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A Novel Surgical Manipulator with Workspace-Conversion Ability for Telesurgery

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ABSTRACT:

Robotics is a fascinating discipline that easily engages engineering students. As robots in education are stimulating and motivating, there are good reasons for introducing robotics activities very early in course curricula, allowing students to easily perceive the relationships between undergraduate courses, in their theory and practice. Robotics also offers a good basis for teaching different engineering disciplines. This Paper proposes a design of robot that is used in tele surgery. The telerobotic surgical system enables long distance tele surgery, covering the distance between patients and surgeons in remote regions of the world (e.g., in the Antarctic continent). Marescaux successfully performed transatlantic robot-assisted tele surgery using the Zeus system.

The surgeons were in New York and the patient was in Strasbourg, France. Arata conducted Japan–Thailand tele surgery experiments with animals using conventional network infrastructures. Using the concept of tele surgery, the Defense Advanced Research Program Agency explored the possibilities of the unmanned surgical operating room for treating wounded soldiers on the battlefield. The unmanned surgical operating room consists of a da Vinci system, a scrub nurse robot arm, and a tool changer. Surgical procedures in battlefields, disaster hit areas, etc., where doctors cannot reach the patients can be performed through this robot proposed in the paper.

These robots increases the distance between the doctors and the patients by enabling control through remote ways. Hence lives can be saved where doctors cannot reach like battlefields, etc. Theworkspace-conversion ability enables the surgical manipulator to attach or detach the surgical tool unit without human assistanceor an assistant robot.

Index Terms:

Robotic surgical system, surgical manipulator, telerobotic surgical system, workspace-conversion ability.

1. INTRODUCTION:

Medical robotics and computer assisted surgery (MRCAS) is an emerging area ofresearch on the application ofcomputers and robotic technology to surgery, in planning and execution ofsurgical operations and in training ofsurgeons. With robotic telesurgery, the goal is to develop robotic tools to augment or replace hand instruments used in surgery. One ofthe main application areas ofMRCAS 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 ofthis technique is the reduced trauma to healthy tissue, which is the leading cause ofpatients' 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 M¨uhe 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 oflaparoscopic techniques has been slower in more complex procedures, largely

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because ofthe 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 ofattention in the research and commercial medical equipment development communities.

2. METHODOLOGY:

The main objective of the proposed surgical anipulator is to implement the ability of orkspace conversion, in which the workspace for MIS can be converted to that for open surgery. Suturing is very complicated and important during surgery, so we assume that it is one of the most important tasks for the surgical manipulator to achieve in both MIS and open surgery with 6 DOF. If the surgical manipulator has a workspace like that of an articulated manipulator, it can attach and detach the surgical tool without human assistance using a tool loader. 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 ofsurgical 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 ofthe 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 of0.5 mm in position and 0.1° in orientation. Data was recorded at 25 samples per second. Each surgeon repeated the task for 5 trials. Concept Design of the Surgical Manipulator To satisfy FR1 in Table I, the surgical manipulator has a kinematic structure with a RCM for MIS, and when the workspace of MIS is converted to that of open surgery, the kinematic structure of the surgical manipulator can be ransformed to create a larger workspace, like that of an articulated manipulator (e.g., PUMA 560 manipulator). To have a RCM for MIS, we can use the kinematic structures such as the double parallelogram, the single spherical linkage, and theC-arm. However, these structures have a mechanically fixed RCM, making it difficult to transform their workspace into that of the articulated manipulator with no RCM by simply adding revolute joints. We present a redundant kinematic structure with three revolute joints on a plane. This kinematic structure enables the manipulator to have an arbitrary and programmed RCM on a plane using software. This RCM can be called a "virtual remote center of motion (virtual RCM)" [29]. The shoulder joints of the proposed surgical manipulator can be implemented to add revolute joints to this redundant kinematic structure. The proposed surgical manipulator consists of two parts, an interchangeable surgical tool unit inserted into the abdominal cavity and a base unit that stays outside of it.

