A Compliance Model to Improve the Accuracy of the da Vinci Research Kit (dVRK)

Grace Chrysilla, Nickolas Eusman, Anton Deguet, Peter Kazanzides

I. Abstract

The da Vinci surgical robotics system is used for minimally-invasive surgery. Small incisions are made on the patient's body, then the da Vinci instruments are inserted into the incisions. The robot system contains encoders to measure the instrument position and orientation. Unfortunately, its measurement is inaccurate, especially when an external force applies to the instrument shaft. The accuracy of these measurements is influenced by non-kinematics errors, such as bending of the instruments due to force applied to it. We developed a compliance model that correct the displacement of the first two joints of the da Vinci Patient Side Manipulator (PSM). The model compensates displacement errors based on the measured joint efforts which are generated by the measured motor currents. The experiment was performed with the open-source da Vinci Research Kit (dVRK) to estimate the model parameters and to evaluate the accuracy improvement resulted from the application of this model. Using two different experiments to evaluate the accuracy improvement. The first experiment results in 0.75 mm accuracy improvement. The second experiment results in 4.5 degree and 3.5 degree correction for the first and second joint respectively.

II. Introduction

The accuracy of the da Vinci robot is crucial when it is used to construct a 3D image of an organ. The da Vinci instrument holds an ultrasound probe and sweeps along an organ to take images of the organ [1]. The da Vinci system registers the starting and ending positions of the images. Therefore, since the da Vinci system does not register the positions accurately, the 3D construction of the organ will be inaccurate as well.

The research presented in this paper is to develop a compliance model of the da Vinci PSM and to use this model to reduce the error of the instrument tip position. The research is performed with the open-source da Vinci Research Kit (dVRK) which provides a full access to all feedback data from the da Vinci system. Our method utilizes the measured joint positions and joint efforts provided by the dVRK. The compliance model results in improvement in the position accuracy of da Vinci instruments

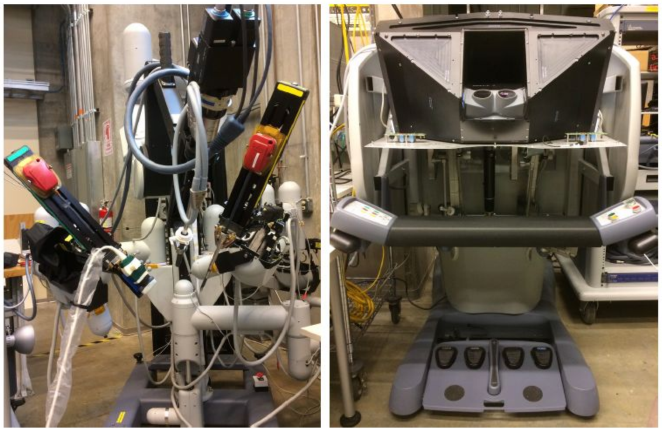


Fig. 1. da Vinci Surgical Robot: patient side robot on left; master console on right.

III. Research Hypothesis

The compliance model that is expected to improve the accuracy of the da Vinci is

$$q_i = q_i - [\delta sgn(T_{meas} - T_0(q_i)) + K(L)(T_{meas} - T_0(q_i))]$$

There are three parameters that influence the accuracy of the da Vinci PSM: compliance of the instrument, torque offset, and backlash. We expect that most instruments with the same diameter will have similar compliance model. Table 1 summarizes the parameters.

TABLE 1
Nomenclature [2]

L	Length, in meters, from remote center of motion (RCM) to contact point on instrument; this corresponds to the position of the third PSM joint.
τ_{meas}	Measured joint torque, in Newton-meters. This is based on the measured motor current, I_{meas}, multiplied by a motor torque constant, K_τ, and gear ratios.
τ_0	Value of τ_{meas} when no external force is applied. This is the control offset torque, typically required to counteract gravity or counter-balance forces.
$K(L)$	Torsional compliance, which is a function of length, L. Units are radians/Newton-meter.
δ	Backlash of instrument shaft, primarily due to clearance between shaft and cannula, measured in radians.
Δq_{def}	Angular displacement due to link deformation, in radians.

