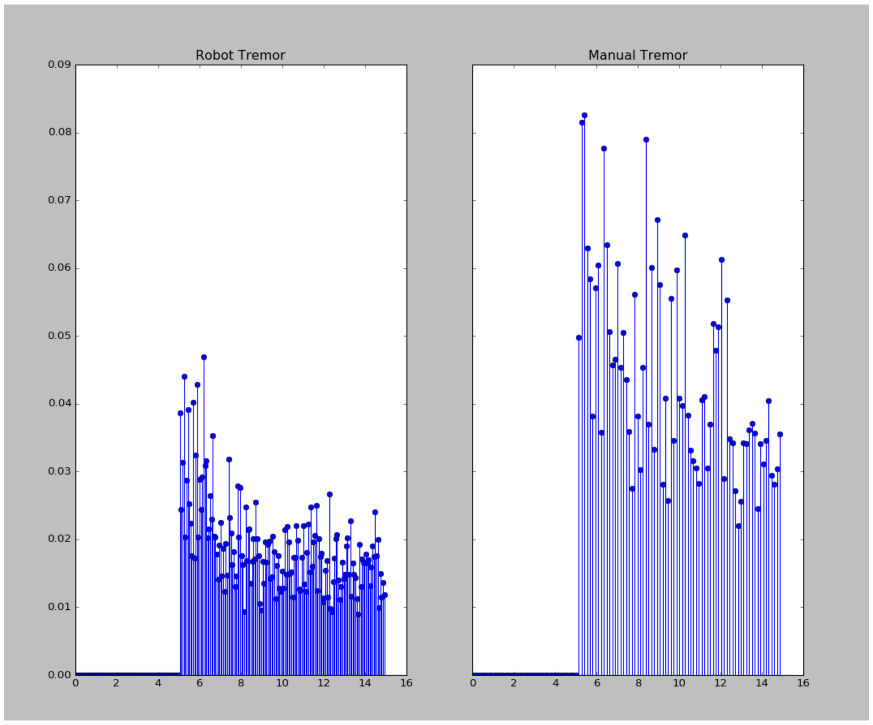


Fig. 7: Tool tremor from 5-15 Hz
Video: suturing_robot_05-04-17-1, suturing_manual_05-04-17-1

Max Tremulous Motion	Magnitude	Frequency
Robot Held Tool	0.050 mm	0.14mm
Hand Held Tool	5.22 Hz	6.67 Hz

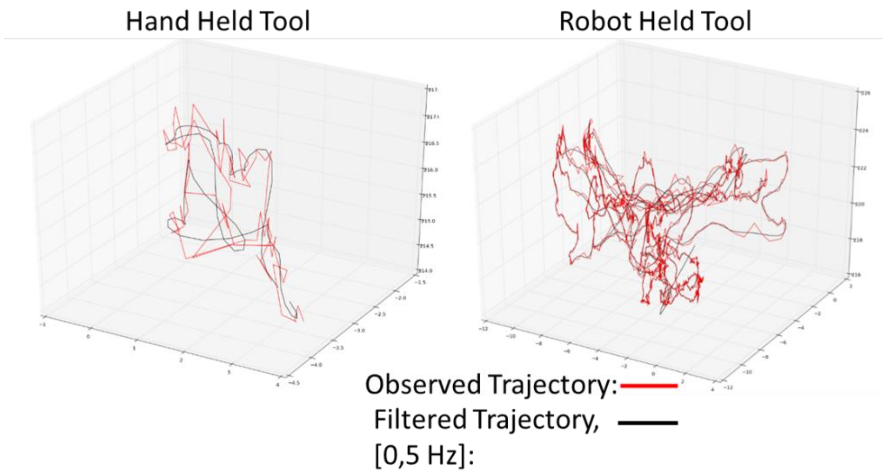


Fig. 8: 3D tool trajectory from hand held tool (left) and robot held tool (right). Background markers with and without microscope motion compensation

Conclusion

<u>Significance</u>

The maximum amplitude of tremulous motion for the robot in the sequence suturing_robot_05-04-17-1 is 50 microns at 5.22 Hz. The largest tremor in the hand-held tool is 140 microns at 6.67 Hz. For the robot trajectory analysis, the magnitude of the tremor slowly decays as the frequency increases. But in the hand-held results there is a spike in movement at frequencies around 6Hz, 10 Hz, and 14 Hz. We can see the effect of physiological hand tremor on the tool movement. Comparing the true and filtered tool trajectories, we can see that the smoothed trajectory follows the true robot trajectory much more closely than it follows the manual trajectory. The robot is moving in the direction of intentional motion but disregarding the unintentional hand tremor.

