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ORIGINAL ARTICLE

A "pickup" stereoscopic camera with visual-motor aligned control for the da Vinci surgical system: a preliminary study

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Abstract

Purpose The current state-of-the-art surgical robotic systems use only a single endoscope to view the surgical field. Research has been conducted to introduce additional cameras to the surgical system, giving rise to new camera angles that cannot be achieved using the endoscope alone. While this additional visualization certainly aids in surgical performance, current systems lack visual-motor compatibility with respect to the additional camera views. We propose a new system that overcomes this limitation.

Methods In this paper, we introduce a novel design of an additional "pickup" camera that can be integrated into the da Vinci Surgical System. We also introduce a solution to work comfortably in the various arbitrary views this camera provides by eliminating visual-motor misalignment. This is done by changing the working frame of the surgical instruments to work with respect to the coordinate system at the "pickup" camera instead of the endoscope.

Results Human user trials ($N = 14$) were conducted to evaluate the effect of visual-motor alignment with respect to the "pickup" camera on surgical performance. An inanimate surgical peg transfer task from the validated Fundamentals of Laparoscopic Surgery (FLS) Training Curriculum was used, and an improvement of 73% in task completion time and 80% in accuracy was observed with the visual-motor alignment over the case without it.

Conclusion Our study shows that there is a requirement to achieve visual-motor alignment when utilizing views from external cameras in current clinical surgical robotics setups. We introduce a complete system that provides additional camera views with visual-motor aligned control. Such a system would be useful in existing surgical procedures and could also impact surgical planning and navigation.

Keywords Surgical robotics · Robot-assisted surgery · Minimally invasive surgery · da Vinci surgical robot · Stereoscopic imaging · Visual-motor alignment

Introduction

Technological advancements in robotics and computation have bolstered robot-assisted surgeries in which robotic arms holding surgical tools are inserted inside the patient's abdomen through small incisions. The surgeon then sits at a remote console and operates another set of robotic arms that control the ones inserted within the patient. 3D visualization, increased dexterity, tremor reduction, and additional degrees of freedom are some of the advantages surgeons enjoy over traditional laparoscopic systems.

The da Vinci Surgical System™ (Intuitive Surgical Inc, CA) has been the most successfully used clinical robot. In a typical robot-assisted surgery with the da Vinci, a single endoscope transmits images from the surgical scene to the stereoscopic display present at the surgeon's master console. The other two (or three) arms hold surgical instruments that perform the procedure. All the robotic arms have a fixed center of motion (point of insertion) about which their distal ends move. This limits the movements of the arms to a confined space that is dependent on the incision point. As a consequence, there are certain views of the surgical scene that the endoscope cannot provide. To overcome this problem, many

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research groups have proposed the use of external camera systems.

Research in this area can be divided into two main categories. First, the use of alternative imaging probes instead of the endoscope and second, the use of these alternative probes complementary to the endoscope. Of the first type, flexible imaging probes are proposed in [16]. Similarly, Hu et al. [6] introduce an imaging device with pan, tilt, and zoom capabilities that can be remotely controlled. Both these designs require external control manipulators like a joystick which would disrupt the surgeon's existing workflow. The concept of inserting and affixing cameras inside the abdominal wall has also been frequently studied. Simi et al. [14] utilize magnets for the insertion and control of camera movement, while Castro et al. [2] use wireless networks to control and stream images from a camera. Concerns of safety in the operating room, however, may arise with the continuous use of magnets. Wireless streams could be interrupted and thus may not be a reliable or secure mode of communication.

More relevant to our proposed system, Velasquez et al. [17] use an actuated imaging probe to provide auxiliary visualization in addition to the areas imaged by the endoscope. The imaging probe shares its axis with a surgical instrument and provides a narrow close-up view of the surgical scene. Their system has the option to switch between the views provided by this additional camera and the endoscope. The result of their user studies ($N = 3$) shows that their system performs favorably when the images from the endoscope are occluded.

An interesting point to note while reviewing the above literature is that the original control of the da Vinci arms has been left unchanged. This means that the surgical tools are controlled with respect to the coordinate system at the endoscope, even when viewing images from additional camera sources. Without correcting for this, these previously mentioned systems would introduce visual-motor misalignment. Studies have been conducted where performance deteriorates as this misalignment increases [8,9]. Embedded in human factor research, it has been shown that teleoperation conditions successfully achieving visual-motor compatibility have the best performance [19]. Applying this concept to the surgical field, it is important to achieve visual-motor alignment in all cases, not just while viewing the endoscopic images. Failing to do so could disorient the surgeon and provide difficulty in performing the task.

At this point, we introduce and summarize the contributions of this paper:

1. Firstly, we introduce a design of a novel "pickup" camera probe that can be inserted inside the patient through a surgical incision and picked up by a surgical instrument.
2. Secondly, we present a method of switching the working frame of the da Vinci arms to work with respect to the coordinate system at the "pickup" camera to provide visual-motor consistency.