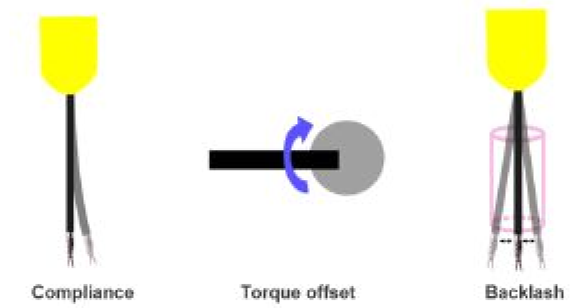


Fig 2. Illustration of the parameters

IV. Procedure

Estimating the stiffness and backlash

Joint 1: The instrument is clamp with a small metal block that close to the tooltip. The instrument is instructed to move from the middle to the left, then to the right and back to the middle. This procedure is repeated for 14 different depths.

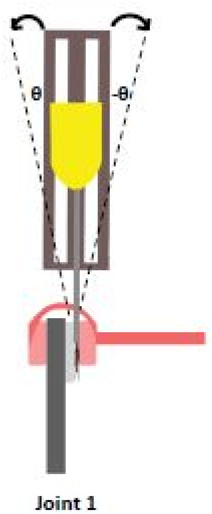


Fig 3. Illustration of the stiffness and backlash estimation method for joint 1

Joint 2: The instrument is clamp with a small metal block that close to the tooltip. The instrument is instructed to move from the middle to inward direction, then to outward direction and back to the middle. This procedure is repeated for 14 different depths.

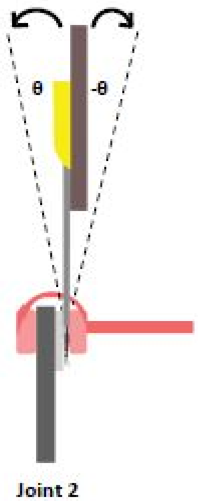


Fig 4. Illustration of the stiffness and backlash estimation method for joint 2

<u>Estimating the torque offset</u>

Joint 1: The arm is positioned to approximately -90'. It is moved by 5' to reach the end position, which is the 90'.

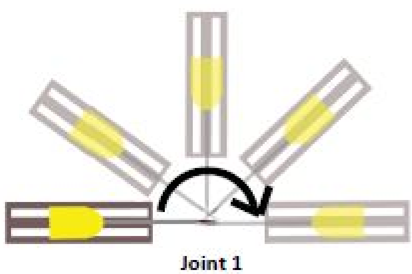


Fig 5. Illustration of the torque offset estimation method for joint 1

Joint 2: The arm is positioned to approximately -90'. It is moved by 5' to reach the end position, which is the 90'.

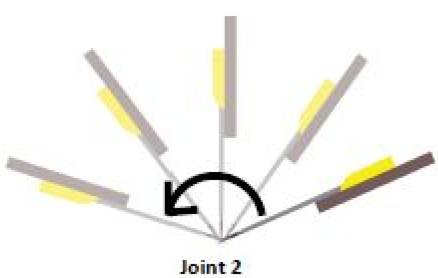


Fig 6. Illustration of the torque offset estimation method for joint 1

Implementation of Compliance Model to the dVRK system

The RobotIO component received data from the hardware. It passes the data to the PID component. The PID component manages joint control. It passes the data to the PSM component. The PSM component manages the Cartesian control of the robot.

We created 2 new components: Compensation component and PSM Read Only component. The PID passes the data in term of joint status to the Compensation component. In here, it performed the calculation to correct the joint status by using the compliance model. The corrected joint status is passed to the PSM Read Only component in order to compare the corrected vs uncorrected joint status

