# Effects of Master-Slave Tool Misalignment in a Teleoperated Surgical Robot

Lawrence H. Kim*, Clifford Bargar*, Yuhang Che*, and Allison M. Okamura, *IEEE Fellow*

*Abstract*— **In a teleoperated system, misalignment between the master and slave manipulators can result from clutching, errors in the kinematic model, and/or sensor errors. This study examines the effects of type and magnitude of misalignment on the performance of the teleoperator. We first characterized the magnitude and direction of orientation misalignment created when clutching and unclutching during use of two surgical robots: the Raven II and the da Vinci Research Kit. We then purposely generated typical misalignments in order to measure the impact of such misalignment on user performance of a peg transfer task with the Raven II. Users were able to compensate for misalignment angles up to approximately 20 degrees in both tool orientation and camera viewpoint misalignment. These results can be used to guide the design and control of teleoperated systems for a variety of applications.**

## I. Introduction

Teleoperated robotic systems give their human operators the ability to act at a distance and manipulate environments that require force and motion scaling. Teleoperation has been successfully used in a number of applications including space robotics, operating in hazardous environments (such as radioactive areas or bomb defusal), and surgery [1]. Since the 1990s, teleoperated surgical systems have been widely used in research communities, hospitals, and clinics around the world. Teleoperated surgical systems improve dexterity, scaling, and visualization in minimally invasive surgery. The da Vinci Surgical System (Intuitive Surgical Inc., Sunnyvale, CA) has been the most successful commercially and a number of other surgical robots have been developed by companies and research labs [2].

However, an issue that can arise in teleoperated surgical systems is misalignment between the master and slave tools in either tool orientation or camera viewpoint. The effects of these misalignments on task performance by a human operator are not well understood. These types of misalignments occur for several different reasons (described in Section I-B) and have implications in the design and control of teleoperated surgical systems, as well as in determining the best training and usage procedures. This work investigates the effects of different angular quantities of misalignment and of differing misalignment axes on users' completion time of a surgically relevant task. The following subsections introduce the surgical platforms used in this investigation and describe relevant prior work.

*These authors contributed equally to this work.

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L. H. Kim, C. Bargar, Y. Che, and A. M. Okamura are with the Department of Mechanical Engineering, Stanford University, Stanford, CA 94305, USA. Email: `lawkim@stanford.edu`, `cbargar@stanford.edu`, `yuhangc@stanford.edu`, `aokamura@stanford.edu`

### A. *Teleoperated Laparoscopic Surgical Research Platforms*

The primary teleoperated surgical system used in this work is the Raven-II. It is a cable-driven patient-side robot with a spherical remote center-of-motion. The Raven-II is both a research and training platform for surgical robotics at universities around the world [3], [4]. A research community has built up around the Raven for sharing of ideas, methods, and software.

Because there have been few studies performed in which subjects used the Raven-II in teleoperation, it was necessary to first validate its performance. To this end, the accuracy of both the Raven and the da Vinci Research Kit (dVRK) are examined, with the dVRK used as a reference for comparison. The dVRK is a research platform that makes use of the first-generation da Vinci master and patient-side manipulators along with open source hardware and software (which are distinct from the drive electronics and control system used by the da Vinci systems in production) [5]. Details on the implementation of the da Vinci system used in this study are described in [6].

### B. *Prior Work on Tool Misalignment*

Teleoperated robotic systems should enable effective remote perception and manipulation [7]. During teleoperation, human perception is degraded due to decoupling from the physical world. Degraded perception leads to deficits in situational awareness, and thus inferior teleoperation performance [8]. While there are various factors that could affect remote perception such as time delay, field of view, and depth perception, this paper focuses on the effects of tool orientation and camera viewpoint misalignments on teleoperation performance [7], [9].

Potential causes of physical misalignment include failure of the operator to properly match the master's orientation to that of slave when unclutching, errors in the kinematic model in the robot's control software, and faulty sensor readings leading to improper position and orientation estimates. Clutching is a method of allowing operators to control a larger workspace on the slave side than on the master side by temporarily disengaging the master from the slave, enabling motion scaling and improved ergonomics. A change in camera angle can also cause the perception of misalignment for the operator.