These results are significant because they illustrate how a surgical robot reduces hand tremor and make microsurgery safer. This algorithm can be used to measure surgeon hand tremor and by extension surgeon skill. The inverse trajectory can illustrate the difference between the surgeon's desired path and the actual path with hand tremor. These 3D trajectories can also be analyzed to find applications where surgical robots can make the most difference. Surgeries with complex paths where the desired and actual trajectories are very different are good candidates to have a surgical robot integrated into the workflow.

Extensions/ Limitations

One limitation of this work is that the tools and background were tracked using color markers. These markers may not be realistic in a real surgical setting. One good thing about the tool tracking is that it does not require any external tracking systems or bulky markers. The painted tools have the same profile as the original tools. A more complicated computer vision approach would be required to track the background without markers in *in-vivo* videos.

My next step in this project is to implement an appearance model for the tool using the known color markers. With the appearance model, we will be able to get the tool position and orientation with detecting a subset of all the markers. This way we will not have to take just the longest continuous trajectory, we will know the tool position throughout the entire video.

A limitation is the code is not real-time. But re-implementing the python code in C++ would make it much faster. The bundle adjustment is already implemented with a sliding window so that could be adjusted to get near real-time performance. Tracking the background markers does not work if all the markers are occluded, but since the markers were designed for a lab setting it is reasonable to require they aren't all covered during the experiment.

Acknowledgements

Thank you Dr. Taylor, Dr. Reiter, and Yunus for your technical support. Thank you Paul for helping me set up the microscope and robot each time I recorded data. Thank you Abhinav for designing the background marker. Thank you Radhika for printing the background marker and for designing and printing the tray. Thank you Alexis for helping me throughout CIS 1 and CIS2!

Management Summary

Who did what?

I was a one person team so I did all of the technical work. Abhinav, an undergraduate student, designed the background marker for me. Radhika printed the background holder and designed and printed a tray to hold the background marker.

Accomplished versus planned:

I met all my final delivarables. Originally I had planned to track the tool using an optical tracker and compare the results with the video tool tracking. We changed these deliverables part way through the semester because I was falling behind schedule and the optical tracking results would not necessarily be more accurate than the video tracking results. I was able get back on schedule and finish the project by the end of the semester.

	Original	Updated
Min	A system capable of measuring tool movement (using existing tracking system)	An algorithm to triangulate 3D points from stereo video and track background motion (with fiducial points)
	Frequency results from tracked tool movement (using existing tracking system)	Tool tracking algorithm using microscope video for painted tool
	An algorithm to triangulate 3D points from stereo video and track background motion (with fiducial points)	
Expected	Tool tracking algorithm using microscope video	Validation of triangulated points using known world motion (robot or measured)
	Frequency analysis of the tool tip motion from a stereo video	Frequency analysis of the tool tip motion from a stereo video
Max	An algorithm to get accurate tool tip motion and tremor from microscope video	Comparison of hand-held and robot-held tool tremor
	Comparison of hand-held and robot-held tool tremor	

Next steps:

The next step for this project is to run the frequency analysis on video of surgeons suturing animal vessels. I will run the code on new experimental video this summer. The next step to improve the code is to implement an appearance model for the tool.

Lessons Learned:

The biggest lesson I learned was to prioritize the deliverables at the beginning of a project. I spent a bit of time early in the semester trying to figure out when I could set up the optical tracking system and how to use the OT system. In the end the optical tracking results weren't necessary. In the future I will find out what deliverables are essential, complete those, then try to finish additional work that would be interesting but not essential.