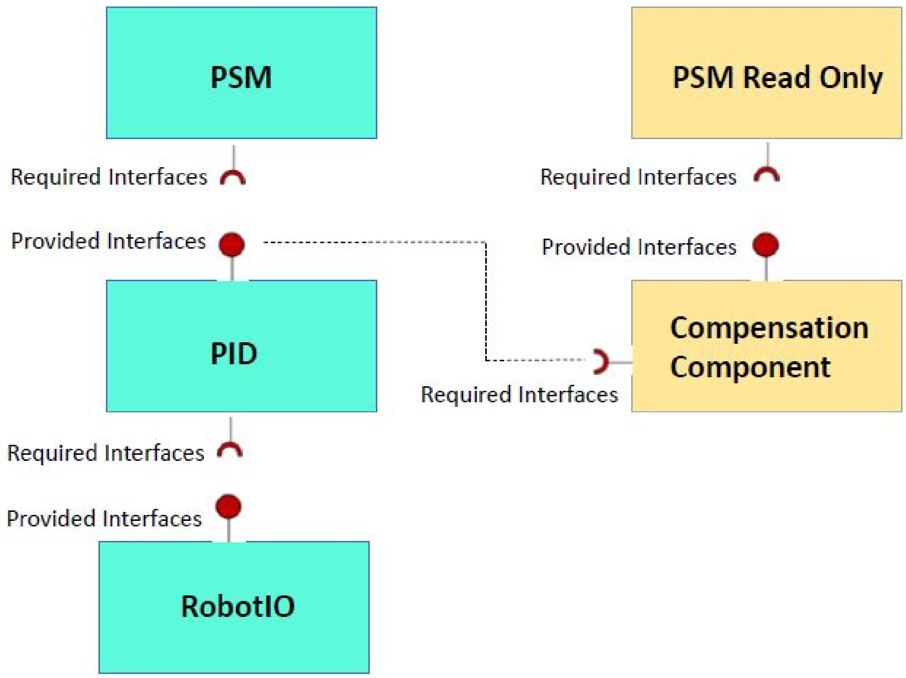


Fig 7. Simplified dVRK system architecture with new component additions

Accuracy Improvement Test 1

We used a teleoperator to control the dVRK to touch 13 different points on a metal plate. The Cartesian position of each point is known. Each point is touched with different amount of joint effort. On each point, the joint Cartesian position is recorded. This enabled us to see how the Cartesian position of each points recorded by the robot compare with the previously known Cartesian position of each points.

Accuracy Improvement Test 2

All the points on the metal plate are pitted. We used a teleoperator to control the dVRK to place the tooltip into one of the points on a metal plate. We moved the tooltip against the surface of the pitted point until the force reached 1 N-m while the PSM joint corrected and uncorrected positions are recorded continuously for plotting a comparison graph. We repeat this procedure four time; each time with different directions based on the joint we tested. We moved the tooltip leftward and rightward for testing joint 1. Inward and outward for testing joint 2.

V. Analysis of Data

Stiffness Plot

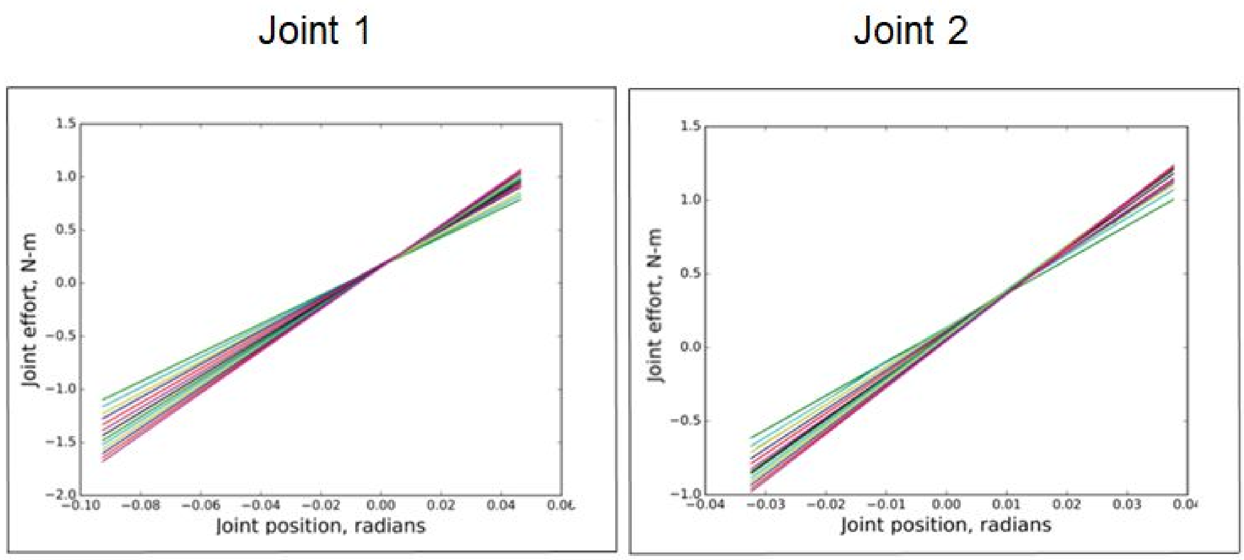


Fig 8. Stiffness plot for joint 1 and joint 2

The different colored lines indicate different instrument depth. The most bottom line on the negative x-axis was generated by performing stiffness estimation method with 0.09 m instrument depth (measured from the RCM point). The top line on the negative x-axis was generated by performing stiffness estimation method with 0.23 m instrument depth (measured from the RCM point)

