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Experimental Evaluation of Contact-Less Hand Tracking Systems for Tele-Operation of Surgical Tasks

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***Abstract*— This paper reports an evaluation of contact-less hand tracking sensors for the use of tele-operation, in particular for surgical robotics applications. Two hand tracking systems are investigated: 3Gear Systems interface with the Microsoft Kinect™sensor, and the Leap Motion sensor system. This paper reports an experimental evaluation and comparison of the two systems range, static positioning error, trajectory accuracy of single finger and hand motions, and latency. Latency and trajectory accuracy were found superior using the Leap system. Kinect™/3Gear was found superior when larger range and gesture control are necessary. 3Gear was used in a simulated surgical positioning task and demonstrated an average translational accuracy of 6.2mm. Given the data we have collected, we conclude that neither system, at present, possesses the high level of accuracy and robustness over the required range that would be a prerequisite for use as a medical robotics master.**

I. Introduction

There are three major limitations prevalent in current master controllers for surgical robots: 1) their large footprint; 2) they are not sterilizable, preventing smooth transition between manual and robotic operation; 3) the mechanical linkage limits range of motion and can be cumbersome to use. As contact-less hand tracking sensors have the potential to remove these shortcomings, this paper seeks to perform evaluation of hand tracking systems for use as masters in medical robotics. In particular, this paper reports an experimental evaluation and comparison for two new promising hand tracking systems: The Microsoft Kinect™sensor (Microsoft Corporation, Redmond, WA) equipped with the 3Gear Systems[1] (3Gear Systems Inc., San Francisco, CA) environment for hand pose detection and tracking, and the Leap Motion Controller[2] (Leap Motion, San Francisco, CA) with its native finger tracking software. Effective sensor range, static positioning error, and trajectory accuracy of finger and hand motions, and latency are reported for both systems. These variables were chosen based on their relevance in functioning as a surgical robotic master. The 3Gear hand tracking system was further evaluated in a simulated surgical laparoscopic positioning task.

A. Prior Art

The current state of the art in surgical robotics is based on a master-slave control paradigm, best represented by the da Vinci™ robot (Intuitive Surgical Inc, Sunnyvale, CA) [1]. The da Vinci™ robot is used for a wide range of surgical procedures including urology, gynecology, cardiothoracic, and general surgery. MiroSurge is another general-purpose medical robotic system developed at the Institute of Robotics and Mechatronics, German Aerospace Centre (DLR) [2]. Another master-slave system is the Raven surgical robot developed at the University of Washington [3]. These medical robots (slaves) are controlled directly by the surgeon operating a master console.

For medical robotics to continue to evolve and gain acceptance in more applications, developers should continue to explore promising novel technologies to adapt and integrate into medical platforms. Among these, hand tracking as master control is especially appealing for medical robotic application because its contact-free operation allows for interaction without compromising sterility and its smaller footprint could allow the surgeon to use the robot at the patients bedside.

Kinect was originally designed for whole-body tracking for indoor gaming applications, but over time researchers have attempted to use the Microsoft Kinect™ for general robotic and virtual reality control [4], [5] and the sensor specifications of the Kinect™ have been analyzed by several authors. Khoshelham [6] characterizes depth data and shows that error in measured depth increases with increasing distance to the sensor from a few millimeters to a few centimeters over the range of the sensor. Dutta [7] reports root-mean-squared errors in coordinate measurements to be 6.5 mm and 5.7 mm in planes perpendicular to the view axis and 10.9 mm along the view axis (depth). Kvalbein [8] also analyzes depth and planar accuracy.

The Kinect™ has been used in several robotic applications including Human-Robot-Interaction (HRI) interface design. In the majority of the Kinect™ -based HRI literature, the whole-body human skeleton is tracked using the OpenNI[3] and Microsoft Kinect[4] Software Development Kits (SDK) (e.g. Perez *et al.* [9] for a recent HRI interface based on Kinect™). Instead of tracking whole-body motion, an ideal contact-less interface in an operating room (OR) would require minimal gross motions, utilizing fine motions and gestures to perform the necessary task. Hand tracking appears to fit these criteria. Researchers have previously used the Kinect™ sensor to implement hand tracking [4],

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[1]http://www.threegear.com/

[2]https://www.leapmotion.com/

[3]http://www.openni.org/

[4]http://www.microsoft.com/en-us/kinectforwindows/develop/overview.aspx

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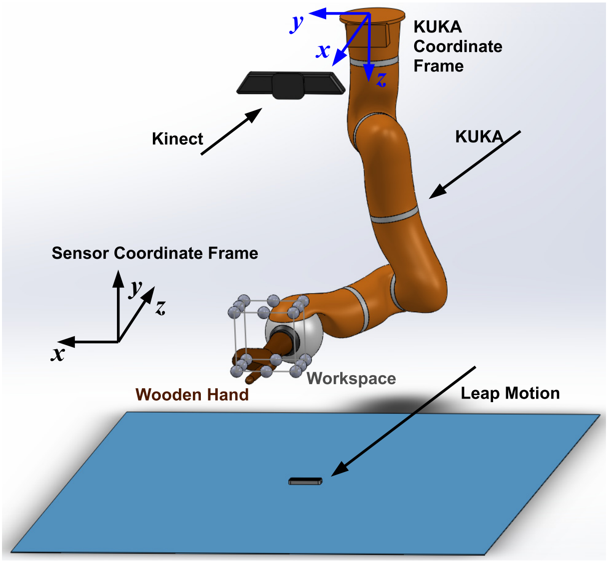

Fig. 1. Schematic drawing of the setup for accuracy evaluation.

and hand gesture tracking (e.g. Ren *et al.* [10] and Oikonomidis *et al.* [11]).