References

[1] S. P. N. Singhy and C. N. Riviere, "Physiological tremor amplitude during retinal microsurgery," in *Bioengineering Conference*, Philadelphia, 2002.

[2] R. N. Stiles, "Frequency and displacement amplitude relations for normal hand tremor," *Journal of Applied Physiology,* vol. 40, no. 1, pp. 44-54, 1976.

[3] K. C. Olds, P. Chalasani, P. Pacheco-Lopez, I. Iordachita, L. M. Akst and R. H. Taylor, "Preliminary evaluation of a new microsurgical robotic system for head and neck surgery," in *International Conference on Intelligent Robots and Systems*, Chicago, 2014.

[4] L. Bouarfa, O. Akman, A. Schneider, P. P. Jonker and J. Dankelman, "In-vivo real-time tracking of surgical instruments in endoscopic video," *Minimally Invasive Therapy & Allied Technologies,* pp. 129-134, 2012.

[5] R. Taylor, "Computer-Integrated Surgery: Point cloud to point cloud rigid transformations," 2016. [Online]. Available: http://www.cs.jhu.edu/cista/445/Lectures/Rigid3D3DCalculations.pdf. [Accessed 11 May 2017].

10600.446/646 – CIS II – Mentors Report

Questionnaire – Project # ___4___

10/10 Overall project and progress

- Were you satisfied with the overall technical progress made in the course of the semester? **Yes**
- Was the total accomplishment appropriate for the number and level (undergrad/graduate) of students on the project? **Yes**
- Will the results be useful to you in the future? **Yes**
- Do you see a prospect for patents or publication to result? **No**

10/10 Report (which the students should have shared with you)

- Does the project report accurately reflect the scope and accomplishment of the project? **Yes**
- Were you given an adequate opportunity to review the report? **Yes**
- Does the report and its appendices, together with the web site, provide sufficient information that subsequent groups can make effective use of the project results. **Yes**
- In particular, are any project designs or code adequately documented. **Yes**

10/10 Web site

- Does the web site reflect the scope and accomplishment of the project? **Yes**
- Do you wish the web site to remain password protected after May 30? If so, for how long? **No**

10/10 Management

- Were the students fully engaged in the project? **Yes**
- How often did they meet with you? Was this enough? **Weekly; Yes**
- Were the “deliverables” and “dependencies” realistic? **Yes**
- Was the plan realistic? Were unmet dependencies approached in an effective manner? **Yes; Yes**

Other comments or suggestions

- Do you have any other comments or suggestions, either about the specific project or about the overall structure of the course for next year.

Technical Appendices

- Code is available in a zip file on the wiki

Users Guide

Tremor Analysis Users Guide

Molly O'Brien
05/16/17

How to use:
TO USE:	put all files in Tremor_Analysis/experiments/Folder_Name

```
		In the folder:
			Calibration/Left_Ims/*
				> Left calibration images
				> image names should be the frame number
			Calibration/Right_Ims/*
				> Right calibration images saved in
				> image names should be the frame number
			left_video.avi
				> left camera experimental video
			right_video.avi
				> right camera experimental video

			Color_Markers/Background/images
				> images with color markers
				> image names should be the frame number
			Color_Markers/Background/binary_masks
				> masks around marker
				> image names should be the frame number
			Color_Markers/Background/template.png
				> template image
			Color_Markers/Tool/images
				> images with tool markers showing
				> image names should be the frame number
			Color_Markers/Tool/binary_masks
				> masks around markers
				> image names should be the frame number
```

* experiments/sample_folder is an empty folder with the correct folder structure needed for each experiment

# TO CALL FUNCTION:

```
cd  "path to folder" /Tremor_Analysis/
```

```
python runTremorAnalysis [Folder_Name]
```

Guide to src Files

Folder: src

Tremor_Analysis

Function	Tremor_Analysis
Input	* Folder_Name: folder with videos, calibration images, and marker information
Return	* saves triangulated 3D points, stabilizing transforms for each frame, plots frequency analysis
Description	* Detects color markers * Performs camera motion compensation * Performs frequency analysis

Folder: src/Bundle Adjustment

File: bundleAdjustment.py

Function	apply_bundle_adjustment
Input	* marker_points: list of array of 3D background marker positions for each frame * T: list of array of 4x4 homogeneous transform from frame n to first frame
Return	* T_bundle: list of array of optimal 4x4 homogeneous transform from frame n to first frame
Description	Given 3D background points for each frame in a video, apply bundle adjustment to get optimal transform from nth frame to first frame. Applies bundle adjustment with a sliding window of 80 frames.