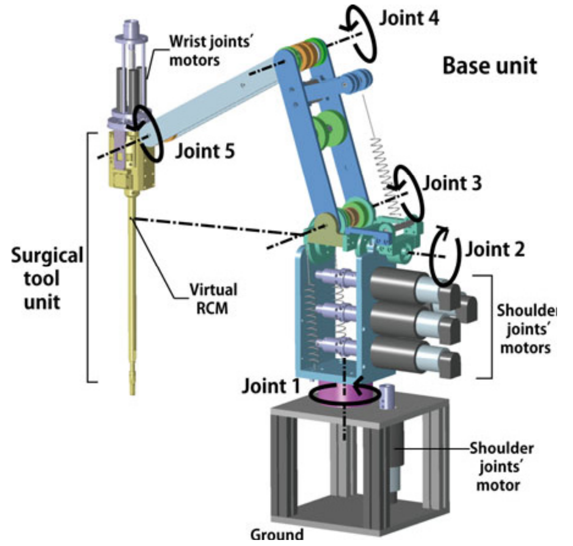
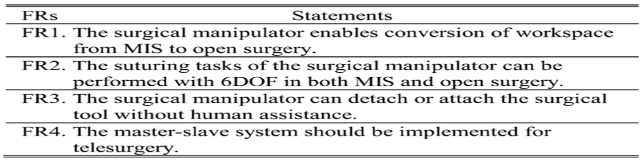


Fig. 1. Concept design of the shoulder joints in the base unit

I.3. IMPLEMENTATION:

3.1Concept Design of the Surgical Manipulator:



FRs	Statements
FR1.	The surgical manipulator enables conversion of workspace from MIS to open surgery.
FR2.	The suturing tasks of the surgical manipulator can be performed with 6DOF in both MIS and open surgery.
FR3.	The surgical manipulator can detach or attach the surgical tool without human assistance.
FR4.	The master-slave system should be implemented for telesurgery.

TABLE I Four functional requirements (FRs)

System Requirements for MIS and Open Surgery
1) Workspace: The size of the workspace for MIS varies by the position of the surgical site, the incision point, and the size of the abdominal cavity of a patient.

The measurements in [30] showthat the full extent of the abdomen can be reached if the endoscopic tool move 90◦ in a lateral/medial direction of a patient and 60◦ in a superior/inferior direction of a patient. A conventional laparoscopic tool, ENDOPATH, Ethicon Endo-Surgery,Inc., can be inserted into the abdomen to a depth of 330mm-from an incision point. We envisage the proposed surgical manipulator being used for, and having the required space for, certain types of surgical procedures such as a cholecystectomy, an appendectomy, a hernia repair, and a aparoscopy—not those that involve the deepest procedures of MIS.We would like to let thegripper of the surgical manipulator be inserted into the abdominal cavity with a depth of at least 330mm and rotate 80◦ at the remote center in both the lateral/medial direction and the superior/interior direction of a patient.

Optimization of link length of the surgical manipulator will satisfy the requirement to fully access the abdomen. There is no constraint for an incision point in open surgery; however, a larger workspace is necessary in opensurgery. The conventional open gastrectomy treating gastric cancer is usually performed through an incision from the xiphoid process (near the solar plexus) to the umbilicus [31]. When the surgical manipulator performs open surgical tasks, it is desirable that its workspace include the entire area of the patient's abdominal cavity. As the optimal waist circumference of a Caucasian male with class II obesity (BMI ≥ 35 kg/m2) is 1240mm [32],the proposed manipulator should have a workspace of a hemisphere with a radius of at least 620 mm, which is the value that the waist circumference is divided by 2. 2) Force, Speed, and Accuracy:

It was reported in [13] that about 8.9N is chosen as a desired xyz MIS manipulator tip force. According to [33], while the experts and nonexperts of robotic surgery perform peg transfer tasks using the da Vinci system, the mean grip forces of the end effectors of the da Vinci system are on average 15.3N. The robotic forceps MIS manipulator developed in [23] and [25] produce bending forces with 6.87 and 4.91 N, respectively, and grip forces with 8.34 and 4.02 N, respectively. The gripper force and the lifting force of a robotic MIS instrument should be at least 4N for suturing. As the size constraint of open surgical instruments is not as severe as that of MIS instruments, their grip forces and tip forces are larger than those of MIS instruments. A compact and lightweight anthropomorphic robot hand can be used as a retractor for robotic open surgery.