This paper reports an evaluation of two promising new hand tracking systems for potential use in medical robotics: the 3Gear System and the Leap Motion. 3Gear System is a hand and gesture tracking system developed by 3Gear Systems, using the Kinect^{TM} as depth camera. The Leap is a new sensor developed by Leap Motion, Inc. with finger and hand tracking available natively.

This paper provides the research and development community with preliminary data to assist in incorporating these and similar hand-based motion controllers into their robotic applications.

II. Methods

A. Robotic Testbed

In order to test the positional consistency and accuracy of the sensor systems, an artificial hand was used rather than a human hand to produce precise motions and trajectories. A wooden right hand mannequin (CW301, Alvin and Co, Windsor, CT) was mounted onto a KUKA lightweight robot (LWR) (KUKA AG, Augsburg, Germany). The KUKA LWR robots manual lists a positional repeatability of $\pm 0.05\ mm$, and its base frame coordinates were used as the standard reference for the two systems' movement data. A nitrile glove was placed on the wooden hand to emulate a surgeons hand and to remove error caused by shape difference between the wooden and human hand. The hand was mounted onto the robot so that the back of the hand would face the active sensor. This was done because an increase in noise was observed due to the shape of the wooden hand on the front side, particularly a steep angle in the distal finger joint. The flatter backside of the wooden hand allowed for cleaner sensor data approximating a human hand. The hand was fixed into a pointing pose (see Figure 2) for all tests because both systems had difficulty detecting the fingers that were tightly

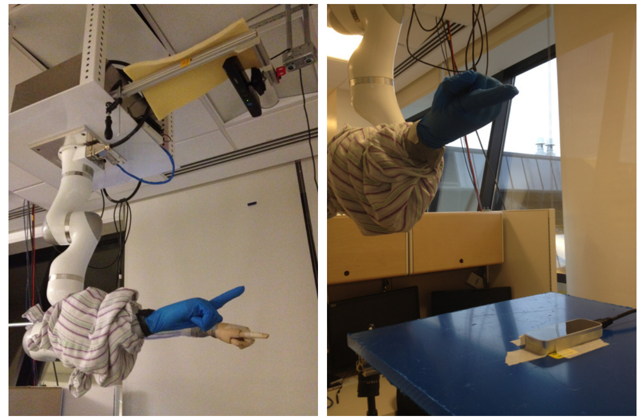

Fig. 2. Photo of the experimental setup showing KUKA arm with the hand and arm sleeve. (Left) Kinect^{TM} sensor equipped with the 3Gear Systems software. (Right) Leap Motion sensor secured to the table.

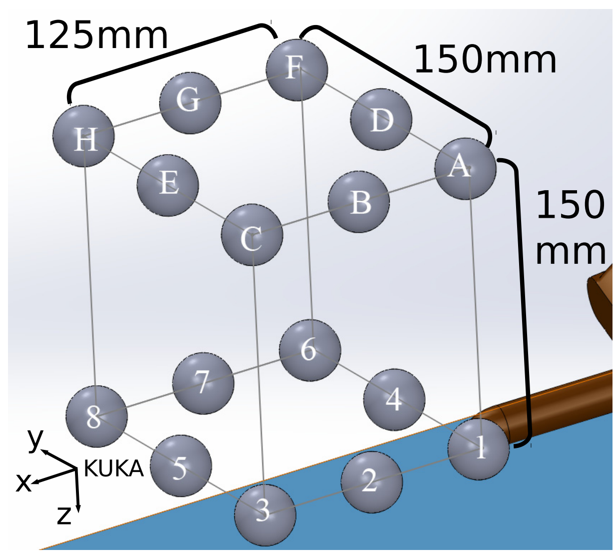

Fig. 3. Drawing of end points of trajectories in the workspace.

spaced when extended. A wooden left hand was mounted in the field of view for the tests using 3Gear because the 3Gear systems recommended usage is with two hands.