Function	bundleAdjustment
Input	* observations: list of array of background points for each frame * T_initial: list of array of 4x4 initial homogeneous transforms from each frame to the first frame
Return	* P_optimal:1xn*6 vector with the optimal transforms for the n frames. Each 1x6 vector represents the 4x4 homogeneous transform from points in frame n to points in frame 0.
Description	Given a list of points in each frame and initial transforms for each frame to the first frame, find the optimal transform from each frame

	to the first frame. The goal is to stabilize background points in microscope video.

Function	extractVector
Input	* T_list: list of N 4x4 homogeneous transforms
Return	* V: 1xN*6 vector. Each transform T_i in T_list is converted into a 1x6 vector v_i = [rx, ry, rz, x, y, z] where rx, ry, and rz are the Rodrigues angles from the rotation in T_i.
Description	Turn a list of N transforms into a 1xN*6 vector. The vector will be optimized in bundle adjustment

Function	ErrorFunction
Input	* P: 1xN*6 vector of parameters being optimized * x: list 3D background points in N frames
Return	* error: 1xN*6 vector, error associated with each transform parameter in P.
Description	Compute the error for a given vector of transforms P being optimized in bundle adjustment. Error for transform i is proportional to the distance and rotation between the points in frame 0 and frame i * transform i

Function	ExtractTransforms
Input	* P: 1xN*6 vector (3 Rodrigues angles, 3 translation variables)
Return	* T: list of N 4x4 homogeneous transforms
Description	Given a vector P with transforms for N frames, extract the transformation for each frame. Return a list of transforms.

Function	FormTransform
Input	* V: 1x6 array (3 Rodrigues angles, 3 translation)
Return	* 4x4 homogeneous transform
Description	Given Rodrigues angles and translation, form a homogeneous transform.

Function	FindError
Input	* points1: Nx3 array of points

	* points2: Nx3 array of points
Return	* error: 1x6 array of error, sumDistances*[rx ry rz x y z] of rotation between point clouds then translation btwn point clouds
Description	Given 2 pairs of corresponding 3D points, find the rotation and translation error between the point clouds. Weight the rotation and translation errors by the sum of distances between corresponding points in the two point clouds.

Function	rotatePoints
Input	* points: Nx3 array of points * T: 4x4 homogeneous transform
Return	* points_rot: points transformed by T
Description	Given a list of 3D points, transform by given 4x4 homogeneous transform.

Function	QuatToRotM
Input	* q: quaternion with the scalar value first [qw, qx, qy, qz]
Return	* R: 3x3 rigid rotation matrix
Description	Turn a quaternion into a rotation matrix, assumed quaternion: q = [w x y z] where w is the scalar, and x y z is the vector

Function	dist
Input	* x: point 1 * y: point 2
Return	* D: distance
Description	Find the Euclidean distance between two points with the same dimension.

Folder: src/Camera Calibration

File: blobParamsApp

Function	createBlobDetectorFile
Input	* Folder_Name: directory with sample images * tool_hist: color histogram for tool markers * N_tool: the channel of the probability image with the tool blob detection

Return	* min_area: int, minimum area of tool marker blobs * max_area: int, max area of tool marker blobs
Description	Let users interactively set blob size parameters for blob detection in tool tracking.

Function	findGoodBlobs
Input	* image: image from video * prob_im: tool marker probability image of image
Return	* min_area: int, minimum area of tool marker blobs * max_area: int, max area of tool marker blobs
Description	Detect blobs in marker probability image. Let the user change the desired blob size until all markers are detected.