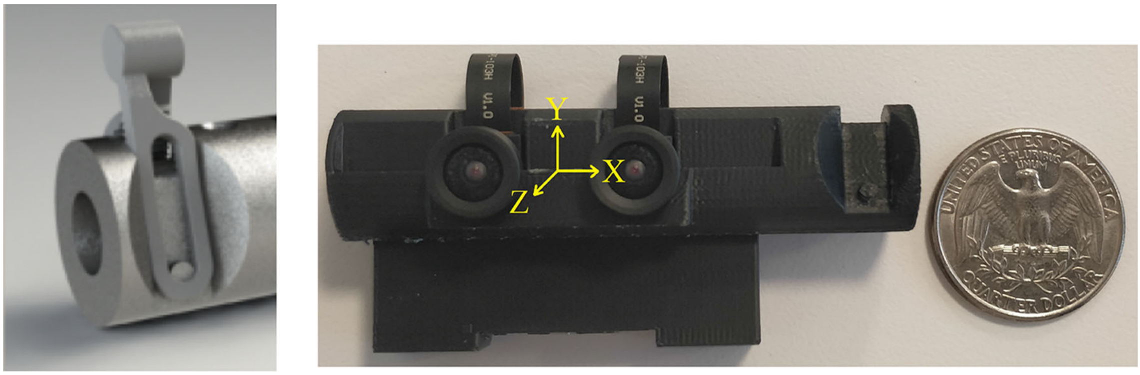
Our work is directly applied to the da Vinci Surgical System and thus allows potentially fast and easy integration of our system into current clinical setups. Control of this "pickup" camera will be through the instrument itself, which is in turn controlled by the master manipulator present at the master console. Thus, no external control device is added to the robotic system, and the surgeon's workflow remains undisrupted. By changing the working frame, we eliminate any visual-motor inconsistency that may arise due to the position of the camera inside the patient. This allows for intuitive control of instruments even in the most extreme camera positions. We hypothesize that working with our proposed system can improve teleoperation and surgical performance compared with previous approaches.

Material and methods

"Pickup" camera design

The design of our camera probe is based on work done previously by our research group [13]. A "pickup" ultrasound transducer was designed and developed that could be dropped inside the patient and grasped by a da Vinci surgical instrument. We used the same "stable grasp" concept to allow the da Vinci ProGrasp forceps to repeatably grasp the camera assembly (see Fig. 1a). Our camera provides 3D views of the scene with a larger stereo baseline (17 mm, compared to 5 mm of the endoscope) which can improve the perception of depth. The schematics of this probe are shown in Fig. 2a, b, and the 3D printed prototype with the cameras is shown in Fig. 1b. With this design, the camera can easily be controlled by the master manipulators present at the surgeon console, thus eliminating the need for additional control hardware. By design, the da Vinci tools possess six degrees of freedom (DOF) in space. These DOFs are automatically transferred to the "pickup" camera, increasing the area of the surgical scene that can be imaged. The camera can thus be tilted and panned in any of these directions.

The "pickup" camera probe would be inserted through the surgical trocar or adjacent to the trocar before the robotic arm has been inserted as mentioned similarly in [13]. A low-resolution camera could be added to the distal end of the probe so that insertion of the "pickup" camera is not carried out blindly. Once dropped, using the images from the endoscope, the surgical tool can be navigated to grasp the probe using the stable grasp design. Thus, the coordinate frame of the camera is fixed relative to the ProGrasp tool tip. Subsequent movement of the robotic arm does not affect this transformation which is utilized in establishing visual-motor



(a) **(b)**

Fig. 1 **a** da Vinci ProGrasp engaged with the mating interface. **b** 3D printed probe: the frame in yellow represents the frame at the "pickup" camera (z-axis points into the view). Coin shown for scale

consistency, as explained later in the paper. In the rest of this paper, the terms "pickup" camera and additional camera refer to the same stereoscopic camera and will be used interchangeably.

Hardware and software

The stereoscopic cameras used are USB 3.0 Colour Stereo cameras from Leopard Imaging (LI-OV580-OV9782ST). The tool used to hold this camera is the da Vinci ProGrasp tool. Additionally, a frame grabber (BlackMagic DeckLink) is used to push the camera images to the surgeon console using a script written in C++.

For safety reasons, the clinical API provided by Intuitive Surgical can be used to only read information from the da Vinci systems. We use the da Vinci Research Kit (dVRK), developed at John Hopkins University, to read information from the da Vinci as well as make changes to the underlying control architecture [7]. Both the clinical API and dVRK are used to read the necessary transforms required for achieving visual-motor consistency as explained in the next section.

All code is written in C++ using the Robot Operating System (ROS) framework. dVRK provides a ROS integration that allows information to be easily read and sent to the da Vinci system. The PC used is a Linux-based system with Ubuntu 16.04, ROS Kinetic, and dVRK v1.6.