Figure 1 shows a schematic drawing of the general test setup and depicts the orientation of the sensors in respect to the KUKA. Figure 2 shows the experimental setup. For the tests, the robot was programmed to move linearly between points in the cubical workspace shown in Figure 3. The cube's sides are formed by axial translations by the KUKA between the Cartesian values described in Table I, and the length of the sides are $125mm \times 150mm \times 150mm$. Points 1-3/A-C were placed to approximately line up with the central YZ-plane of the sensors, and points 4-8/D-H occupied the operators right side of the sensors. Assuming that the sensors' performances are approximately symmetrical across their YZ-plane, the size of the evaluated area would be about $125mm \times 300mm \times 150mm$, making it approximately half of the da Vinci^{TM} master's maximum range (measured to be approximately $250mm \times 650mm \times 300mm$). The Leap

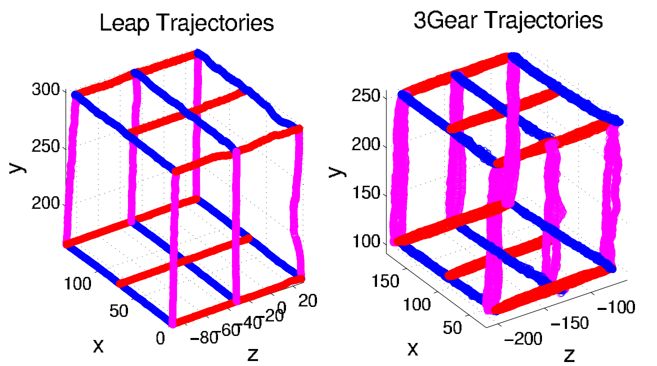

Fig. 4. 3D plots of axial trajectories measured by Leap and 3Gear.

KUKA frame	x_{min}	x_{max}	y_{min}	y_{max}	z_{min}	z_{max}
3Gear	400	525	100	250	550	700
Leap	450	575	100	250	700	850

TABLE I
THE LOCATIONS OF THE AXIAL AND DIAGONAL TRAJECTORY ENDPOINTS IN KUKA COORDINATE FRAME.

was placed approximately 17.5cm below point 2, and the Kinect™ was mounted approximately 67cm above point 2.

B. Contact-less Hand Tracking Systems

The Leap Motion Controller hardware tested in these experiments was the developer's version v.06.5 with software v0.7.4. The Leap API implements a listener class that receives a frame containing the positions and orientation of all pointers and hands detected by the Leap. This is a pre-release hardware and software for developers. The 3Gear system was tested using a single Kinect™ for Windows sensor with the 3Gear software version v0.9.21, also a pre-release. The 3Gear API analyzes each frame of the Kinect™ and constructs multiple messages with different sets of data that consist of joint frame, position, and orientation of fingers and hands. The API then sequentially receives these messages through a listener class. Both the Leap and the 3Gear system return pointer and hand objects, where a pointer contains the 3D position, yaw, and pitch of the tip of the index finger (and any other elongated object in the field for the Leap), and the hand contains the 3D position, yaw, pitch, and roll of the palm or back of the hand. Thus, fingers are tracked with 5 DOF, and hands are tracked with 6 DOF. To collect data, we developed recording programs to store every frame received from the listener class, and the data was later extracted for analysis using MATLAB (Mathworks, Natick, MA). The 3Gear system required calibration before usage. A calibration pattern[5] was placed approximately 2.5 feet below the Kinect™ to follow the recommended setup. For use with the robotic system, human hands were used for shape calibration, as the wooden mannequins fingers could not be spread as needed. After shape calibration, finger scale parameters were found in the calibration files and proportionally modified to reflect the longer fingers of the manikins. The mannequin was then shaped into the 6 poses utilized by the 3Gear system (pinch, OK, handshake, microphone, L, and pointing) to calibrate the poses. Through all tests, only one sensor was active in the field to prevent interference. We tested both systems for a number of criteria that motion-control systems should fulfill to be acceptable for use as a medical robot master.

[5] `http://www.threegear.com/latest/doc/4x5-1.5.pdf`

C. Sensor Range

The larger the field of view or range of a sensor, the easier a system can track hand movements made during surgery without the need for clutching. The operating range for both systems was experimentally estimated by moving the hands slowly towards the edge of the sensors' range until the data showed either: 1) a quick, significant, persistent change in orientation; 2) visibly significant increase in frequency and amplitude of noise; or 3) complete or frequent loss of hand tracking. The angular ranges of both systems were also estimated by slowly rotating a hand at the center of the workspace using yaw, pitch, and roll motions until the system visibly ceased to track the orientation correctly.

D. Static Position Error

Medical robot masters should have as little noise interfering with its operation as possible to prevent the slave from executing an involuntary motion and to reduce the need for filtering that may reduce the responsiveness of the system. In order to test the noise produced by the sensor in absence of movement, the wooden hand was held by the robot at point 2, in the middle of the sensors' range, and the sensor data was collected for ten seconds. To test the practical resolution of the systems, the robot was moved from point 2 incrementally +1 mm in each axial direction and the recording program stored all incoming data at each point for 10 seconds in order to measure static position error. The recorded point cloud at eleven static positions was recorded with each sensor. Standard deviations of the static position errors in x, y, and z were calculated for hand and pointer position for the eleven positions for both sensors.