In particular, we are interested in two types of misalignment that can result from the above problems: tool ori-

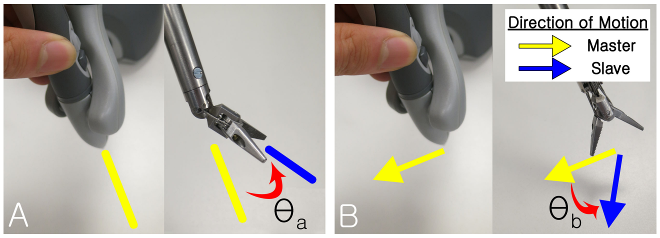



Fig. 1: The two types of misalignment under consideration. (a) Orientation misalignment occurs when the orientations of the end effector of the master and slave manipulators differ. (b) Camera viewpoint misalignment occurs when the slave manipulator's reference frame differs from the master manipulator's reference frame by a fixed rotation.

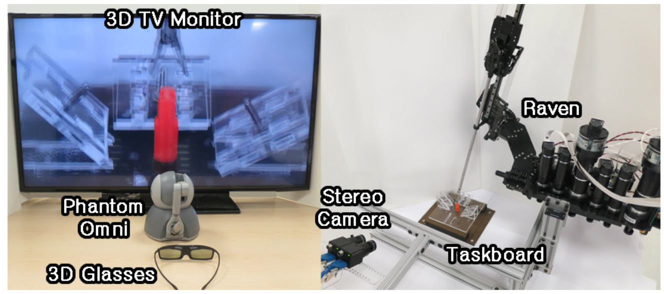



Fig. 2: Experimental setup consisting of the Omni manipulator, 3D TV, 3D glasses, Flea3 cameras and mounting, the Raven-II robot and task board.

entation misalignment and camera viewpoint misalignment. Orientation misalignment is a difference in angle between the operator's expected orientation (the master manipulator orientation) and the orientation of the slave manipulator. Camera viewpoint misalignment is when the slave manipulator's reference frame differs from the master's reference frame; this is typically caused by an offset in the camera's view angle (e.g. moving an endoscope without properly accounting for the coordinate frame changes). These are illustrated in Fig. 1. While prior works have focused on viewpoint misalignment using manual laparoscopic instruments [10] and in performing simple teleoperation tasks in simulation [11], none have examined the effects of multiple types and angles of misalignment on dextrous manipulations.

Mahler, et al. [12] quantified position and orientation errors in a Raven system resulting from sensing errors and insufficient kinematic modeling and corrected for errors using external sensors and statistical techniques. This is an important step for improving the reliability of cable-driven robots for autonomous tasks but still requires the use of external sensors. In teleoperation, operators are able to correct for some errors that standard machine vision may be unable to measure, but misalignment still contributes to degraded performance. This work focuses on quantifying the effects on user performance of different types and amounts of misalignment.

## II. Experimental Platform

### A. Raven II Surgical System - Teleoperation Setup

The primary components of the experimental setup (Fig. 2) are the Raven-II surgical system, used as the slave robot, and a PHANToM Omni (now marketed as the Geomagic Touch), used as the master. In this work, only the right arm of the Raven and one Omni are used. To control the Raven, we use a modified version of the standard source code made available on GitHub by the Robot Learning Lab at the University of California, Berkeley [13].

Because the Raven's encoders are located at the base of the manipulators (where the motors are mounted), it is difficult to compensate for cable coupling and/or slack or stretch in the cables. While this problem is not unique to the Raven, this lack of compensation can lead to large errors in state estimation with a slight slack or stretch in the cables or inaccurate cable coupling calculations. Naerum, et al. [14] attempt to mitigate some of these issues by using an Unscented Kalman Filter on a one-DOF version of the Raven.

The vision system used in our setup consists of two Point Grey Flea3 (FL3-U3-32S2C-CS) cameras (Point Grey Research, Richmond, BC, Canada), a custom laser-cut adjustable mount, open-source software for outputting live stereo video, and a Samsung UN46FH6030 3D TV. The stereo cameras allow all users to observe the Raven's manipulator from the same point of view, with depth perception. The software for creating stereo output and the CAD model of the camera mount are both available publicly [15].