Transformation change

To achieve visual-motor consistency in the additional camera view, we changed the control scheme of the da Vinci arms so that they move with respect to the "pickup" camera coordinate system. Using our method, the surgeon can easily switch between the views of the endoscope and the "pickup" camera and the control scheme will change accordingly to maintain visual-motor consistency. To make this change, we first review the various coordinate frames present in the da Vinci system and the transformations required.

Each da Vinci Patient-Side Manipulator (PSM) is supported by Setup Joints (SUJ) that connect it to the central robot shaft. These SUJs position the PSMs at pre-planned incision ports and remain stationary. The point of incision serves as a remote center of motion, and the tool tip moves about this center. Thus, the SUJs essentially fix the base of each arm. The main coordinate frames to consider are shown in Fig. 3. The endoscope is held by the Endoscope Control Manipulator (ECM). The transformation ${}^{X}\mathbf{H}_{Y}$ represents the transformation from frame Y to frame X. The black and blue paths in Fig. 3 show the existing transformation used to control the tool tips with respect to the coordinate frame at the ECM tip. The positions of the tool tip (defined with respect to the PSM Base) are transformed to the ECM frame by using this transformation, as shown in Fig. 3 in black and blue and outlined in Eq. 1. This way, all movements of the tool tip will be in the frame of the endoscope, thus maintaining visual-motor consistency when looking at the images from the endoscope. Equation 1 shows the existing transformation for one of the PSMs.

$$ {}^{ET}\mathbf{H}_{PT1} = {}^{ET}\mathbf{H}_{EB}\,{}^{EB}\mathbf{H}_{RB}\,{}^{RB}\mathbf{H}_{PB1}\,{}^{PB1}\mathbf{H}_{PT1} \tag{1} $$

The black and red paths in Fig. 3 show the transformation required to change the base working frame to that of the additional camera instead of the endoscope. The final required transformation is Eq. 2. Here, the chain runs through the base frame of PSM1, to the robot base frame, to the base frame of PSM2, to the PSM2 tool tip, and finally to the frame present at the "pickup" camera. Again, the transformation for only one arm (PSM1) is shown. The "pickup" camera is held by

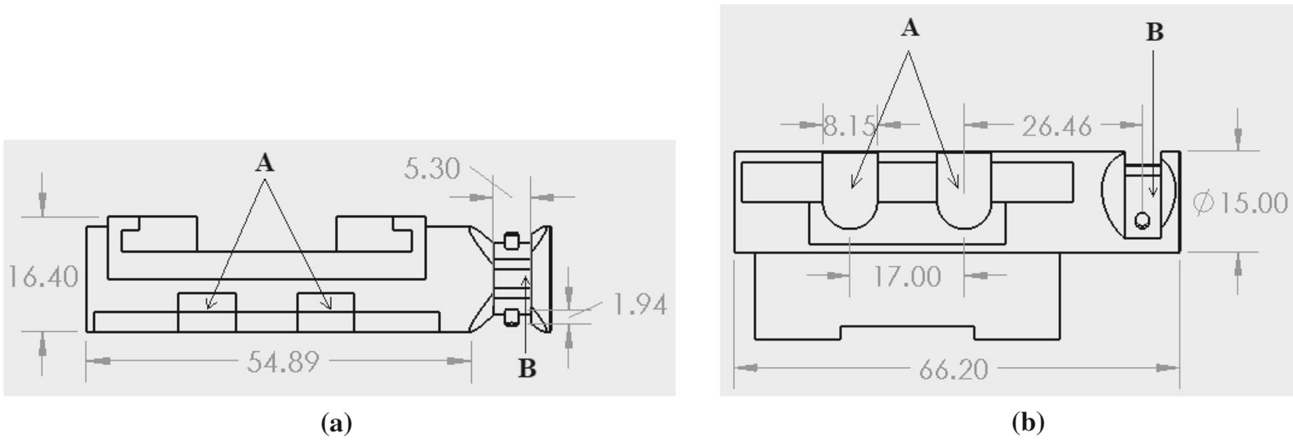


Fig. 2 "Pickup" camera schematics: **a** Top view. **b** Front view. All dimensions shown are in millimeters (mm). **A** The area where the cameras as placed and **B** the grasping interface