E. Trajectory Error

A human operator is able to correct for small distance errors and scaling that may be present in a robotic system using visual feedback. Therefore, rather than precise displacement accuracy, motion trajectory tracking and consistency is more important as it provides the surgeon with intuitive control of the robot. To test if the displacement and trajectory sensing would hold through movements in different areas of the workspace, the robot was used to move the hand linearly, while maintaining a single rotational frame, through 18 axial trajectories as shown in Figure 4. Each trajectory was traveled 5 times back and forth at a speed of 0.02m/s. Positional errors were calculated for the movements in form of absolute distance between end points and in deviation of points to the line through endpoints. The positional errors were calculated for pointer and hand positions for both sensors.

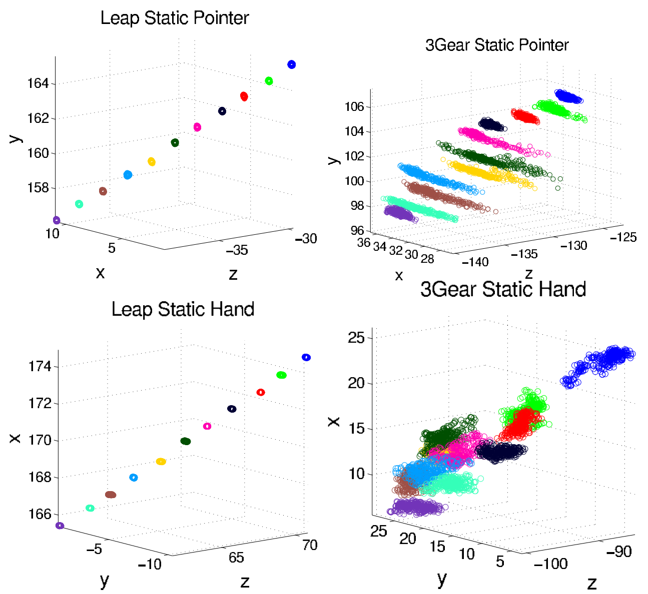

Fig. 5. 3D plots of eleven static point clouds along a diagonal. The top most point cloud was gathered at point 2 according to Figure 3. Each subsequent point cloud was gathered at +1mm x +1mm x +1mm in KUKA coordinates away from the previous point.

F. Latency

Latency is an important factor for surgical robotics, since surgeons need to react quickly, in particular to targets that are often mobile in a moving, breathing patient. The latencies for both systems were experimentally measured. The recording program stored a computer timestamp along with each frame and message as it recorded a finger clicking on a mouse button that was oriented perpendicularly to the sensor's z-axis. The cursor of the mouse was placed over a Qt-framework QPushButton[6] that would store the computer timestamp on button release. We estimated latency by analyzing the delay between the click timestamp and the frame where movement away from the mouse is detected. The pointer z-value of each frame was plotted against time, and a line was fitted into points before and after each mouse-click timestamp. The timestamp of the frame/message that was closest to the intersection of the two lines was chosen as the response time.

G. Surgical Positioning Task

Four trained surgeons from Childrens National Medical Center operated a robotic simulation using the 3Gear Kinect system to further investigate the capabilities and potentials of the 3Gear Kinect control system in medical robotics. 3Gear was selected over Leap for this test due to its larger range and gesture control capabilities.

The simulation was designed in Robot Operating System (ROS)[7]. Figure 6 on the left displays the simulated robot, which is modeled after an experimental laparoscopic surgical robot used at Childrens National Medical Center [12]. It consists of a KUKA LWR robot arm and a custom designed articulated stapling tool. The simulated robot has nine DOF in total, seven in the KUKA LWR arm and two additional +/- 90 degrees rotational DOF in the tool. The tip of the tool consists of a pinching mechanism, a needle driver, and a stapling mechanism. The robot was situated as if mounted to an operating table over a patient. The 3Gear Kinect control system was used to track the surgeons right hand and move the robot simulation accordingly in translation and rotation. Additionally, the tool was constrained to a remote center of motion (RCM) representing a laparoscopic entry port. The surgeons were asked to place staples at random locations within the workspace of the robot. A target, a translucent copy of the end piece of the robot tool encased in a translucent orange cylinder, was displayed in the simulation. The surgeons goal was to manipulate the robot so that the end piece of the robot aligned with the target in translation and rotation. Once the surgeon was satisfied with the positioning, they pressed a foot pedal, imitating placement of a staple. Once the foot pedal was pressed, a new target would appear. The surgeon then tried to align the robot with the new target. The experiment consisted of thirteen targets, the first three for practice, and the following ten to be recorded to measure accuracy and time needed to reach each target. Figure 6 on the right displays the tool tip and shows the accuracy measurements for the experiment. Each time the foot pedal was pressed the transformation matrix of the robot tool tip to the target tool tip was recorded. The magnitude of the vector from the robot tool tip to the target tool tip is the translational error. Roll, pitch, and yaw angles were determined from the rotational matrix of the recorded transformation matrix according to Figure 6.