### B. System Accuracy Evaluation

In order to validate the Raven's accuracy for use in a teleoperation study, the accuracy of both the Raven and the dVRK was quantified by measuring the difference in orientation of each robot from that of the corresponding master along the end-effector's roll, pitch, and yaw axes. The Raven and dVRK were controlled by an Omni and by the da Vinci master manipulator, respectively. Note that the accuracy measured will vary depending on the software used to control each system.

Six-degree of freedom magnetic pose trackers (trakSTAR, Ascension Technology) were attached to the master manipulator and to the Raven's gripper to measure their relative orientations, as shown in Fig. 3. We also performed the same calibration on the dVRK system as a comparison. However, because the da Vinci tool was smaller, a 3D-printed mounting plate was designed to hold the sensor (Fig. 3d). Data from the magnetic sensors were collected at 120 Hz while a user manipulated each device for 120 seconds, testing as wide a range of orientations within the workspace as possible. During the entire calibration procedure, the "quality number" [16] of the magnetic tracker was monitored and maintained within the recommended range.

Figures 4a and 4b present the results of the evaluation of the system's accuracy, in terms of misalignment angle in roll, pitch and yaw. All the results are calculated in the end-effector reference frame. The overall average value of the misalignment error is 13.5° (standard deviation 5.8°) and 12.1° (standard deviation 6.8°), respectively, for the Raven and dVRK systems. While most of this measured misalignment is due to the issues stated above, as addressed in [12], a small amount is due to mounting the magnetic tracker to each tool and the magnetic tracker itself. (The trakSTAR is reported to have static accuracy of 1.4 mm RMS in position and 0.5 degree RMS in orientation [16].)

We also conducted an experiment to evaluate the Raven system's ability to generate a constant orientation misalignment between the master and slave manipulators. The results are presented in Fig. 5. For each desired misalignment value, the actual orientation misalignment was measured at different tool configurations. There is approximately 15° of orientation misalignment measured even when the desired misalignment is 0°, which is close to the 13.5° error discussed above. When no orientation misalignment is commanded, there still exists a base amount of misalignment inherent to the system; when only small amounts are commanded, it will sometimes counteract the inherent misalignment. As the desired orientation misalignment increases, the measured misalignment and the command misalignment tend to converge.

## III. Misalignment Error Pre-Study

### A. Pre-Study Methods

Seven users participated in a pre-study using only the Omni haptic device. The purpose of this test was to simulate the orientation error (both magnitude and direction) resulting when an operator unclutches a teleoperated surgical robot using a passive master manipulator with some visual guidance. Each user participated in 100 trials in which a screen displayed a randomly oriented "desired" set of axes and the user was given five seconds to re-orient the manipulator (represented on screen by another set of axes sharing an origin) to match the desired axes.

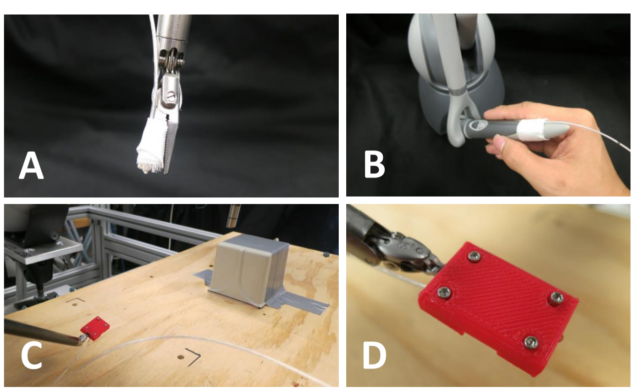
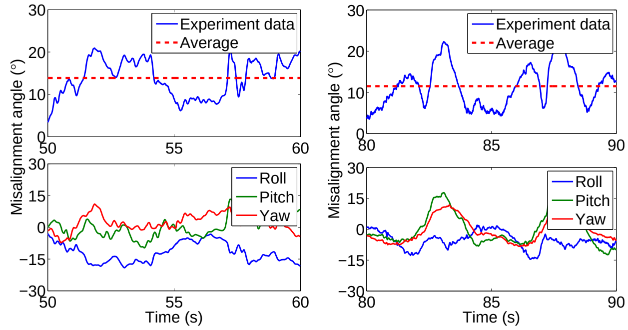