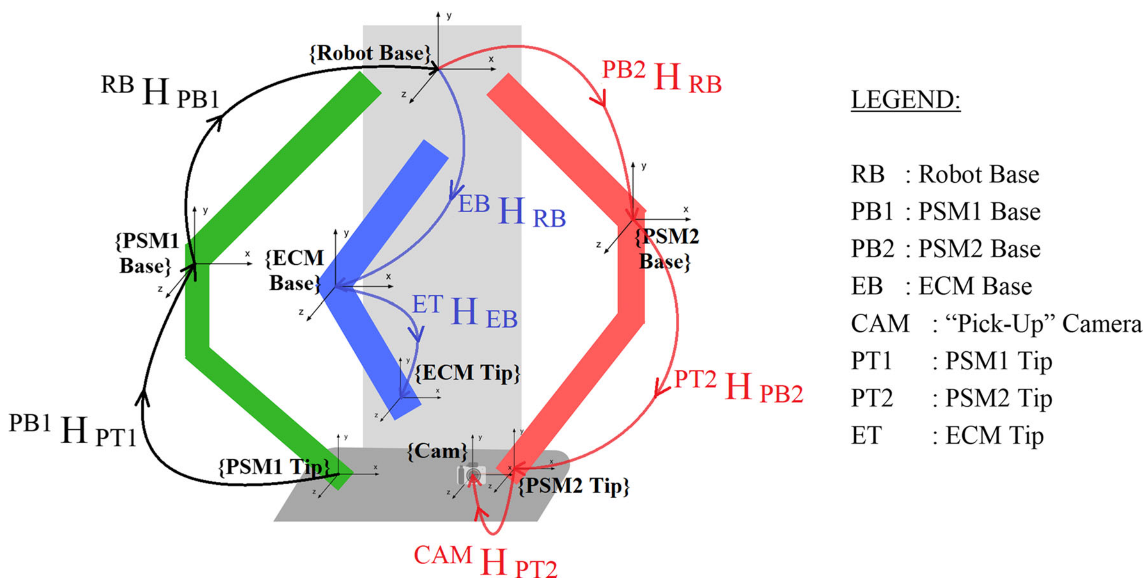


Fig. 3 Relevant coordinate systems of the da Vinci Standard and the relevant transformations. The transformation with respect to ECM is shown in black and blue paths. The transformation with respect to "pickup" camera is shown in black and red paths

PSM2. A similar transformation can be applied for the third arm (PSM3).

$$^{CAM}\mathbf{H}_{PT1} = {}^{CAM}\mathbf{H}_{PT2}{}^{PT2}\mathbf{H}_{PB2}{}^{PB2}\mathbf{H}_{RB}{}^{RB}\mathbf{H}_{PB1}{}^{PB1}\mathbf{H}_{PT1} \quad (2)$$

Once the SUJs are fixed, the arms are held in place and the transformations between the Robot Base and the PSM Bases ($^{PB2}\mathbf{H}_{RB}$ and $^{RB}\mathbf{H}_{PB1}$) are constant rigid transforms that can be read through the clinical API. The tool tip positions with respect to the PSM base frames ($^{PB1}\mathbf{H}_{PT1}$ and $^{PB2}\mathbf{H}_{PT2}$) are computed from the DH parameters and are continuously read through dVRK. The transform from the tool tip to the center of the additional camera ($^{CAM}\mathbf{H}_{PT2}$) is a fixed rigid transform obtained from the CAD models of the additional camera probe.

Experimental evaluation

Experimental setup

We conducted a user study ($N = 14$) to evaluate our proposed system. The setup is shown in Fig. 4. The dVRK was used to retrieve the position of surgical instruments, calculate the necessary coordinate transformations, and set the working frames of the patient-side robotic arms. Two computers were utilized for the study: one computer (PC1) for handling coordinate transformations and communication with the dVRK, and another computer (PC2) for projecting the additional camera views onto the surgeon master console. The additional camera was held directly by a da Vinci instrument (see Fig. 4c) and was placed in a position that cannot normally be reached by the endoscope without moving the entire setup joint and repositioning, which is not normally done during surgery. We simulated a case in which a visual occlusion is present in the endoscopic view, blocking the surgeon from viewing the surgical areas and/or surgical tools (see Fig. 4b). In such a scenario, the additional camera is helpful in providing an alternative view of the surgical scene which provides the surgeon with valuable information (see Fig. 4c).

User study

Subjects were asked to perform an inanimate surgical peg transfer task from the Fundamentals of Laparoscopic Surgery (FLS) Training Curriculum [11] using the da Vinci Surgical System. The task involves transferring triangles placed on pegs from one side of the board to the other and back, by transferring them mid-air between the two tools. It is a bimanual task that tests the user's ability to manipulate the instrument translationally, reorient the tool to enable smooth transfer from non-dominant to dominant hand, and gauge depth to pick up and place the triangles back down. For our study, we asked subjects to transfer three triangles from their non-dominant to their dominant hand.

We conducted a repeated-measures study in which each subject performed the same task twice: once in the control setting and once in the experimental setting. In the control setting, subjects were asked to perform the task using the view from the additional camera but in the working frame of the endoscope (as would be the current setting, with visual-motor misalignment). In the experimental setting, subjects were asked to perform the task using the view from the additional camera while working in the frame of the additional camera (using our method, eliminating the visual-motor misalignment). At all times, subjects viewed the surgical field as seen from the additional camera. Before each task, the subjects were given five minutes to familiarize themselves with the respective control setting and the task. To account for any learning bias in this within-subject design, counterbalancing was employed by controlling the order in which each subject performs the two tasks.