III. Experimental Results

Experiments were designed to assess contact-less motion control of surgical robots. The criteria that we consider important for such a system include range of motion and accurate 6 degrees-of-freedom (DOF) tracking to control a surgical tool as a master. The accuracy and precision of positioning is particulary important because of the fine-motion requirements of surgical tools and the potential harm surgical robots can inflict.

Since the surgeon must be able to respond quickly to the changing surgical environment, we also consider low latencies to be necessary. In this section, we report performance results of the two sensor systems under these criteria.

A. Range Results

The approximate effective work space of Leap and 3Gear are depicted in Figure 7. Table II lists the approximate XZ ranges at the lower, maximum, and upper Y values, where the maximum corresponds to the height with greatest XZ range. The angular ranges in the center of the workspace are shown in Table III. Assessing the effective working range, the 3Gear system had a significantly larger work volume with a maximum XZ range of 780mm $\times$700mm with a Y range of 900mm, compared to the maximum XZ range of 350mm $\times$270mm with Y range of 275mm for Leap. The

[6] http://qt-project.org/
[7] http://wiki.ros.org/rviz

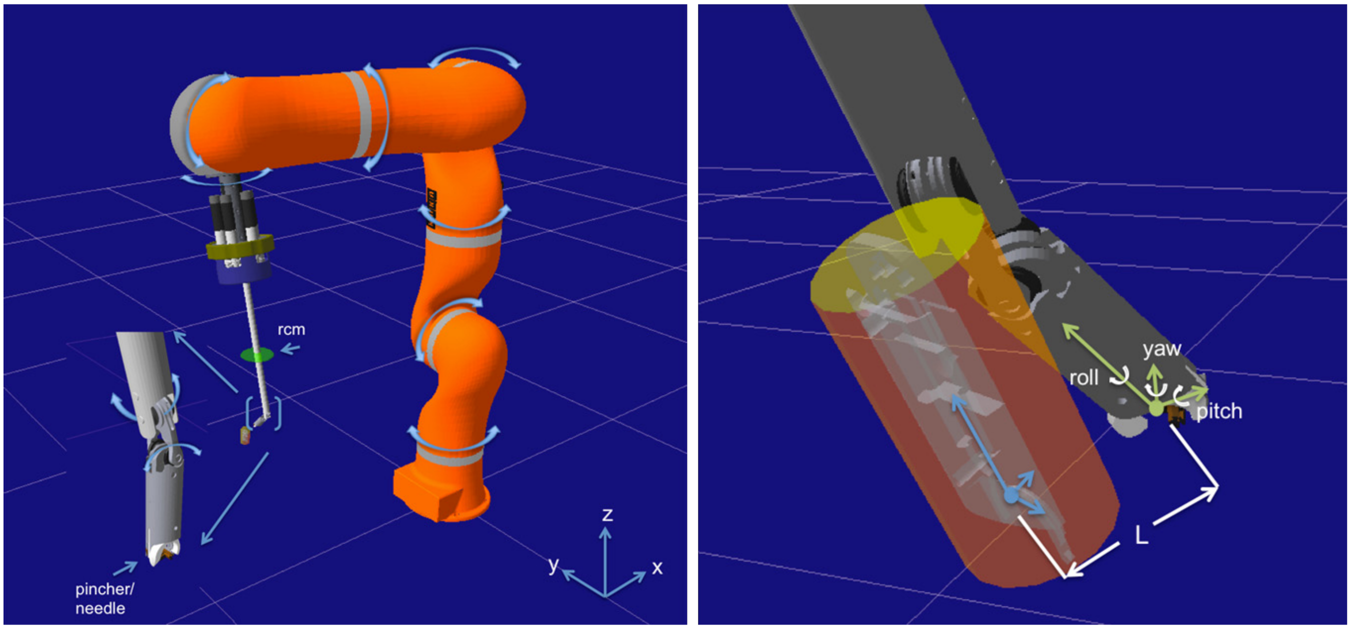

Fig. 6. Screenshots of the rviz simulation program: Picture of the simulated robot (left) for the surgical positioning task. Picture displaying the tool tip with error measurements (right).

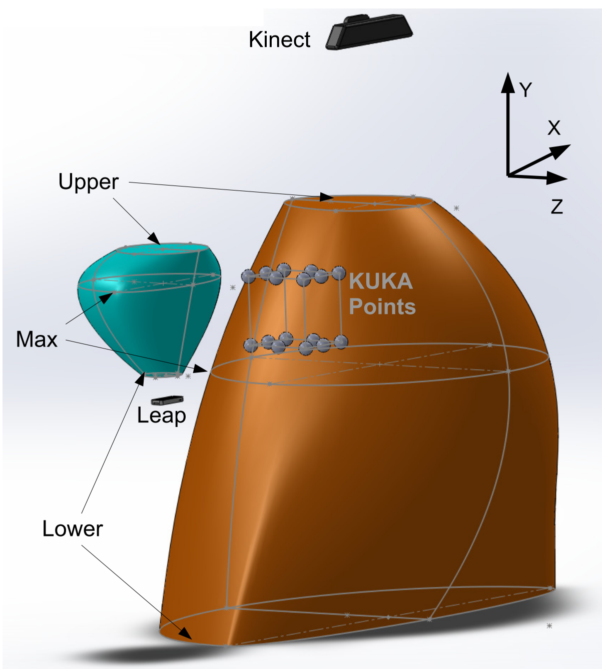

Fig. 7. Approximate effective workspace ranges of 3Gear and Leap.