Stiffness variation with depths

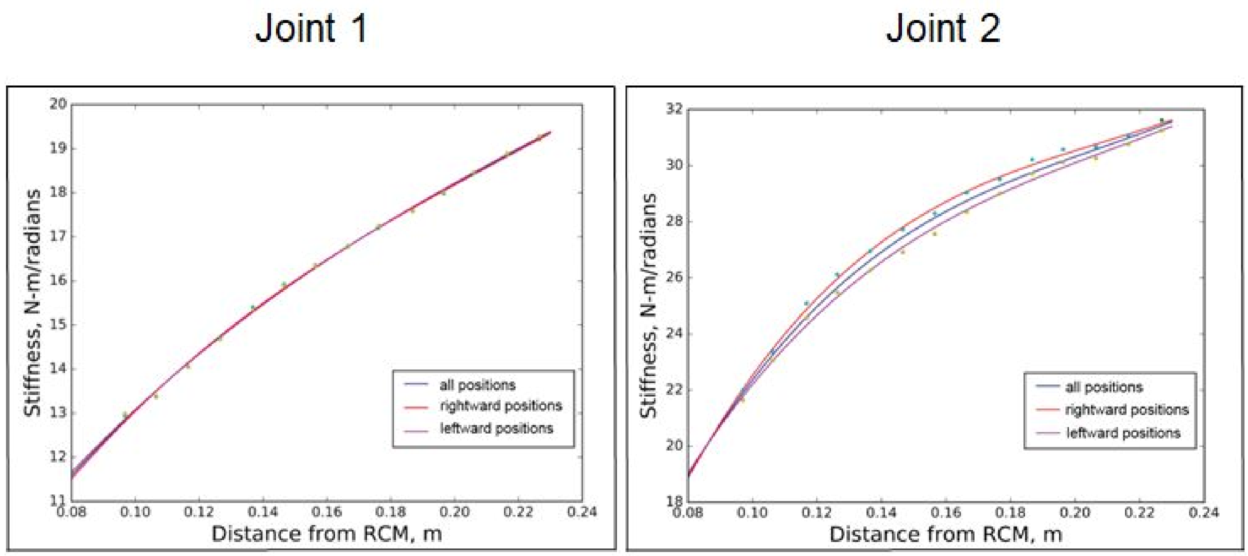


Fig 9. Stiffness variation with depths for joint 1 and joint 2

From the Fig.8 graphs we generated the stiffness variation with depth. The depth has a direct relationship with the stiffness of the instrument. From the graphs, we were able to generate cubic polynomial functions as the compliance estimation for both joints.

Joint 1:

$$K(L) = \frac{1}{639.16L^3 - 432.35L^2 + 136.32L + 3.12}$$

Joint 2:

$$K(L) = \frac{1}{-3163.17L^3 - 1969.15L^2 + 448.92L - 6.00}$$

Torque offset plots

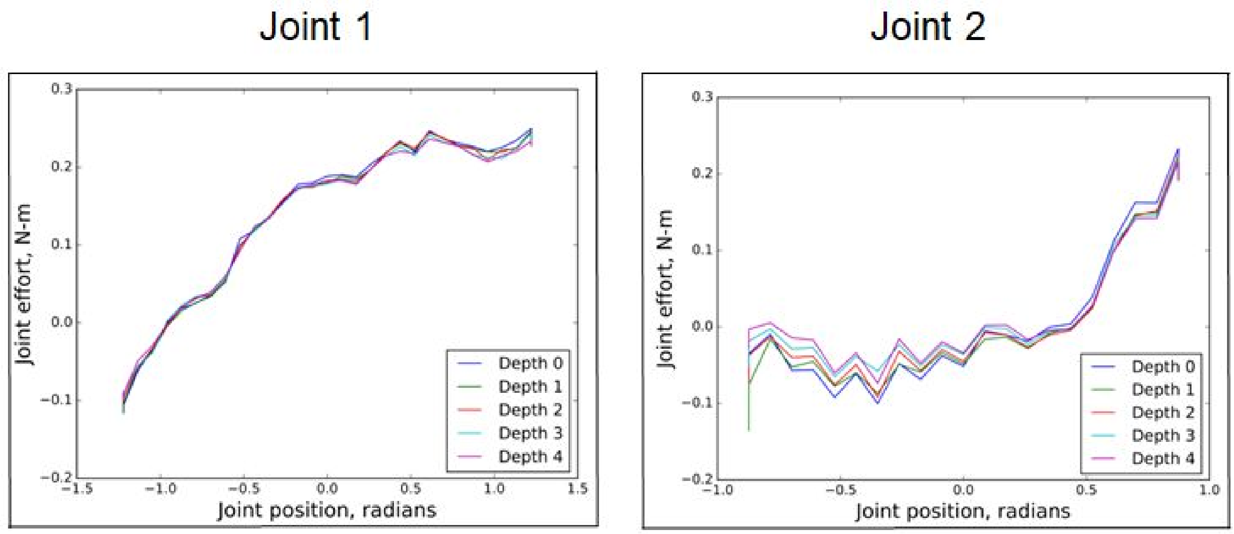


Fig 10. Torque offset plot for joint 1 and joint 2

All the tested depth formed very similar graph with one another which indicates that the depth of the instrument does not influence the amount of torque offset generated by the robot arm.

Torque offset variation with depth

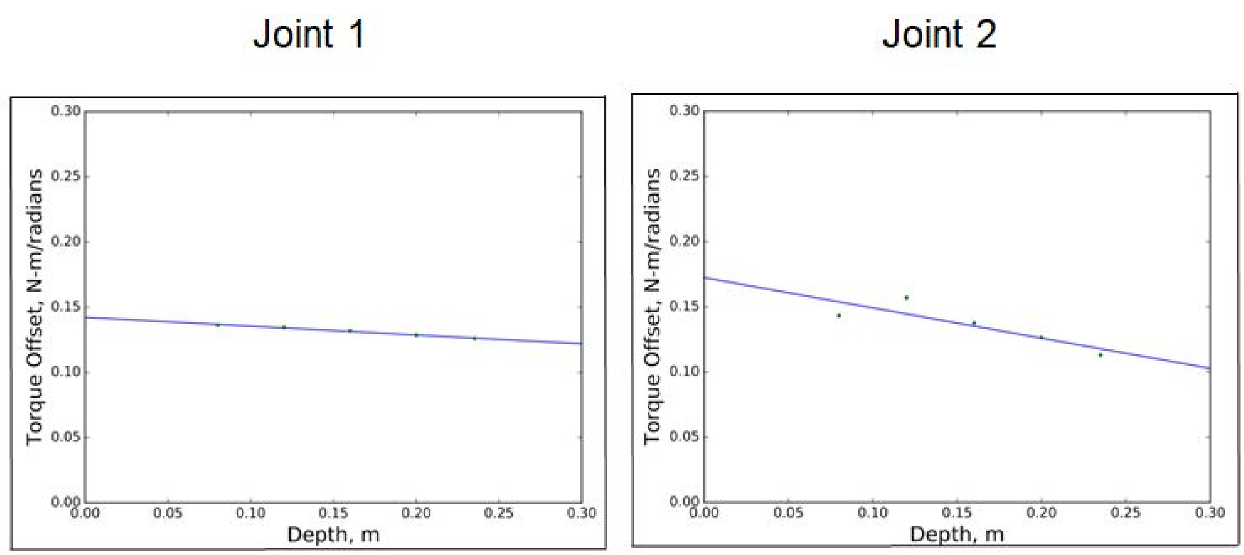


Fig 11. Torque offset variation with depth for joint 1 and joint 2

The estimate we obtained from joint 1 is approximately constant because the difference between points are negligible. For joint 2 the points are a little bit varied, we tried using a linear function but the correction was not significantly different at all. So we decided to have it as a constant as well.