File: stereoCalibration

Function	stereoCalibration
Input	* left_dir: folder with left calibration images * right_dir: folder with right calibration images * camCalFileName: file name to save calibration results * stereoCalFileName: file name to save stereo calibration results * output: file where results & debugging info are saved
Return	* ObjectPoints: the 3D checkerboard corner positions used in calibration * leftCalIms: the left images were the L & R ims had checkerboards detected (and were used in calibration) * rightCalIms: the right images that were used in calibration
Description	Given left and right images from a stereo camera find the stereo calibration and stereo rectification matrices

Function	findCorners
Input	* leftIm: left image * rightIm: right image * patternsize: (corners along cols, corners along rows)
Return	* foundL: True/False if all corners were found * cornersL: corners on left image * foundR: True/False if all corners were found * cornersR: corners on right image
Description	Find corners in stereo ims of a calibration checkerboard.

File: computeCameraCalibration

Function	computeCameraCalibration
Input	* leftImsDir: left image directory * rightImsDir: right image directory * camCalFile: camera calibration file * sterCalFile: stereo calibration file * rectCalFile: stereo rectification file
Return	Save camera calibration file and stereo calibration file
Description	* read in left and right calibration images * perform calibration on left/right cameras individually * perform stereo calibration * perform stereo rectification * save results to files

File: ICP

Function	findTransform
Input	* A: point cloud 1 (points ordered so that pt 1 in A matches pt 1 in B) * B: point cloud 2
Return	* R: rotation between A and B * t: translation between A and B
Description	Find the rotation between 2 point clouds A and B with point correspondences such that: R*A + t = B

Function	quatToRotM (see Bundle Adjustment)

Function	stabilizePoints
Input	* points3D: list of 3D point cloud found in each frame * T: T[i] is the transform from frame i's cooridnate to frame (i-1)'s coordinates. T[0]*T[1]*...T[i]*points3D[i] transforms points3D[i] into the first frame's coordinates
Return	* points3D from all frames transformed into first frame's coordinates
Description	Read in 3D point clouds from video frame and frame-to-frame transforms. Apply frame-to-frame transform iteratively to transform each point cloud into the first frame's coordinates

Function	rotatePoints (see Bundle Adjustment)

File: loadCheckerBoard

Function	loadCheckerboard
Input	* num: which checkerboard being used. Parameters can be saved for multiple physical checkerboards * num_ims: number of calibration images
Return	* objectPoints: the 3D coordinates of internal checkerboard corners in world cooridnates
Description	Create calibration points for checkerboard in "world" coordinates

File: loadParams

Function	LoadCamCal
Input	* filename: camera calibration filename
Return	* foundL: boolean array, true for left calibration images where checkerboard was found * rvecsL: vector of camera rotation vectors with respect to checkerboards in left calibration images * tvecsL: vector of camera translation vectors with respect to checkerboards in left calibration images * foundR: boolean array, true for right calibration images where checkerboard was found * rvecsR: vector of camera rotation vectors with respect to checkerboards in right calibration images * tvecsR: vector of camera translation vectors with respect to checkerboards in right calibration images * image_list: list of calibration image names
Description	load camera calibration results

Function	LoadSterCal
Input	* filename: stereo calibration filename
Return	* retval: RMS reprojection error (for a good calibration it should be ~ 0.1-1 pixels)

	* cameraMatrixL: projection matrix for left camera. = [f_x 0 c_x; o f_y c_y; 0 0 1]. f_x, f_y: x/y focal length. (c_x, c_y): principle pt (center of image). * distCoeffsL: distortion coefficients of left camera, (k1, k2, p1, p2, k3, k4, k5, k6) k's: radial distortion, p's: tangential distortion * cameraMatrixR: projection matrix for right camera * distCoeffsR: distortion coefficients for right camera R: rotation matrix btwn 1st and 2nd image (L and R image) T: translation btwn L & R camera coordinate systems E: essential matrix F: fundamental matrix
Description	Load stereo calibration results

File: readInCalIms

Function	readInCalIms
Input	* left_dir: folder containing left images * right_dir: folder containing right images * output: file where results & debugging info are saved
Return	* left_ims: list with left calibration images * right_ims: list with right calibration images * image_list: list of calibration image names
Description	read in images for stereo calibration from left_im_folder and right_im_folder

File: triangulate

Function	triangulate
Input	* camCalFile: camera calibration filename * sterCalFile: stereo calibration filename * pointsL: feature positions (in pixels) in left image * pointsR: feature positions (in pixels) in right image
Return	* worldPoints: feature points in 3D camera coordinates
Description	Given feature position in left and right image, find point position in 3D camera coordinates.