Fig. 3: Magnetic tracking system configuration for system evaluation: (a) the magnetic tracking sensor on the Raven manipulator; (b) the sensor on the Omni for Raven teleoperation; (c) the dVRK system setup with magnetic field transmitter; and (d) the magnetic sensor on the da Vinci large needle driver.




(a) Raven accuracy data (b) dVRK accuracy data

Fig. 4: Measured orientation misalignment between master and slave manipulators for (a) the Raven system and (b) dVRK. Top: overall misalignment angle from the axis-angle representation; the red horizontal line is the average value. Bottom: misalignment angles in roll, pitch and yaw representations. Both are 10 s segments from the entire 120 s experiment.

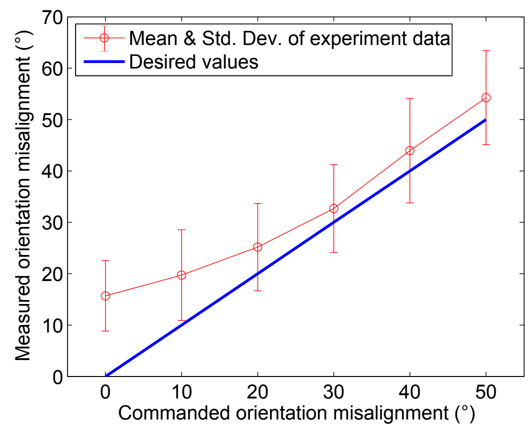
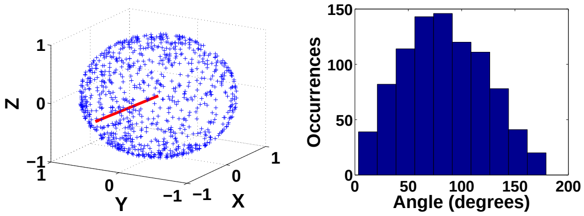



Fig. 5: Experimentally measured misalignment for each commanded misalignment angle using the Raven. The system's inherent orientation misalignment is always present, increasing the overall misalignment in the early cases but converging with the desired misalignment in later cases. The red is data gathered using the magnetic tracking system while the blue line is the desired orientation misalignment. The bars represent the standard deviation.

### B. Pre-Study Results

Due to the two-dimensional visualization of the orientations, there were trials when the subjects completely failed to perceive the desired orientation. Thus, all misalignments greater than 30° were considered to be failed trials and were eliminated from the analysis (removing 9.3% of the original data). Of the remaining misalignments, the mean misalignment angle was 3.6° with a standard deviation of 4.3°.

We analyzed the rotation axes from the angle-axis representations of the transformations for each misalignment to see if there were any common trends in misalignment




(a) (b)

Fig. 6: Analysis of unclutching performance results showing that the axes are fairly evenly distributed. (a) Distribution of the directions of each misalignment axis, with the mean axis in red. (b) Angle between each rotation axis and the mean axis.

direction. To see if the axes were uniformly distributed we applied Stephens' criteria [17] and Cuesta-Albertos' test [18]. The result of both of these tests (performed at the $5\%$ significance level) was to reject the hypothesis that the misalignment axes were uniformly distributed. However, the plot of all of the axes represented as unit vectors (see Fig. 6a) does not show any obvious patterns. These results were used to determine the misalignment directions in the following studies.