Joint 1: 0.13149 N-m/rad

Joint 2: 0.13549 N-m/rad

Backlash plot

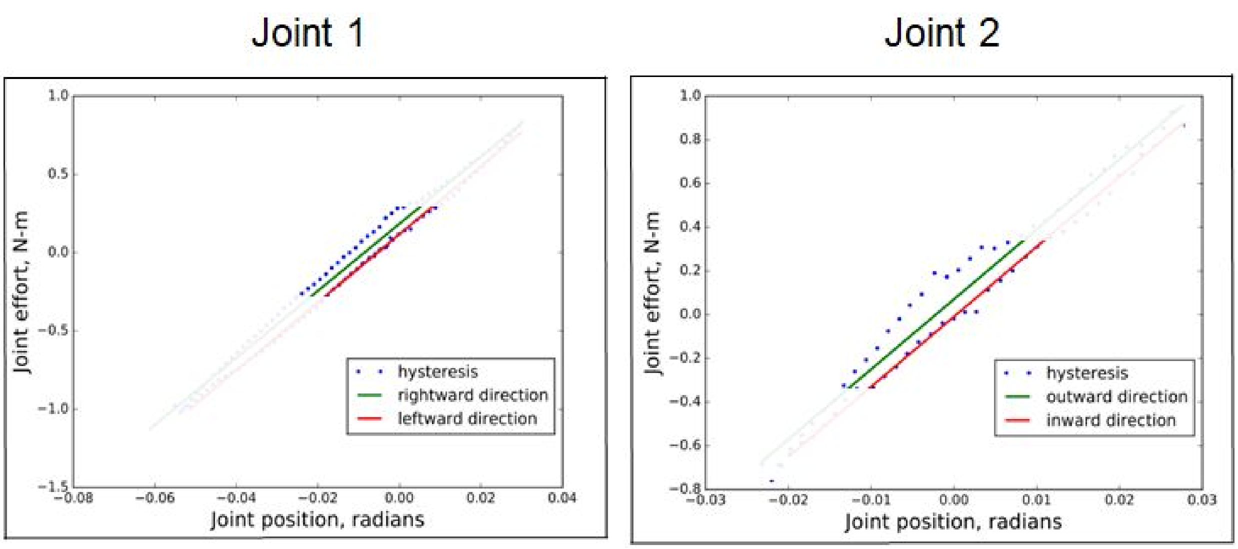


Fig 12. Backlash plot for joint 1 and joint 2

The experiment formed hysteresis graphs. To calculate the backlash, we were only interested on the parts around the resting position because if the instrument is already touching either side if the cannula, the backlash does not exist on that point.

Backlash variation with depth

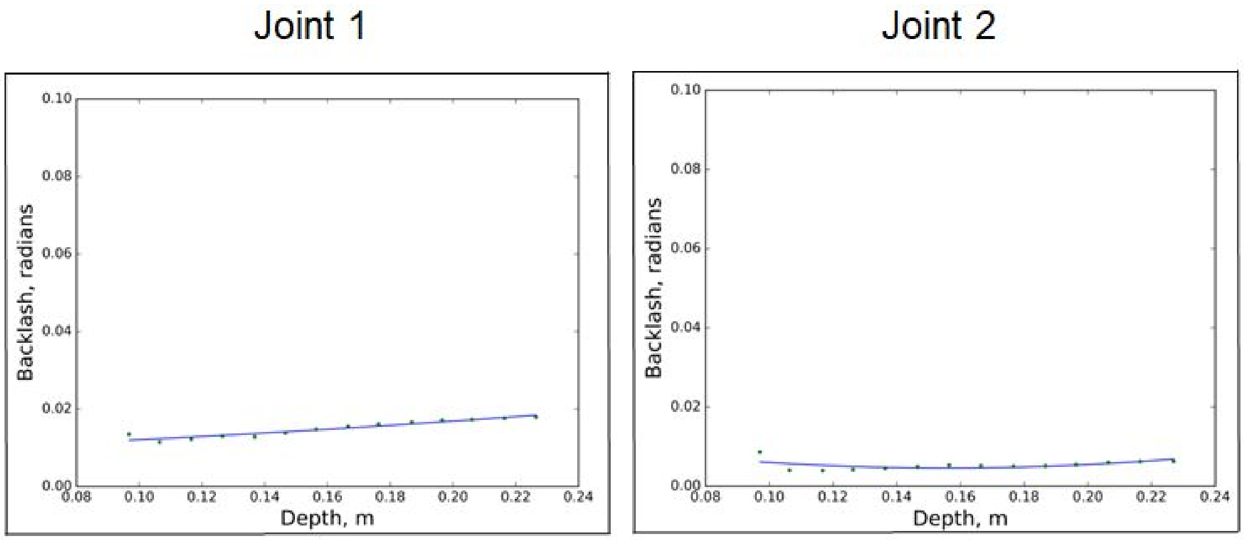


Fig 13. Backlash variation with depth for joint 1 and joint 2

The backlash for both joints are constant because the gap between the instrument and the cannula does not change regardless how deep the instrument is moved

