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Workspace Analysis of Robotic Manipulators for a Teleoperated Suturing Task

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Abstract

An important missing piece in the medical robotics literature is the lack of systematic methods to quantitatively compare different manipulator designs, and to evaluate kinematic configurations chosen for telesurgical manipulators in application-critical tasks. Such a quantitative method is especially important during design stage to make an informed decision between various design alternatives. In this paper, a quantitative method to evaluate the kinematic ability of surgical manipulators to perform the critical tasks of suturing and knot tying is presented. The proposed method does not require a physical prototype. This is achieved by running typical tool motions during these tasks through the inverse kinematics of the manipulators and checking if the system can accommodate the desired motions. The system can perform a given motion if the whole trajectory lies continuously within the workspace of the manipulator. Open surgical suturing motion data collected from experiments done with expert surgeons is used as the set of desired tool motions used in the analysis. The method is applied to compare two different wrist configurations of telesurgical slave manipulators, intended for use in minimally invasive surgery, by looking at the requirements on joint ranges and wrist manipulability during these motions.

Keywords — Medical robotics, robotic telesurgery, kinematics, workspace analysis, laparoscopy, thoracoscopy.

1 Introduction

Medical robotics and computer assisted surgery (MRCAS) is an emerging area of research on the application of computers and robotic technology to surgery, in planning and execution of surgical operations and in training of surgeons. With robotic telesurgery, the goal is to develop robotic tools to augment or replace hand instruments used in surgery.

One of the main application areas of MRCAS is minimally invasive surgery (MIS). MIS is a revolutionary technique in surgery [10], where the operation is performed with instruments and viewing equipment inserted through small incisions (typically less than 10mm in diameter) rather than by making a large incision to expose and provide access to the operation site. The main advantage of this technique is the reduced trauma to healthy tissue, which is the leading cause of patients' post-operative pain and long hospital stay. The hospital stay and rest periods, and therefore the procedure costs, can be significantly reduced with MIS, but MIS procedures are more demanding on the surgeon, requiring more difficult surgical techniques.

The first major laparoscopic surgery (MIS in the abdominal cavity), for cholecystectomy (removal of the gall bladder), was performed in 1985 by Mühe in (West) Germany. In less than a decade, there was a quick shift from open surgery to laparoscopic surgery for relatively simple procedures, with 67% of cholecystectomies performed laparoscopically in the US in 1993 [3]. Adoption of laparoscopic techniques has been slower in more complex procedures, largely because of the greater difficulty due to the surgeon's reduced dexterity and perception. The next frontier in MIS is thoracoscopy (MIS in the chest cavity), in particular minimally invasive coronary artery bypass grafting surgery, which has been recently getting a lot of attention in the research and commercial medical equipment development communities.

Typical laparoscopic and thoracoscopic instruments have only 4 degrees of freedom (DOF) (see Fig. 1),

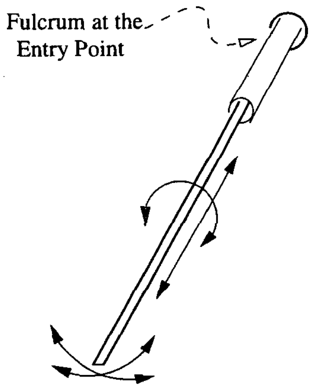


Figure 1: 4 DOF available in conventional laparoscopic instruments

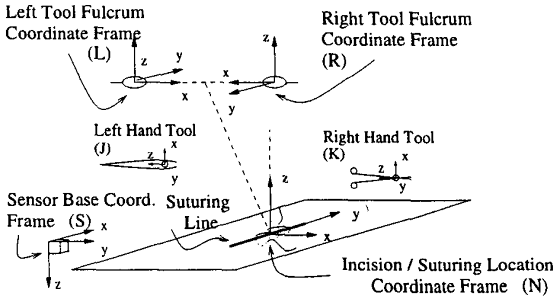


Figure 2: Coordinate frames used in the analysis.

preventing the ability to arbitrarily orient the instrument tip at a given location in space [8]. Dexterity is significantly reduced because of the lost DOF's and motion reversal due to the fulcrum at the entry point. Force feedback is reduced due to the friction at the airtight trocar and the stiffness of the inflated abdominal wall. There is no tactile sensing, on which surgeons highly depend in open surgery to locate arteries and tumors hidden in tissue. In these applications, use of a robotic telesurgical system (RTS) has been proposed as a way to improve the dexterity, hand-eye coordination, and sensation in MIS. There are several RTS developed by university and commercial companies, including the telesurgical system for open surgery with 4 DOF manipulators developed at SRI International [4] (a laparoscopic version has also been developed), the telerobotic assistant for laparoscopic surgery developed by Taylor et.al. [7], the Robotic Telesurgical Workstation developed at UC Berkeley and UCSF [2, 1], the Silver and Black Falcon manipulators by Madhani et.al. [5, 6], the Zeus system developed by Computer Motion Inc., Goleta, CA, and the daVinci system developed by Intuitive Surgical Inc., Palo Alto, CA.