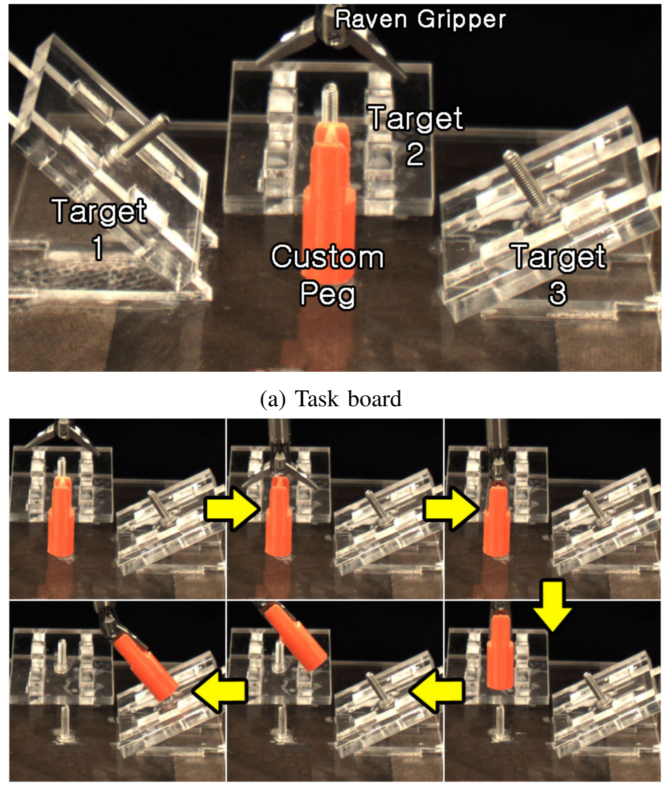
## IV. Study Methods

The two main studies measured the effects of tool orientation misalignment and camera viewpoint misalignment, respectively, on operator performance when teleoperating the Raven. All participants were between the ages of 22 and 29 years old and provided informed consent. This protocol was approved by the Stanford University Institutional Review Board.

### A. Task and Analysis for Misalignment Studies

The task for both the tool orientation misalignment and camera viewpoint misalignment studies is a 3-dimensional modification of the standard Fundamentals of Laparoscopic Surgery (FLS) peg transfer task [19], designed to force the user to not only pick up and place the peg but also to reorient it. Using the task board shown in Fig. 7a, the participant is told to pick up the peg, transfer it onto the designated target platform (either left, right or middle) without releasing the gripper, return back to the origin, release the peg, and return the Raven's gripper to the starting point above the peg with the grippers open. This sequence is repeated on each trial, with the following factors being changed: the *desired target*, the *axis of misalignment*, and/or the *misalignment angle*. Fig. 7b shows the stages of one of the trials with the rightmost platform as the target.

In order to account for first-order carryover effects, we used a balanced Latin square experimental design to determine the order of misalignment angles for each participant for both studies. Trials with a constant misalignment angle were performed in large blocks, while the axis of misalignment and the desired target were varied within each block.




(a) Task board

(b) Transfer task

Fig. 7: (a) The task board as seen by the vision system, along with the Raven gripper and custom peg. The three targets are numbered. (b) An illustration of the first half of a trial of the peg transfer task using target 3.

Based on the accuracy results in Section II-B, we chose to vary the misalignment angle in $10°$ increments.

Because the unclutching analysis (Section III) didn't show any significant trends we chose the set of misalignment axes to be four general ones: one each about the end-effector's x-, y-, and z-axes (pitch, yaw, and roll, respectively), and one about an equal combination of the x, y and z-axes. The misalignment axes are illustrated in Fig. 8.

Each study consisted of the participant first performing a training session followed by the experiment section. The training session consisted of four trials at each misalignment angle (with random misalignment axes). The experiment section was broken up into blocks at constant misalignment angles, each of which was further divided into a 4 trial retraining segment followed by 12 actual trials (one each for each of the three targets with each of the four misalignment axes). The macro ordering of the major blocks varied between each participant according to the balanced Latin square design described above.

We plotted the data across different factors and performed ANOVA to determine statistical significance [20], [21]. We also looked at the learning that occurred during the study and how many times (and on which misalignment angles) each user drops the peg. While the mean and standard deviations of the two studies were $35.5s \pm 17.0s$ and $31.7s \pm 17.7s$ (for tool orientation and camera viewpoint, respectively), 98.8% of the trials for each study took between $5s$ and $90s$ for the subject to complete. Trials taking fewer than $2s$ or more than $100s$ were assumed to be errors on the part of the subjects and were omitted from the analysis.