Performance metrics

The completion times and number of errors made in both conditions were recorded to evaluate the performance of the subject. The completion time was recorded from the time the subject attempted to pick up the first triangle to the time the last triangle was dropped onto the peg. An error was considered to occur if a triangle was dropped anywhere but the peg over which it was supposed to be placed. In such a case, the subject was told to leave the dropped triangle and move onto the next one. The completion times were recorded using a stopwatch on a mobile phone, and the number of errors was visually recorded. Lastly, each subject was asked to fill out the NASA Task Load Index [5] after each task as a measure of the subjective load experienced by the participant.

Results

The recruited subjects were novice users of the da Vinci Surgical System. Fully informed consent was obtained from all individual participants, and the study was conducted with approval from the UBC Research Ethics Board (Study Number: H18-01845). To determine the total sample size for the final study, a pilot study ($N = 4$) was conducted and an a priori power analysis was conducted using the G*Power application [4]. The chosen test family was the t test; the chosen statistical test was the 'Means: Difference between two dependent means (matched pairs)' test. The effect size was calculated based on the mean of the difference in completion times (142.75 s) and standard deviation (SD = 81.67). The calculated effect size was 1.74. Choosing an input error probability of ($\alpha = 0.05$) and desired power of ($1 - \beta = 0.95$), the computed sample size was 6. To account for any possible outliers and/or loss of data, we recruited 15 subjects for the study. The completion times and the number of errors for all the subjects were recorded. Data from one subject was incomplete due to a system failure during the experiment and hence was discarded. This brought the total number of valid subject data to 14.

Figure 5a shows the completion time (in seconds) for each subject, with the control task in blue and the experimental task in red. The mean completion times show an improvement of 72.9% for the experimental condition (115 s) over the control condition (425 s). For all subjects, the completion time of the experimental task is at least 41 s lower than that of the control task. The minimum difference between the two tasks (41 s) was achieved by Subject 4, while the maximum difference (653 s) was achieved by Subject 7. This shows an improvement in completion times across all 14 subjects with our method. Similarly, Fig. 5b shows the number of errors made by each subject. Entries marked with an asterisk (*) represent zero errors and are not missing data. Fifty-seven percentage of the subjects made one or more errors during the control task, while only 14% made one or more errors during the experimental task. This clearly shows that accuracy is also improved with our method. On average, subjects were 80% more accurate with our method. Therefore, the results confirm that both completion times and accuracy are improved when visual-motor consistency is maintained.

Data was analyzed using the t test function in MATLAB. Figure 6 shows the box plots of the completion times and accuracy across all 14 subjects. Statistical significance was achieved between the two sets of time measurements ($p =$