Function	formA
Input	* pointL: feature position (in pixels) in left image * projL: projection matrix for left image * pointR: feature position (in pixels) in right image

	* projR: projection matrix for right image
Return	* A: [4x3] matrix, will be used to triangulate 3D point position
Description	Given points in left and right images and left and right projection matrices, form matrix A to be used for triangulation.

Function	formB
Input	* pointL: feature position (in pixels) in left image * projL: projection matrix for left image * pointR: feature position (in pixels) in right image * projR: projection matrix for right image
Return	* b: [4x1] vector, will be used to triangulate 3D point position
Description	Given points in left and right images and left and right projection matrices, form matrix b to be used for triangulation.

File: undistortStereoIms

Function	undistortStereoIms
Input	* sterCalFile: stereo calibration filename * imageL: left image with lense distortion * imageR: right image with lense distortion
Return	* undistortL: left image with lense distortion removed * undistortR: right image with lense distortion removed
Description	Given camera calibration parameters, remove lense distortion.

File: computeCameraMovement

Function	computeCameraMovement
Input	* capLeft: left video * capRight: right video * HistInfo: list of color marker histogram info. For each type of color marker the list has [color marker histogram, number of Gaussian Mixture Model modes, probability image channel for detections, histogram string key, (if tool min blob detection area, max blob detection area)]. * camCalFile: camera calibration file * sterCalFile: stereo calibration file * outputFile: text file to write program info to * trialName: experiment name * outL: left output video

	* outR: right output video * template_L: background marker template for left video * template_points_L: center of background markers in left template image * template_R: background marker template for right video * template_points_R: center of background markers in right template image
Return	* marker_points3D: list of 3D background points in each video frame * tool_points3D: list of 3D tool points in each video frame * frameTransform: 4x4 homogeneous transform from each frame to the first frame
Description	* read in calibration files * take in left and right videos * detect color markers, match in left and right frames * triangulate a 3D feature point cloud for each frame * estimate the 3D transform between each frame

Function	triangulate_marker_points
Input	* frameL: left image * frameR: right image * HistInfo: color histogram info for each color marker * camCalFile: camera calibration file * sterCalFile: stereo calibration file * outputFile: text file to write program info to * trialName: experiment name * outL: left output video * outR: right output video * template_L: background marker template for left video * template_points_L: center of background markers in left template image * template_R: background marker template for right video * template_points_R: center of background markers in right template image * frameCount: current frame number * prevMarkerParams: the rotation and translation of the background markers in the previous frame
Return	* marker_points: 3D background marker positions * tool_points: 3D tool marker positions * bestMarkerMatchParams: the best rotation and translation of the background markers in the left and right frames * marker_matches: background marker points in the left and right frames

Description	* read in left and right images * compute marker probability images for each different kind of marker * match background marker to template * detect centers of other markers * return 3D locations of markers

Function	saveVideo
Input	* name: video name * points: list of 3D points
Return	Saves a video
Description	Takes in a sequence of 3D point clouds, saves each points cloud as a frame in the video.

Function	saveVideoMarkersAndTools
Input	* name: video name * marker_points: list of 3D background marker points * tool_points: list of 3D tool marker points
Return	Saves a video
Description	Takes in a 3D point clouds of marker and tool points, saves animation of 3D points.