An important missing piece in the MRCAS literature is the lack of systematic methods to quantitatively compare different manipulator designs, and to evaluate kinematic configurations chosen for telesurgical manipulators in application-critical tasks. Such a quantitative method is especially important during design of the manipulators to make an informed decision between various design alternatives.

In this paper, a novel approach to evaluate the kinematic ability of surgical manipulators to perform the critical tasks of suturing and knot tying without actually building a physical prototype is presented. This is achieved by running typical tool motions during these tasks through the inverse kinematics calculations of the manipulators and checking if the system can accommodate the desired motions. The system can perform a given motion if the whole trajectory lies continuously within the workspace of the manipulator. The method is then used to compare two manipulator kinematic configurations, by looking at the requirements on joint ranges and wrist manipulability during these motions.

The method uses open (i.e., non-MIS) surgical suturing motion data collected from experiments done with expert surgeons. One of the goals of robotic telesurgical systems is to enable the surgeons to use open surgical techniques for suturing and knot tying in the MIS setting by having robotic tools with sufficient dexterity and a suitable user interface. Therefore, open surgical suturing motion data is used in the analysis. This way, it is possible to evaluate if the system can be used with the natural open surgical techniques, without the need of learning new ways to perform these tasks.

2 Method

We used the open surgical suturing motion data obtained in Villanueva (2000) [9]. In that study, five experienced surgeons (four surgical fellows and one faculty from UCSF Department of Surgery) were asked to perform a simple knot tying task while the motions of surgical instruments were tracked by 6 DOF trackers. The task involved driving a curved needle into a foam rubber pad followed by tying several knots in an open surgical setting. The surgeon used a pair of needle drivers with their right hand and forceps with their left hand. The motions of the instruments were tracked by miniBIRD 6 DOF magnetic tracking devices (by Ascencion Technologies, Inc.) placed on the instruments. The miniBIRD was selected because the small size of the receiver (18 mm x 8.1 mm x 8.1 mm) allowed the surgeons to perform the task with minimal physical constraint. It has a resolution of 0.5 mm in position and 0.1° in orientation. Data was recorded at 25 samples per second. Each surgeon repeated the task for 5 trials. Fig. 2 shows the coordinate frames and the experimental setup.

Motion tracking of the instruments gives the trajectories of the left and right hand instruments as

$$g_{sj}(t) : [0,T] \rightarrow \mathrm{SE}(3) \tag{1}$$

$$g_{sk}(t) : [0,T] \rightarrow \mathrm{SE}(3) \tag{2}$$

in the sensor coordinate frame[1]. These trajectories are converted to the incision (suturing location) coordinate frame as

$$g_{nj}(t) = g_{ns}g_{sj}(t) \tag{3}$$

$$g_{nk}(t) = g_{ns}g_{sk}(t). \tag{4}$$

Here, g_{ns} is the coordinate transformation relating the sensor coordinate frame S to the incision coordinate frame N. The advantage of using trajectories in the incision coordinate frame is that it is easier and more intuitive to specify the location and orientation of the entry ports of the robot (configuration of the fulcrum coordinate frame of the robot) with respect to the suturing site.

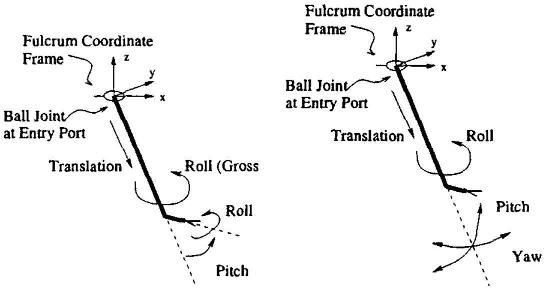
If the left and right hand robots are located (and oriented) respectively at g_{nl} and g_{nr} with respect to the incision coordinate frame, we will have the desired trajectories for the robots

$$g_{l_d}(t) = g_{ln}g_{nj}(t) \tag{5}$$

$$g_{r_d}(t) = g_{rn}g_{nk}(t), \tag{6}$$

which then can be mapped through the inverse kinematics to the joint trajectories $\theta_{l_d}(t), \theta_{r_d}(t)$. If the inverse kinematics have solution at every point during the motion and the resulting joint trajectory is continuous, then the manipulator can perform the desired motion.

Alternatively, this method can be used to determine the required joint ranges for a particular manipulator kinematic configuration, by removing the joint limits during the inverse kinematics calculations.



(a) (b)

Figure 3: Telesurgical slave manipulators with (a) Roll-Pitch-Roll and (b) Roll-Pitch-Yaw wrist configurations.