3Gear system also had a larger overall angular range, having a smaller pitch range of ±40 compared to Leap's pitch range of ±50, but having a larger yaw and roll ranges of ±60 each over Leap's yaw and roll ranges of ±40 each. In addition, the Leap was unable to differentiate between the palm and the back of the hand, while the 3Gear system was able to do so, effectively doubling 3Gear's unique roll measurement range while the Leap does not.

B. Static Position Results

Figure 5 shows a 3D plot of the hand and pointer coordinates measured by 3Gear and Leap for eleven consecutive static points along a diagonal.

Table IV lists the average XYZ standard deviations for each system. The standard deviations of Leap's static data were significantly lower than 3Gear's, with Leap's axial standard deviations ranging from 0.01mm to 0.04mm compared to 3Gear's axial standard deviations that range from 0.35mm to 1.66mm. The elongated nature of 3Gear's point cloud was most likely caused by 3Gear's hand tracking algorithm rapidly switching between extending and flexing the non-pointer fingers when the hand was still, causing the measured index finger and hand position to shift back and forth erroneously. To test this, ellipsoids were fitted into 3Gear's point clouds, and the average of their major axis vectors was found to be only 3.2 degrees different from the direction vector of the pointer, supporting this theory.

		Y [mm]	X Range [mm]	Z Range [mm]
Leap	Y_{lower}	50	80	90
	Y_{max}	250	350	270
	Y_{upper}	325	200	200
3Gear	Y_{lower}	-550	1150	552
	Y_{max}	0	780	700
	Y_{upper}	350	275	343

TABLE II

APPROXIMATE XZ RANGES AT DIFFERENT Y VALUES (HEIGHT) FOR LEAP AND 3GEAR. Y_{max} IS THE Y VALUE WITH THE LARGEST XZ RANGES.

C. Linear Translation Results

The point clouds generated by each motion were inspected, and the points corresponding to the pauses in the robots movements at each endpoint were identified. The averages of these endpoint sets were used to construct a line that represents the ideal linear trajectory between the measured endpoints. The deviation of the non-endpoint sets of each axial trajectory for the large movements are plotted in Figure 8. The linear trajectories are labeled according to their respective endpoints according to Figure 3. For example, a trajectory along the X axis from point A to point 2 is called x_{A1}. The analysis data for combined axial movements are listed in Table V. Both systems' deviations varied significantly depending on the location of the trajectory in the workspace. In most trajectories, the 3Gear system had greater deviations than Leap for both pointers and hands, with 3Gear's mean deviations ranging from 2.2mm to 4.8mm, while Leap's mean deviations ranged from 0.37mm to 2.76mm. However, Leap's hand deviation showed much greater outliers in certain trajectories, going as high as 455.2mm, compared to the 3Gear's maximum of 22.2mm. Leap's pointer tracking did not have this problem, as its maximum deviation was only 6.7mm compared to 3Gear pointer's maximum deviation of 17.1mm. This was likely caused by the fact that the trajectories got too close to the edge of the effective workspace ranges of the Leap hand-tracking algorithm, as seen by the fact that Leap was not able to track the hand for parts of a few trajectories.

Overall, we measured lower errors in trajectory distance with 3Gear, which had a minimum average distance error of -0.2mm and the maximum distance error of 8.1mm, while the Leap had a minimum distance error of -0.5mm and a maximum distance error of -19.2mm. This suggests that Leap requires calibration to better match its coordinates to real-world distances.

D. Latency Results

Table VI shows the latency measurement results. Leap had a lower latency of 34.9 milliseconds compared to 3Gear's latency of 74.9 milliseconds. Leap also had a much greater frame rate of 111.4 frames per second over 3Gear's 30.0 frames per second.

E. Surgical Positioning Results

Time and accuracy results of the four surgeons performing the surgical positioning task in form of translational and angular positioning errors are displayed in Table VII. The average tanslational error was 6.2mm and angular errors were 8.2, 8.1, and 33.7 degrees for yaw, pitch, and roll respectively. The large errors in roll were most likely due to the difficulty to visually discern the target roll on the screen. The four surgeons needed an average of 50.4 seconds to position the simulated tool per target. Surgeons cited limited training on the system and poor visualization and lack of depth perception as contributors to errors.

IV. Conclusion and Discussion

This paper reported an evaluation of two contact-less hand tracking systems Leap Motion controller and the Kinect-based 3Gear system to assess their potential for use in control of medical robots.