### B. Tool Orientation Misalignment Trials

$50°$ is the maximum misalignment angle that could be achieved within the joint limits of the Raven. Thus, six misalignment angles are chosen to be experiment parameters for the tool orientation misalignment study: $0°$, $10°$, $20°$, $30°$, $40°$ and $50°$. The training session consisted of 24 trials – four trials for each of the six misalignment angles. In the main experiment session each of these six misalignment angles corresponds to a major block; within each block there are 4 retraining trials, one for each of the four misalignment axes, and 12 actual trials, one for each combination of one of the three targets and four misalignment axes. There were six different permutations of blocks to maintain the balanced Latin square design described above. A total of 12 users completed the orientation misalignment study, with each permutation of blocks performed by two users.

### C. Camera Viewpoint Misalignment Trials

The camera viewpoint misalignment was implemented by applying a transformation consisting of a pure rotation to the control signal sent from master side to the slave side rather than physically rotating the camera. During an initial pilot study we found that a misalignment angle of $50°$ proved to be too difficult for the users performing the camera viewpoint misalignment study. Thus, to reduce the overall experiment time, only $0°$ through $40°$ were used. For the camera viewpoint misalignment study, the training and experiment sessions include 20 and 80 trials respectively (five sets of 4 retraining trials and 12 actual trials). Because there were only five misalignment angles only five different orderings were used. To use the balanced Latin square experimental design for 5 orderings, only 10 users completed the camera viewpoint misalignment study (a subset of the 12 who performed the orientation misalignment study), with each permutation of blocks performed by two users.

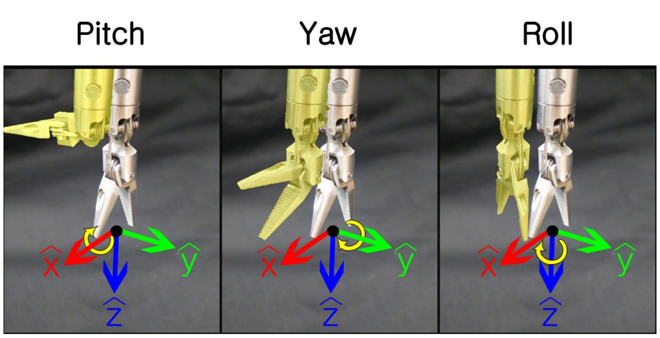



Fig. 8: We varied the misalignment angle about the Raven's pitch, yaw, and roll axes, as well as a combination of all three.

## V. Study Results

### A. Tool Orientation Misalignment

A 4-way ANOVA analysis showed a statistically significant difference between each user's performance at different angles (with a $p$-value below $0.001$). Interestingly, there is a significant difference in completion times for both the misalignment axes and the desired targets (with $p$-values of $0.002$ and $0.012$, respectively). While there is a significant difference between some of the participants ($p < 0.001$), Fig. 9 shows that the majority of performances are clustered within a factor of two of the overall mean.

Figure 10 shows the combined performance of all participants at each misalignment angle. There is a clear drop-off in performance for misalignment angles above $20°$, continuing to worsen with increasing misalignment angle. Averaging the performance for all trials between $0°$ and $20°$, the increases in mean task completion time for $30°$, $40°$, and $50°$ are $14.4\%$, $19.1\%$, and $33.3\%$, respectively.

The mean completion times for each axis are 32.63 s (with standard deviation $\sigma = 11.64$ s), 34.10 s ($\sigma = 12.52$ s), 31.77 s ($\sigma = 11.76$ s), and 30.73 s ($\sigma = 11.43$ s) for the pitch, yaw, roll, and combined axes, respectively (Fig. 8). Table I shows the results of a post-hoc comparison between the task completion times for each pair of misalignment axes. The axis analysis indicates that a rotation about the yaw axis (which consists of a rotation about the gripper) is significantly more difficult to correct for than a rotation about the combined axis (while no other pairing exhibits a significant difference).