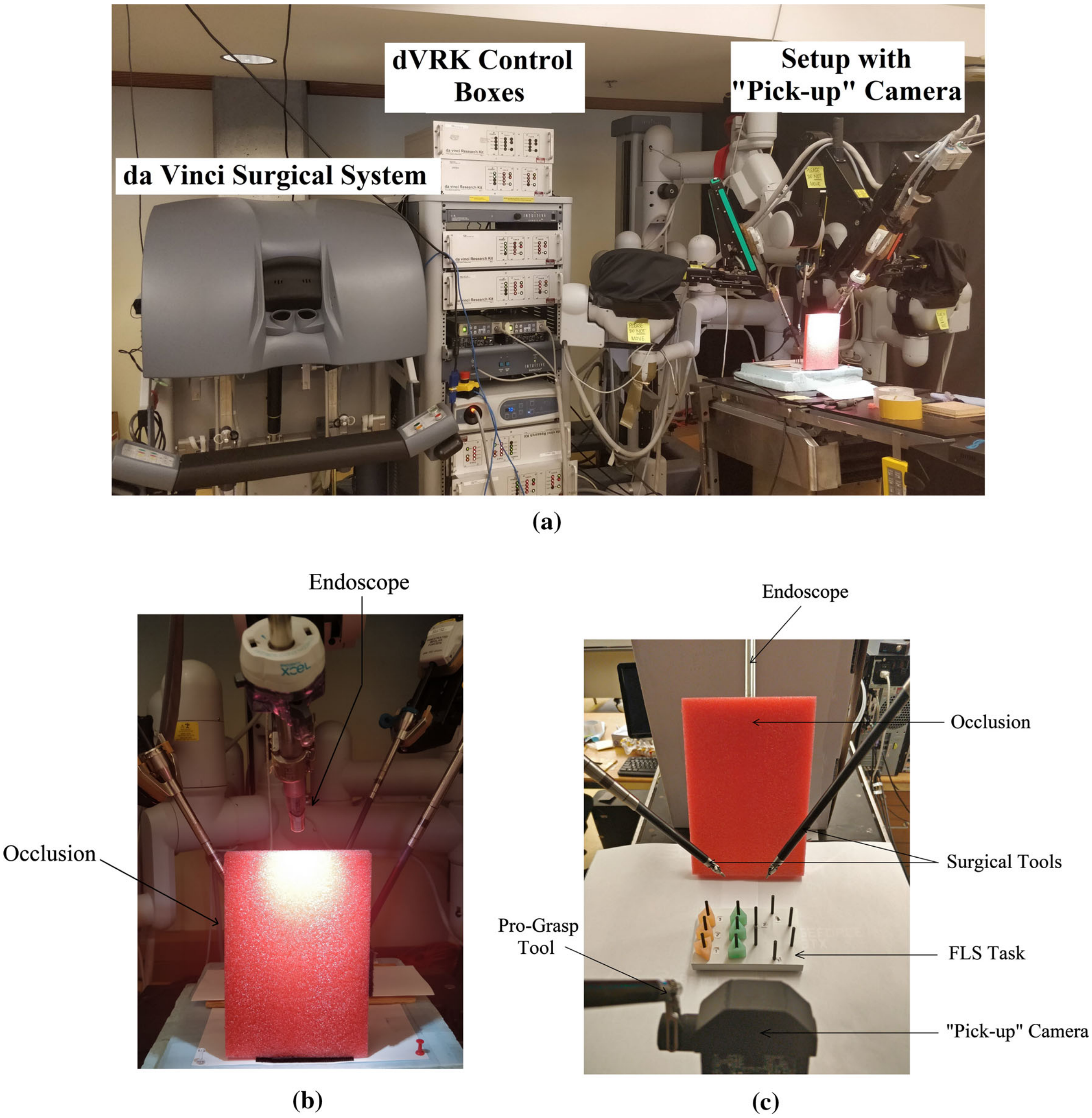


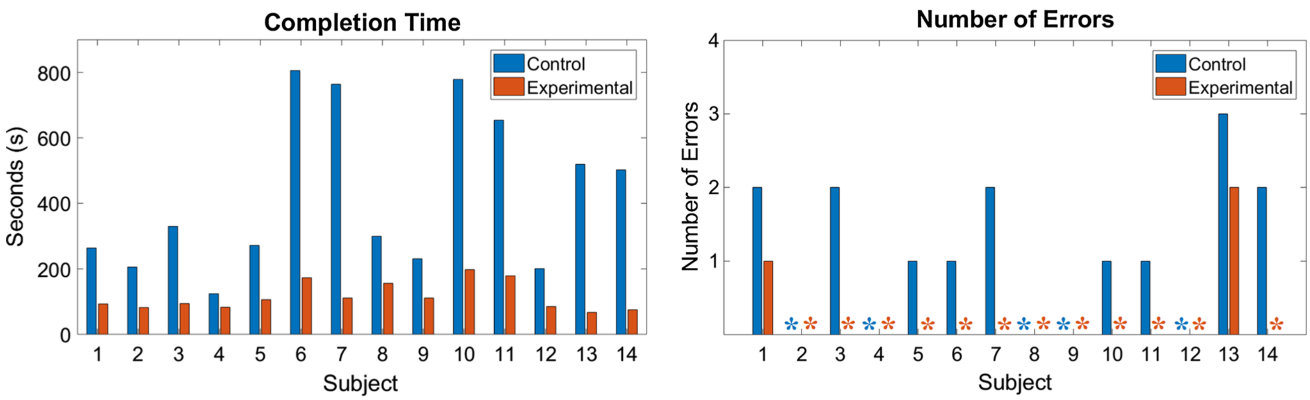
Fig. 4 Experimental setup: **a** da Vinci Standard Surgical System with dVRK. **b** As seen from the endoscope side. **c** As seen from the "pickup" camera side

0.0001) and error measurements ($p = 0.0011$). A post hoc power analysis was conducted with G*Power. An input error probability of ($\alpha = 0.05$) was chosen, and the effect size was calculated based on the mean of the difference in completion times ($309.85s$) and SD (216.69). The calculated effect size was 1.4299. The computed power of the experiment was found to be 0.99.

The NASA Task Load Index requires subjects to rate six performance measures on a 21-point scale to assess the subjective load of performing each task. The lower the rating for each performance measure, the better the subject feels about his/her performance. From Fig. 7, it can be seen that on average, all subjects felt more favorably toward the experimental task (statistical significance levels mentioned). There was no statistical difference in the temporal demand ratings. The temporal demand is a function of the task, and since the same task was used in both conditions, we did not expect any statistical difference. For our experiment, we were particularly interested in the mental demand, physical demand, and frustration experienced by the subjects. Ninety-three percentage of the subjects submitted lower scores for mental demand, 78% for physical demand, and 93% were less frustrated when executing the experimental task.