The range of 3Gears allows enough space to make the same motions surgeons would make on the da Vinci's master. 3Gear's long y-axis range also allows mounting of the sensor away from the surgeon, eliminating issues with sterility. The Leap's range was significantly shorter, which also increases the possibility that a surgeon may accidentally touch the device during use. The larger angular range of the 3Gear system also allows for the surgeon to control the pose of the robotic tool more freely compared to Leap.

Leap's static noise for both pointer and hand, measured in the center of the sensor range, was significantly lower than 3Gear's. This could potentially allow for very fine tool position control that would not be possible with 3Gear's system. However, when considering movements further away from the center of the sensor's range, errors increased significantly for both sensors.

Overall, we measured lower errors in trajectory distance with 3Gear compared to Leap, suggesting that Leap requires calibration to better match its coordinates to real-world distances. In terms of deviation away from the trajectory, both systems' deviations varied significantly depending on the location of the trajectory in the workspace. While generally, 3Gear showed larger deviations compared to Leap, Leap's measured hand data had much greater deviations in some specific trajectories compared to any deviations produced by 3Gear.

Angular degrees of freedom are measured more accurately with Leap compared to 3Gears. Finger/pointer are more

Sensor	Yaw	Pitch	Roll
Leap	± 40	± 50	± 40
3Gear	± 60	± 40	± 60

TABLE III

Approximate effective angular ranges of 3Gear and Leap in degrees.

	Pointer			Hand		
Sensor	zstd	xstd	ystd	zstd	xstd	ystd
3Gear	1.66	0.35	0.61	1.06	1.27	0.84
Leap	0.02	0.01	0.03	0.04	0.01	0.01

TABLE IV

Axial standard deviations in mm of the static pointer and hand positions measured by 3Gear and Leap.

Sensor	**Avg. Frame Rate** (fps)	**Avg. Latency** (ms)
Leap	111.4	34.9
3Gear	30.0	74.9

TABLE VI

Frame rate and latency measurements for 3Gear and Leap.