Additionally, Fig. 11 shows that, on average, participants performed better as the study went on. This trend continued across days, as participants started at a lower baseline and continued to improve on the second day.

Another measure of performance is the number of drops, i.e. failures to complete the task due to dropping the peg. In the orientation study there is an increasing trend in the total number of drops as misalignment angle increases. The yaw axis also exhibits the most drops. The number of drops varied

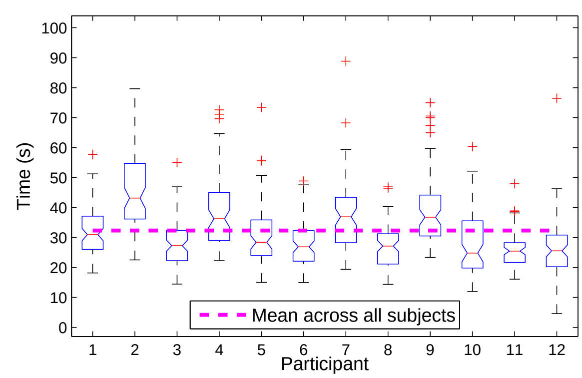



Fig. 9: Each participant's task completion times for each trial, showing the median trial time, the 25th/75th percentile trial times, and outliers for the orientation misalignment study.

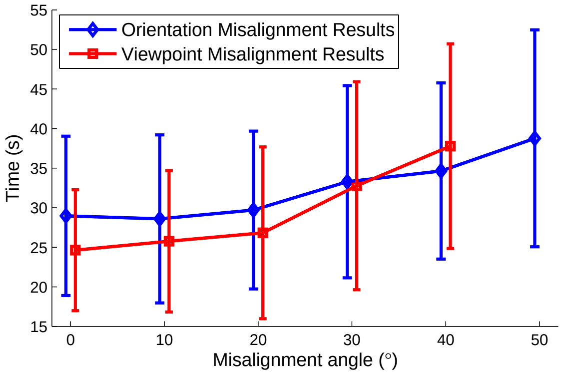



Fig. 10: Mean completion times for each angle for both the orientation misalignment study and the camera viewpoint misalignment study, with bars indicating the standard deviation. The data points have been shifted slightly horizontally for legibility.

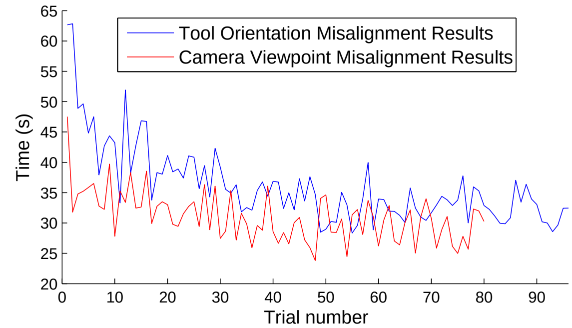



Fig. 11: Mean completion times for each trial for both the orientation misalignment study (day one) and the viewpoint misalignment study (day two). Participants improved their performance as the study went on, demonstrating learning effects.

widely by participant (with some never dropping) and was fairly small relative to the number of trials. There were no noticeable trends in drops during the viewpoint misalignment study.

### *B. Camera Viewpoint Misalignment*

Similar to the orientation misalignment case, a 4-way ANOVA shows a significant difference in completion time between misalignment angles (with a $p$-value below 0.001). The performances of each participant, shown in Fig. 12, also have statistically significant differences ($p < 0.001$) but are still clustered within a factor of two around the mean completion time of all participants.

As shown in Fig. 10, participants performed better at small angles in the viewpoint misalignment test than in the orientation misalignment test, likely due to learning effects (Fig. 11). There is a slight increasing trend in task completion times between misalignment angles of $0°$ and $20°$. Beyond these three misalignment angles, the drop off in performance is even more stark than in the orientation misalignment study: for $30°$ and $40°$ the increase in task completion time is $27.3\%$ and $46.8\%$, respectively.