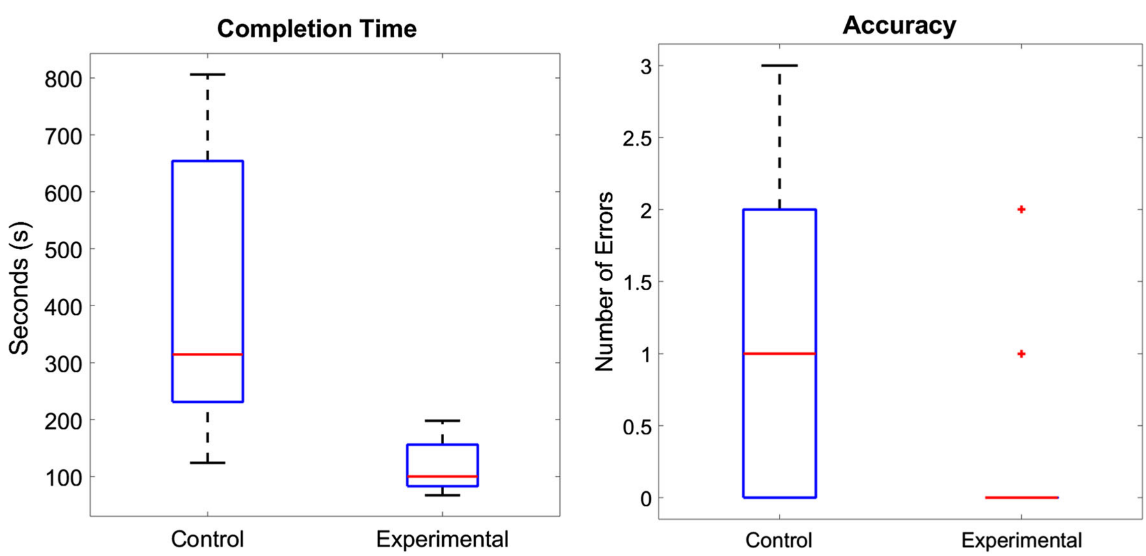
Discussion

The results show that visual-motor alignment is necessary to provide the best surgical performance. We simulated a



(a) **(b)**

Fig. 5 Comparison of the subjects' individual performances using both methods: **a** Completion times. **b** Accuracy: entries marked with an asterisk (*) represent 0 errors and are not missing data



(a) **(b)**

Fig. 6 **a** Completion time. On average, time taken to perform the task in the experimental setting was 72.9% lower. **b** Accuracy. On average, participants made 80% fewer errors in the experimental setting

situation in which the surgical task is completely occluded from the endoscopic view. With the design of our "pickup" camera, the surgeon has the freedom to place it in any position that would provide better views of the surgical scene. In our user study, it was placed opposite to the position of the endoscope, thereby getting around the occlusion. For the purpose of this preliminary proof-of-concept study, we kept the position of this "pickup" camera fixed. However, in practical usage, the surgeon would be able to move the camera dynamically and still achieve visual-motor alignment at every given point and time with our method. To exploit the full use of the imaging probe's design, we plan to conduct further experiments with dynamically moving camera views. With our change in working frame, visual-motor consistency will be continuously established at each instant; eliminating any potential mental strain the surgeon will experience. The surgeon's workflow will remain uninterrupted, allowing for a comfortable switch between two different views: endoscopic and additional camera.

A possible application of our system would be partial nephrectomy, a surgery in which a kidney tumor must be removed [15]. The tumor margins may not be visible from the main endoscope as the kidney itself may block the view. Placing an additional camera opposite to the endoscope would eliminate the need to do this, and the surgeon could perform the resection utilizing views from both the endoscope and the additional camera. Colorectal resection requires multiple placements of the endoscope to provide