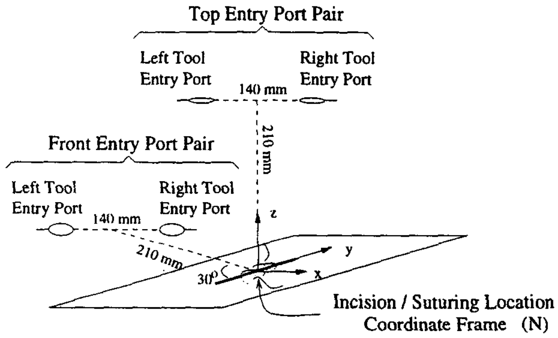


Figure 4: Entry ports of the surgical manipulators used in the workspace analysis. Top access ports correspond to steep approach angle and front access ports correspond to shallow approach angle to the suturing surface.

3 Workspace Analysis Applied to Roll-Pitch-Roll and Roll-Pitch-Yaw Wrist Configurations

In this section, the workspace analysis is applied to two telesurgical slave robots with different wrist configurations, first to determine the joint ranges required for either manipulator to replicate open surgical suturing motions for two different entry port locations, and then to determine which of these two wrist configurations is better suited for which entry port location.

The two manipulator configurations considered are shown in Fig. 3. Both manipulators have a ball joint followed by a translational joint at the base to model the entry port kinematics. The first manipulator configuration has a Roll-Pitch-Roll (RPR) wrist (the wrist

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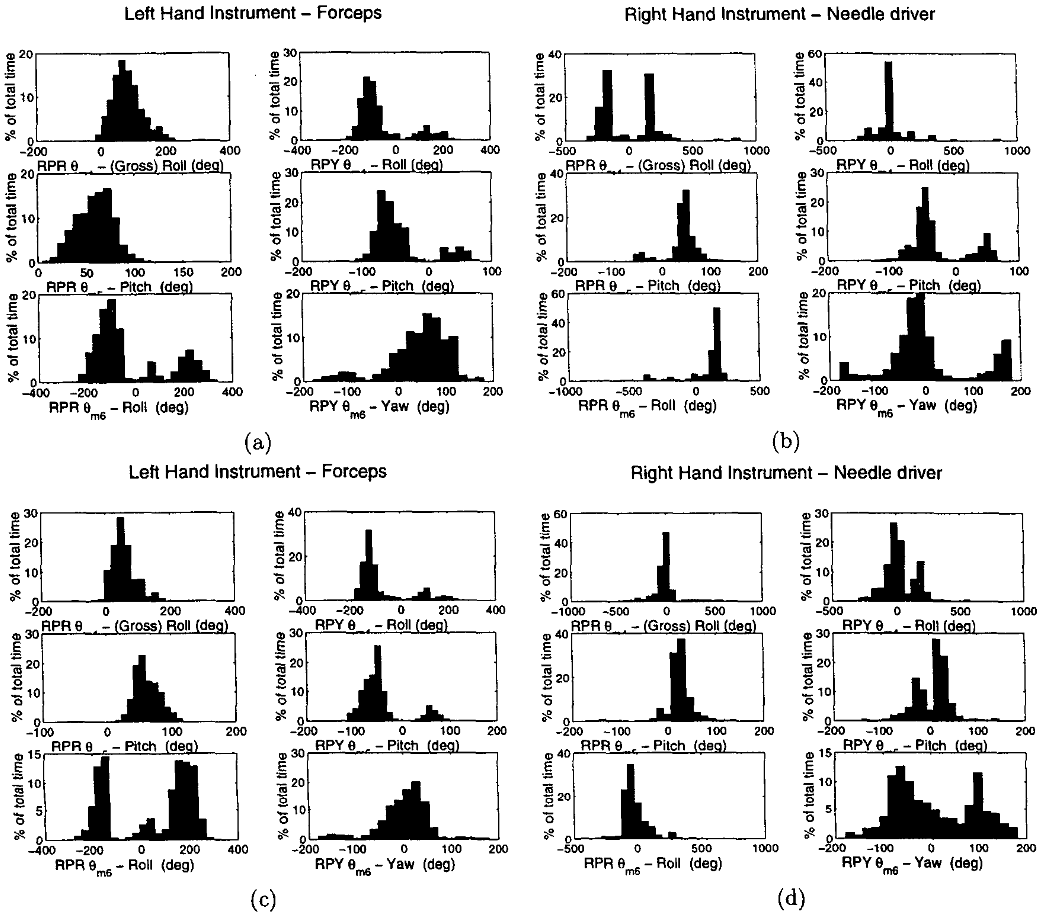
[1] For brevity, we have used continuous trajectories although the trajectories obtained experimentally are discrete samples of the actual continuous trajectory.