Joint 1: 0.010312 rad

Joint 2: 0.003431 rad

Accuracy Improvement Test 1 Results

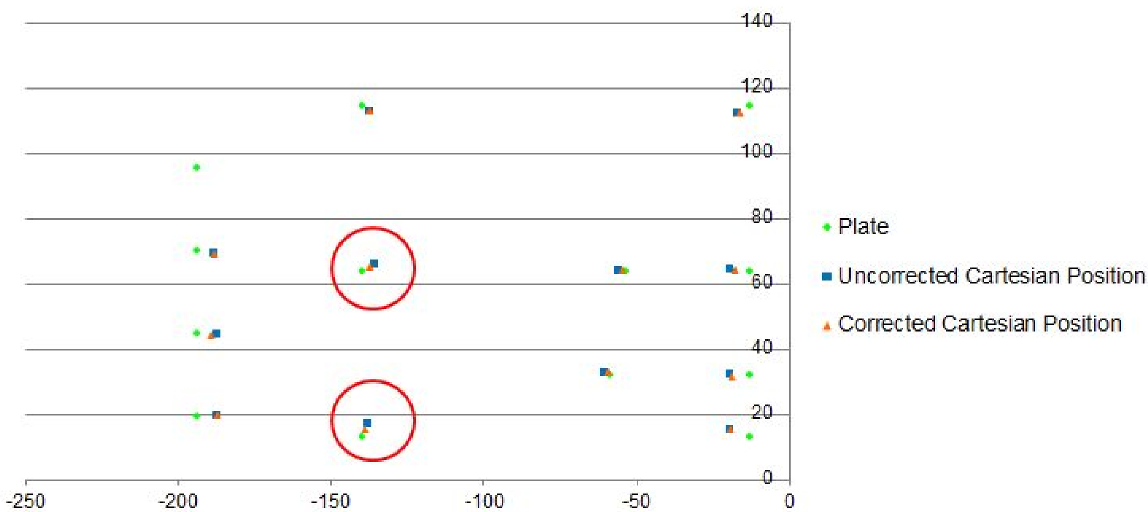
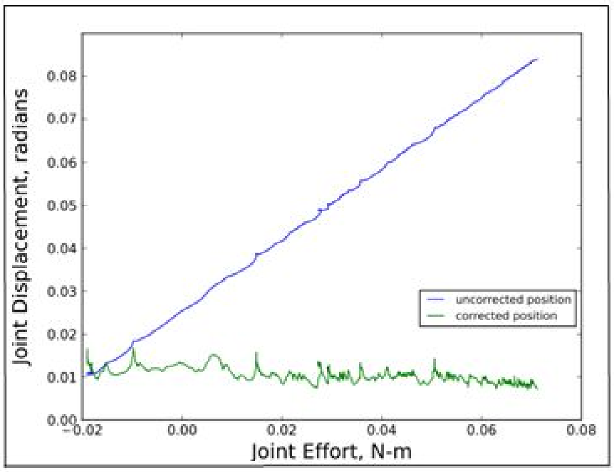