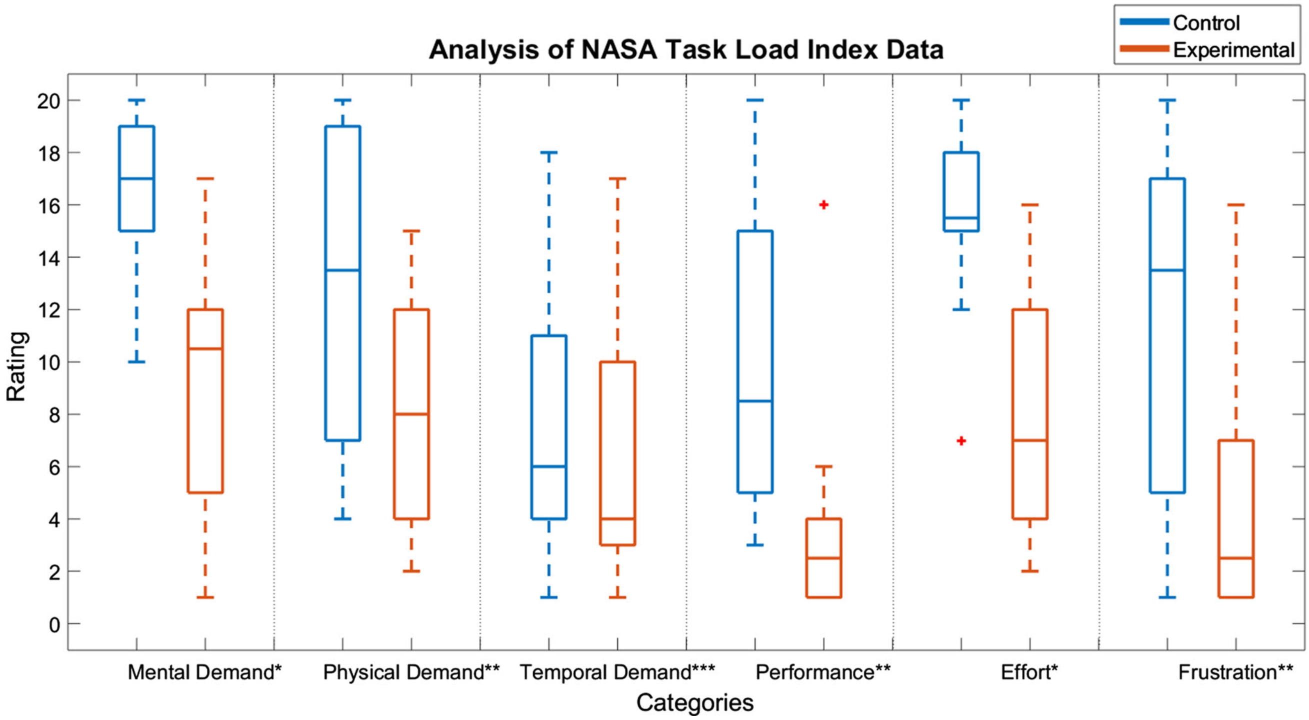


Fig. 7 Analysis of NASA Task Load Index data: TLX ratings as submitted by the subjects for both control and experimental settings. Significance levels were calculated using a t test in MATLAB and are indicated with $^{***}p = 0.20918$, $^{**}p < 0.0005$ and $^{*}p < 0.00005$ next to the corresponding X axis labels

the surgeon with better views of the surgical field [18]. This can be eliminated by using an additional camera in the required alternative position and switching between the available views as required, reducing and optimizing total operation times. Similarly, other areas of application of our proposed system would be the retroperitoneal lymph node dissection (RPLND) [3], robot-assisted radical cystectomy with extracorporeal urinary diversion [10] and with intracorporeal urinary diversion [12].

Besides current surgical procedures that would benefit from having multiple views, being able to work comfortably in any arbitrary camera view opens up further possibilities. An important part of robot-assisted minimally invasive surgery is port placement. The identification of optimal incision points on the patient's body is a vital step in the surgical planning procedure. The selection of these points are based on certain criteria that can be achieved: visibility, dexterity, reachability, patient trauma, and surgeon comfort [1]. Surgeon comfort here refers to the degree of hand-eye (or visual-motor) alignment. Points that optimize these criteria are chosen for incision. Currently, visibility is offered only by the endoscope. Our system introduces not only another tool that offers visibility, but also contributes to surgeon comfort with those views. Having access to an additional such "tool" could modify the port placement procedure and consequently potentially modify the conduction of the surgery itself. The introduction of this system could generate new plans to perform surgical procedures; new methods could prove to be more effective than the existing protocols. We believe that the availability of this technology will impact future surgical planning and implementation.

Conclusion and future work

Current robot-assisted systems utilize a single endoscope to provide the surgeon with images of the surgical site inside the patient. While prior work has included added cameras to the da Vinci system, this paper outlines the necessity of achieving visual-motor consistency with these additional camera views. We presented a novel design of an additional imaging probe and also implemented a method to change the working frame of the da Vinci Surgical arms to work with respect to the coordinate system at this additional camera. A randomized control study was conducted to evaluate the effect of this system on surgical performance. Our results show that the proposed method leads to a 73% improvement in completion time and 80% improvement in accuracy of a surgical task. Based on a standard subjective assessment tool, the subjects also felt more comfortable and confident working with our proposed system. This new imaging probe, along with the change in working frame, can be used together to allow surgeons to work comfortably in new and different views.

Our current system is an initial prototype meant only to serve as a proof-of-concept model and warrants design improvements before it can be considered for animal studies. The current prototype includes a casing for the electronics board of the camera which makes the module larger than a 15-mm-diameter cylinder. However, future design iterations would reduce the overall size of the probe to be easily dropped and manipulated within the human body. Use of an alternate camera with more compact electronics, for example, can be easily made to fit in a cylinder of 15 mm. This can be inserted either through a trocar or adjacent to it, as proposed in [13]. Finally, a real prototype would have to have some mechanism (wiper, irrigation) to wash out blood and debris that may accumulate on the camera. This could be done easily as the camera can be "seen" by the main endoscope.

We plan to test the newer prototype, more suitable for in vivo animal trials, with wet laboratory tasks such as suturing. More realistic experimental setups such as when the endoscopic views are only partially occluded would also be included in the testing. Another direction of future work is to identify the ideal placement of the "pickup" camera so as to improve perception of depth. This would be accompanied by tests that compare depth sensing as achieved by the "pickup" camera against that achieved by the current endoscope. We believe this system could be valuable in surgeries like the partial nephrectomy where having multiple viewpoints could facilitate smoother conduction of the procedure. The introduction of this system could also impact surgical planning, introducing novel ways of attacking existing problems and consequently producing better surgical outcomes.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

Ethical approval All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Declaration of Helsinki and its later amendments or comparable ethical standards.

Informed consent Informed consent was obtained from all individual participants included in the study.

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