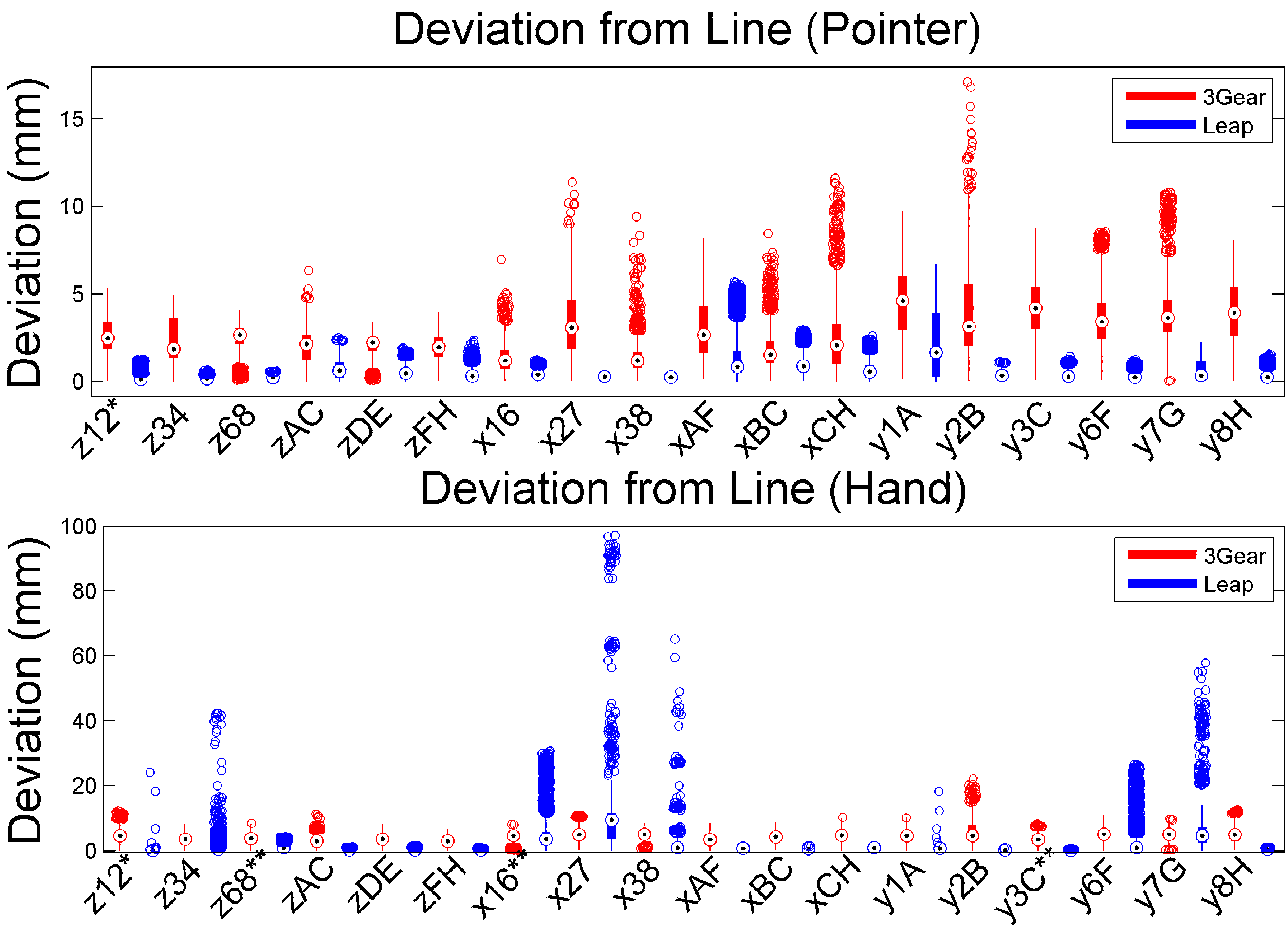

Fig. 8. Box plot of pointer and hand measurement deviation from linear trajectories. *Leap had two outlier deviations of 455.17mm and 225.24mm in $Z_{1,2}$ that are not displayed in the boxplot. **End points could not be obtained for marked Leap trajectories due to hand tracking loss near one of the endpoints.

Direction	Sensor	Pointer				Hand			
		μ	σ	m	d	μ	σ	m	d
z	3Gear	2.24	0.96	6.33	-2.09	3.59	1.73	12.38	-0.43
	Leap	0.38	0.36	2.52	-9.01	0.37	2.85	455.17	-15.02*
x	3Gear	2.24	1.68	11.60	-1.19	4.65	1.77	10.96	8.07
	Leap	0.68	0.75	5.72	-10.31	2.76	7.60	140.29	-0.48*
y	3Gear	3.97	1.94	17.10	-0.16	4.78	2.30	22.17	0.42
	Leap	0.73	1.18	6.67	-16.27	1.36	2.83	57.85	-19.23*

TABLE V

LINEAR TRANSLATION ERRORS FOR AXIAL MOTIONS IN MM FOR POINTER AND HAND. MEAN (μ), STANDARD DEVIATION (σ), AND MAXIMUM (m) DEVIATION FROM LINEAR TRAJECTORY, AS WELL AS ERRORS IN DISTANCE (d) BETWEEN ENDPOINTS ARE SHOWN. *END POINTS COULD NOT BE OBTAINED FOR ONE LEAP TRAJECTORY PER AXIS DUE TO HAND TRACKING LOSS NEAR ONE OF THE ENDPOINTS. THE DEVIATION FOR THESE TRAJECTORIES WERE CALCULATED AGAINST THE LINEAR TRAJECTORY OF THE CORRESPONDING POINTER MEASUREMENTS. THE MARKED DISTANCE BETWEEN END POINTS ARE AVERAGES OF FIVE TRAJECTORIES, AS OPPOSED TO SIX.

accurate compared to hand tracking for position as well as yaw and pitch for both sensors. Since only hand data provides roll, and all 6DOF are necessary for tool control, the best strategy is to use pointer for position control, yaw, and pitch. Hand data should be only used for roll.

The measured frame rate and latency of the Leap was superior to the 3Gear system, which is limited by the Kinect's frame rate of 30 frames per second versus 111 frames per second for the Leap.

While we have not formally compared gesture recognition of both tracking systems for this paper, it was evident when working with both systems, that 3Gear has a distinct advantage over Leap in this area.

3Gear was successfully used in a simulated surgical posi-

Error	Translation [mm]	Yaw [degrees]	Pitch[degrees]	Roll [degrees]	Time [sec]
Surgeon 1 [$Avg \pm Stdv$]	10.0 ± 3.3	12.9 ± 10.2	9.8 ± 7.9	24.3 ± 10.0	49.7 ± 23.9
Surgeon 2 [$Avg \pm Stdv$]	6.6 ± 2.1	5.7 ± 7.5	6.6 ± 3.8	39.0 ± 26.5	32.6 ± 19.9
Surgeon 3 [$Avg \pm Stdv$]	4.1 ± 1.6	4.8 ± 2.8	8.5 ± 3.8	26.5 ± 18.5	19.9 ± 65.3
Surgeon 4 [$Avg \pm Stdv$]	4.1 ± 1.9	9.7 ± 6.6	7.5 ± 6.8	54.1 ± 24.2	53.9 ± 27.0
Average [$Avg \pm Stdv$]	6.2 ± 2.8	8.3 ± 3.7	8.1 ± 1.3	33.7 ± 15.9	50.4 ± 13.5

TABLE VII

TRANSLATIONAL AND ROTATIONAL ERRORS IN SURGICAL POSITIONING TASK

tioning task by four surgeons and demonstrated an average translational accuracy of 6.2mm. Increased amount of training and better depth perception in the visualization would help improve these results.

Given the data we have collected, we conclude that neither system, at present, has the high level of accuracy and robustness over the required range that would be a prerequisite for use as a medical robotics master. However, it should be noted that both of these systems are still in the process of undergoing optimizations and improvements, and we expect the performance of both systems to improve over time. In addition, post-processing of sensory data in form of added filtering and smoothing and down scaling motions could further improve the performance for both systems.

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