(a) (b) (c) (d)

Figure 5: Distribution of joint angles for top (a,b) and front (c,d) entry ports.

configuration used in the UC Berkeley/UCSF RTS) and the second configuration has a Roll-Pitch-Yaw (RPY) wrist (similar[2] to the wrist configuration of the Silver Falcon system). Due to space limitations, we are only going to focus on the wrist motions of the manipulators ignoring the gross positioning stages.

In the analysis below, we will not constrain the joint limits for the inverse kinematics solution a priori, but instead find the necessary joint ranges to be able to accommodate the desired motions with a continuous motion. When the joint limits of the rotational axes are not considered, the workspace of either manipulator is connected, which implies that if every point on the desired trajectory has a solution for inverse kinematics then it is possible to generate a joint space trajectory that is continuous.

Consider the two entry port locations shown in Fig. 4. The first location is directly above the suturing location, and the second entry port has a shallow approach angle. They respectively represent the typical approach angles for laparoscopic and thoracoscopic procedures.

Fig. 5 shows the distribution of the wrist joint angles aggregated over all the trials of all the subjects. These plots give the required angular ranges for each of the joints.

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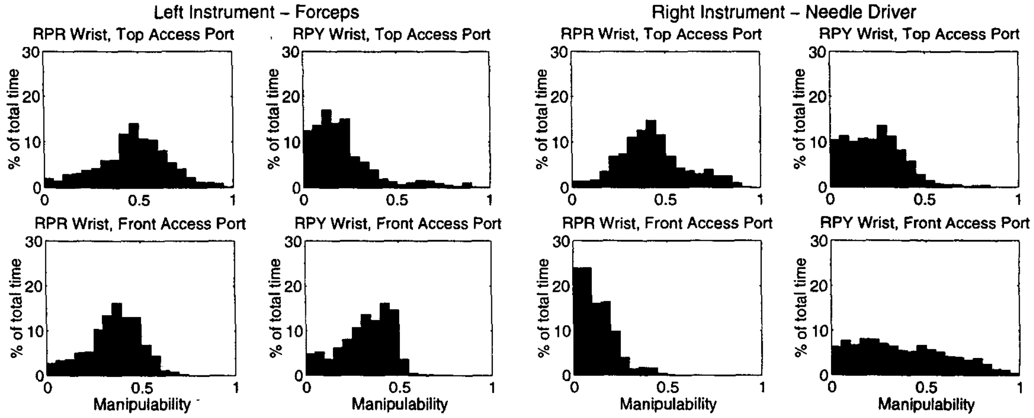
[2] The wrist of the Silver Falcon system is slightly different than the RPY configuration discussed here since the pitch and yaw axes in the wrist of the Silver Falcon system do not intersect.



(a) (b)

Figure 6: Manipulability of the wrist for left (a) and right (b) hand instruments.

Another informative measure to look at is the manipulability of the mechanism during the tasks. Here, we will use the ratio of the smallest singular value of the manipulator Jacobian to the largest singular value as the manipulability measure ($\mu = \sigma_{min}(J)/\sigma_{max}(J)$). Since the focus of this work is the wrist mechanisms, it is appropriate to consider the portion of the manipulator Jacobian corresponding to the wrist joints, and the orientation of the tool. Fig. 6 shows the distribution of the manipulability for the two wrists and two entry ports. In this manipulability measure, values close to zero indicate that the manipulator is close to a singular configuration. Therefore, during a dextrous task it is desirable to stay away from zero as much as possible. Then, Fig. 6 suggests that the Roll-Pitch-Roll wrist configuration is preferable when there is a steep approach angle to the suturing surface, which is typical for laparoscopy, and the Roll-Pitch-Yaw wrist configuration is preferable when the approach angle to the suturing surface is shallow, which is common in thoracoscopy.

4 Concluding Remarks

In this paper, a quantitative method to evaluate kinematic properties of robotic telesurgical manipulators using open surgical suturing and knot tying motion data recorded from experiments with expert surgeons is presented. Since open surgical motion data is used to evaluate the effectiveness of the system to perform suturing and knot tying tasks in minimally invasive setting, it might be desirable to segment the critical and non-critical parts of the recorded open surgical motion, especially to remove the segments corresponding to the parts of the motion when the instrument is not being actively used. This way, it possible to avoid over-conservative results.

It is also important to note that this method cannot evaluate if the system will have the complete dexterity necessary, since it looks at the problem from a purely kinematic point of view, and dexterity includes the dynamical properties of the manipulator as well as kinematics.

This method not only provides the means to evaluate a kinematic design, but also helps to determine the requirements on various design parameters, such as joint ranges. In the analysis, it is also possible to move the robot with respect to the suturing site, to evaluate the suturing abilities of the system at different location and orientations in the workspace, and this can be used to find the optimal entry port location and robot configuration for optimal performance in suturing.

Acknowledgments

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