The post-hoc comparisons of completion times for each pair of misalignment axes are shown in Table II; in the viewpoint misalignment study, misalignments about both the pitch and roll axes are significantly more difficult to compensate for than the combined axis. The mean completion times are 30.51 s ($\sigma = 12.97$ s), 28.94 s ($\sigma = 11.56$ s), 31.75 s ($\sigma = 12.56$ s), and 26.77 s ($\sigma = 10.02$ s) for the pitch, yaw, roll, and combined axes, respectively.

TABLE I: $p$-values for the post-hoc comparison of each pair of misalignment axes using the t-test for the orientation study.

| Axis | Yaw | Roll | Combination |
|---|---|---|---|
| Pitch | 0.2068 | 0.4468 | 0.0895 |
| Yaw | – | 0.0469 | 0.0038 |
| Roll | – | – | 0.3539 |

Using the Bonferroni adjustment, for $\alpha = 0.05$ the corrected value becomes $\alpha_c = 0.0083$. Statistically significant values are highlighted in red.

## VI. Conclusions

In this study, we quantitatively evaluated the effect of two types of misalignment in teleoperated systems: tool orientation misalignment and camera viewpoint misalignment between the master and slave end-effectors. Our analysis shows a clear drop-off in user performance when the misalignment angle is greater than $20°$ in both studies. For orientation misalignment, the mean trial completion times are increased by $14.4\%$, $19.1\%$ and $33.3\%$ for misalignment angles of $30°$, $40°$ and $50°$ respectively when compared to the average completion time for $0°$ to $20°$ misalignment angles. For camera viewpoint misalignment, the increase in completion time is $27.3\%$ and $46.8\%$ for misalignment angles of $30°$ and $40°$ respectively. Note that the values of the misalignment angles are the desired values, which differ from the actual misalignment angle due to the system's accuracy.

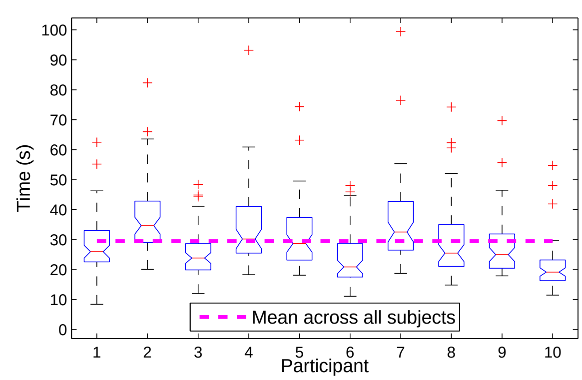



Fig. 12: Each participant's task completion times for each trial, showing the median trial time, the 25th/75th percentile trial times, and outliers for the camera viewpoint misalignment study.

TABLE II: $p$-values for the post-hoc comparison of each pair of misalignment axes using the t-test for the viewpoint misaligment study.

| Axis | Yaw | Roll | Combination |
|---|---|---|---|
| Pitch | 0.2739 | 0.4012 | 0.0059 |
| Yaw | – | 0.0442 | 0.0836 |
| Roll | – | – | 0.0002 |

Using the Bonferroni adjustment, for $\alpha = 0.05$ the corrected value becomes $\alpha_c = 0.0083$. Statistically significant values are highlighted in red.

The relation between the desired and actual misalignment angle is presented in Fig. 5.

The results suggest that humans can adapt to and compensate for approximately $20 - 30°$ of misalignment in a teleoperated system. As the misalignment angle increases, the task becomes significantly more difficult and arduous. Because the effects of the misalignment axes varied between studies we conclude that this factor does not contribute to the performance as significantly as the misalignment angle.

The results from this study can contribute to a better understanding of human ability to perceive and compensate for teleoperation misalignments. One can also use the results as a guideline to balance trade-off between accuracy and cost when designing a teleoperated robotic system. As a future extension of this work, we would like to investigate the effect of tool misalignment in bi-manual teleoperation tasks, as most surgical teleoperation requires bi-manual manipulation. Another interesting research topic is to explore the possibility to reduce or compensate for tool misalignment in teleoperated systems using visual and haptic feedback. We are particularly interested in cutaneous tactile feedback as guidance signal in teleoperation.

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