Function	updatePoints
Input	* count: frame count * marker_points: 3D background marker points * tool_points: 3D tool marker points * lines: function animation * fig: figure to draw on * boundaries: x, y, z axis limits
Return	Write image to animation
Description	Helper function to update points in video being saved with marker and tool 3D points

Function	updatePoints1PtCloud
Input	* count: frame count * points: 3D marker points

	* lines: function animation * fig: figure to draw on * boundaries: x, y, z axis limits
Return	Write image to animation
Description	Helper function to update points in video being saved with one point cloud

File: dist

Function	dist (see Bundle Adjustment)

Folder: src/Color Marker Detection

File: blobDetector

Function	MSERBlobDetector
Input	* image: probability image * min_area: minimum marker blob area * max_area: maximum marker blob area
Return	* keypoints: blob keypoints
Description	Find blobs in input image.

Function	MSERBlobDetectorDebugging
Input	* image: probability image * key: string indicating "tool" or "marker"
Return	* keypoints: blob keypoints * points: center of blob locations in image * blobImage: image with detected blobs drawn on image
Description	Find blobs in input image. (same as MSERBlobDetector but with slightly different arguments)

Function	pruneKeypoints
Input	* keypoints: keypoints
Return	* good_keypoints: pruned keypoints, require at distance of at least 2 pixels between keypoints
Description	Get one keypoint at each location (ignore multiple detections)

File: blobMatch

Function	BlobMatch

Input	* frame1: image 1 * frame2: image 2 * HistInfo: list of color marker histogram info. For each type of color marker the list has [color marker histogram, number of Gaussian Mixture Model modes, probability image channel for detections, histogram string key, (if tool min blob detection area, max blob detection area)]. * frameNum: frame number
Return	* matches1: array of feature point locations in image 1 * matches2: corresponding array of feature point locations in image 2 * kp1: array of keypoints in image 1 * kp2: corresponding array of keypoints in image 2
Description	Given 2 images, find blobs, match between the images.

Function	findMatches
Input	* points1: feature points in frame 1 * points2: feature points in frame 2 * d: max distance allowed between matching feature point locations in 2 images
Return	* matches1: array with points in points1 st F*points1 - points2 < d * matches2: array with points in points2 st F*points2 - points2 < d * matchKp1: array of keypoints in image 1 * matchKp2: corresponding array of keypoints in image 2
Description	Match marker feature points between left and right images.

File: createMarkerHistFile

Function	createMarkerHistFile
Input	* Folder_Name: experiment folder name * background_Hist: color histogram for background markers * tool_Hist: color histogram for tool markers * N_m: number of Gaussian mixture model modes for the background marker probability * N_t: number of Gaussian mixture model modes for the tool marker probability
Return	* N_m_select: channel of background probability image with background marker detections * N_t_select: channel of tool probability image with tool marker detections

Description	Let the user pick which probability image channel gives good color marker detections.

File: greedyMatch

Function	greedyMatch
Input	* points1: first point cloud * points2: second point cloud
Return	* ordered_points1: points in first point cloud orders so ordered_points1[i] matches with ordered_points2[i] * ordered_points2: points in second point cloud orders so ordered_points1[i] matches with ordered_points2[i]
Description	Given 2 unordered sets of corresponding points, find matches using greedy search.

File: markerHistogramExtractor

Function	markerHistogramExtractor
Input	* image dir: directory where reference marker images are * mask dir: directory where binary marker masks are
Return	* H_hist: histogram in Hue space * S_hist: histogram in Saturation space
Description	Given images, binary masks for the markers compute a color histogram for the color marker.

Function	ComputeGaussMixModel
Input	* N: int, number of clusters * Hist: histogram computed with np.histogram2d
Return	* em: Gaussian mixture model
Description	Given a histogram, compute a Gaussian Mixture Model with N clusters.

Function	ComputeMarkerProb
Input	* image_dir: directory where images live * GMM: GaussMixModel with prob pixel val in H&S was a marker * N: number of modes in GMM

	* val_thresh: min value required to be considered to be a marker, needed for blue markers because low val, blue areas are often shadows
Return	* probIm: binary image, white pixel = high marker prob
Description	Given images, hue and saturation histograms of markers, compute the the probability of each pixel in images of being a marker.