Fig 14. Cartesian positions comparison result

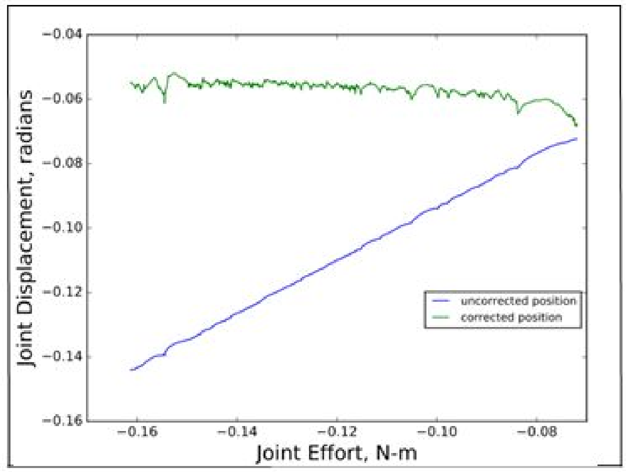
The dVRK does not show the inaccuracy of joint positions when the joint effort is 0 or very close to zero. The larger the joint effort, the more inaccurate the joint position becomes. The points circled in red indicate a noticeable accuracy improvement for the corrected Cartesian position. The reason is that a larger effort was applied on these points during the experiment. In contrast, the effort applied to the rest of the points was very close to zero. After we measured, the Cartesian improvement from our model is approximately ¾ mm

Accuracy Improvement Test 2 Results

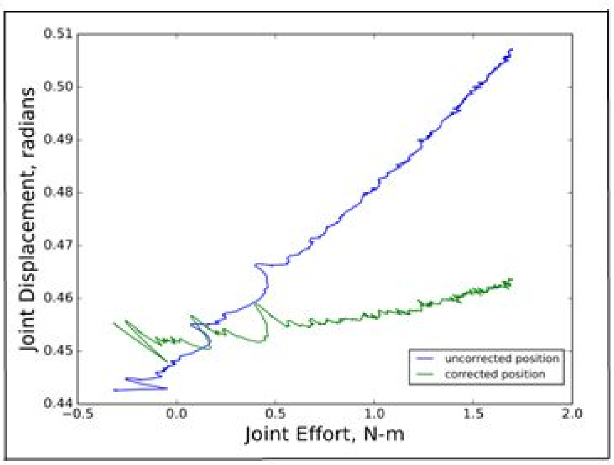
Joint 1 Left Direction



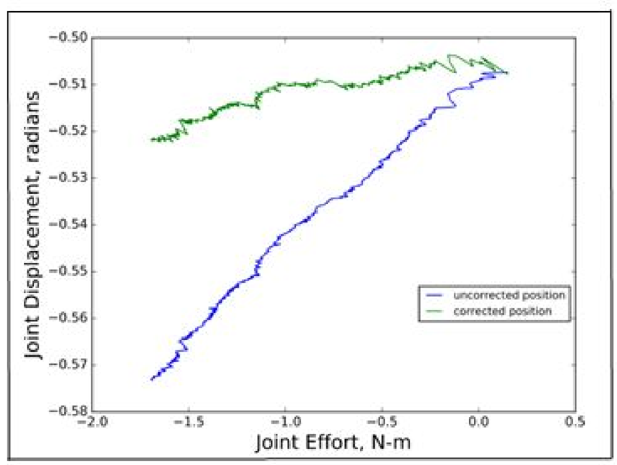
Joint 1 Right Direction



Joint 2 Inward Direction



Joint 2 Outward Direction



During the experiment, the tooltip inside a pitted point on the metal plate did none or very small displacement within the point. Both graphs indicate the joint displacement recorded during the experiment. As the effort increases, the uncorrected line shows a linear displacement of the tooltip which is inaccurate since the tooltip stayed within the pitted point. In contrast, the corrected line indicates a more accurate position of the tooltip since it is relatively constant. The correction for joint 1 is approximately 0.08 rad which is about 4.5’. The correction for joint 2 is approximately 0.06 rad which is about 3.5’

VI. Conclusions

The Compliance model improves the accuracy of the dVRK.

References

[1] C.Schneider, C.Nguan, R. Rohling, and S. Salcudean, “Tracked “pickup” ultrasound for robot-assisted minimally invasive surgery,” *IEEE Trans. on Biomedical Engineering,* vol. 63, no. 2, pp. 260-268, Feb 2016.

[2] N.Eusman, A.Deguet, and P.Kazanzides, *A Compliance Model to Improve the Accuracy of the da Vinci Research Kit (dVRK).*

Appendices

1. The research was performed using the dVRK. The dVRK is only used for research purposes and not used for any human subject.
2. The knowledge and skills I have gained through the program led me to an academic pursuance in medical robotics
3. The highlights of the program is that we were able to work very closely with professors who work on the cutting-edge research. Also, the trips to different science and engineering facilities are great.