Function	markerMatch
Input	* image: binary probability image, white pixels = high marker prob * templateIm: binary image with ground truth indv marker positions. The marker is rigid so the relative pos of indv markers is constant * templatePts: pixel locations of centers of indv markers in markerIm * prevEst: boolean flag, are there previous match parameters? * prevParams: translation and rotation of marker match in previous frame
Return	* imagePts: pixel locations of centers of indv markers in image * params: translation and rotation of marker match
Description	Match a marker template image to a marker probability image. Return location of all marker keypoints. Check possible marker translations and rotations.

Function	RotatePoints2D
Input	* points: array of 2D points * R: 2D rotation * t: 2D translation
Return	* worldPoints: transformed points
Description	Transform 2D points

Folder: src/Frequency Analysis

File: buildTrajectory

Function	BuildTrajectory
Input	* list of 3D point clouds in video frames
Return	* list of position trajectories

Description	Take in cloud of 3D points for video frame, associate points across frames to generate trajectories.

Function	PruneTraj
Input	* traj: list of trajectories
Return	* longTraj: list of long trajectories
Description	Only save trajectories with len> MIN_LEN.

Function	buildXYZ_Trajectories
Input	* trajectory: trajectory of 3D points
Return	* x_traj: trajectory of x coordinates * y_traj: trajectory of y coordinates * z_traj: trajectory of z coordinates
Description	Take trajectories of 3D points and seperate into list of x, y, and z coordinates.

Function	LinkToolTrajs
Input	* trajectories: list of absolute trajectories
Return	* linked_traj: long trajectory with relative positions from all trajectories
Description	Given short, absolute trajectories, link into 1 continuous trajectory by subtracting the translational offset between traj_n-1[last] and traj_n[first].

Function	frequencyAnalysis
Input	* function: signal to take DFT of * FsBy2: sampling frequency / 2
Return	* f_tremor: the DFT magnitude of function in tremor range
Description	Given a function and a sampling frequency, take the DFT, convert to angle and magnitude representation, high pass filter to see tremor, compare 3D trajectory with and without tremor.

Function	FilterTremor
Input	* w: array with frequency corresponding to each element in f (Hz) * f: frequency component magnitudes
Return	* f: f filtered so components above tremor threshold are 0 * w: w (same as before)

Description	Given trajectory frequency analysis results, find the frequency components magnitude in the tremor region.

Function	ComparePaths
Input	* f: frequency component magnitudes * tremor_thresh: tremor threshold (Hz) * w: array with frequency corresponding to each element in f (Hz)
Return	* plot 3D trajectories
Description	Given a DFT and a tremor threshold plot the path with tremor and the path without.

Function	InverseToPath
Input	* fx: DFT(x(t)) * fy: DFT(y(t)) * fz: DFT(z(t))
Return	* path: 3D path in time
Description	Given a DFT, find the path in world coordinates.

Function	ConvertDFT
Input	* f: DFT in OpenCV format * N: length of original signal * FsBy2: sampling frequency / 2
Return	* f_mag: magnitude of frequency response at each frequency * f_ang: angle of frequency response at each frequency * w: array with frequency corresponding to each element in f (Hz)
Description	Convert DFT from OpenCV format to magnitude and angle.

Function	RunFrequencyAnalysis
Input	* tool_points3D: 3D trajectory
Return	* tool_x_linked: magnitude of frequency response of x(t) from linked trajectories (see linkToolTraj) * tool_y_linked: magnitude of frequency response of y(t) from linked trajectories (see linkToolTraj) * tool_z_linked: magnitude of frequency response of z(t) from linked trajectories (see linkToolTraj) * Fs/2: sampling frequency / 2
Description	Call this function to run the frequency analysis on a set of 3D points.

Function	CompareRobotAndManual

Input	*None, manually change experiment name*
Return	* Plots hand-held and robot-held tool tracking results side by side
Description	Plot hand-held and robot-held tool tracking results side by side.

Function	beforeAfterMotionCompensation
Input	*None*
Return	Plots tracking results with and without camera motion compensation side by side.
Description	Plot tracking results with and without camera motion compensation side by side.