The maximum grip force of the compact and lightweight anthropomorphic hand suggested in [34] is estimated to be 126 N, which is smaller than humangrip force. In this paper, as the FRs of the surgical manipulator are focused on performing a suturing task among open surgical tasks, we will attempt to validate the performance of the surgical anipulator in suturing tasks in both MIS and open surgery. Table II represents minimum required forces of the surgical manipulator for suturing.

In the undamentals of laparoscopic surgery (FLS) tasks, the required absolute positioning accuracy for suturing and knot tying is smaller than 1 mm. Time requirements of block transfer and simple suture with an intracorporeal knot in FLS tasks are 48 and 112 s, respectively. It is mentioned that the robot end effector should be able to move at a speed of at least 60 mm/s and 30◦/s in beating-heart surgery [19].

3) Sterilization and Safety: The proposed surgical manipulator consists of two parts: 1) an interchangeable surgical tool unit inserted into the abdominal cavity; and 2) a base unit that stays outside of the cavity. The surgical tool unit can be sterilized in an autoclave or with ethylene oxide gas, whereas the base unit not in direct contact with the body of the patient can be covered with sterile drapes. When the base unit is draped, allthe motors attached to the base unit are also draped.

The drapes should be flexible not to disturb the motion of the manipulator. Contact parts between the distal portion of the base unit and the proximal portion of the surgical tool unit can be covered with thin films. Otherwise, the contact parts should be disposable parts. When the power is turned OFF, motors with built-in brakes are utilized in the base unit of the surgical manipulator to prevent the surgical manipulator from falling on a patient's body.

We also use a counterbalance in the base unit to prevent the manipulator from falling down. The counterbalancing of the base unit has two main advantages: 1) it can reduce the motor torque required to activate the joints of the base unit; and2) it can reduce the load applied to the joints so that the wire ropes do not break. The manipulator is fixed on a vertical lifter with vertical adjustment capabilities, and the horizontal position can be adjusted by hand. For the maintenance of the proposed manipulator, we attached tensioning devices to all the joints of the manipulator so that the tension of the wire ropes is kept constant.

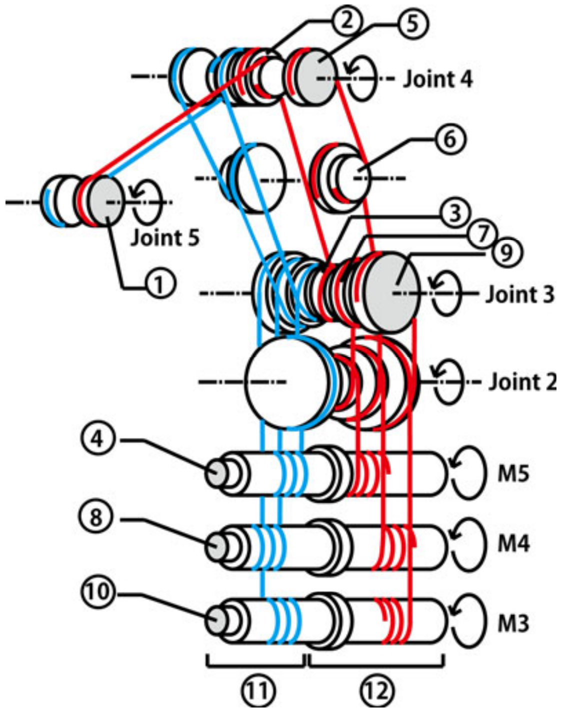


Fig 2: Cable-pulley transmission of Joints 3, 4 and 5. _1 Driving pulley at Joint 5._2 Reduction pulley._3 Idle pulley._4 Actuating shaft._5 Driving pulley at Joint 4. _6 Reduction pulley. _7 Idle pulley. _8 Actuating shaft. _9 Driving pulley at Joint 3._10 Actuating shaft. _11 First shaft. _12 Second shaft.

Another informative measure to look at is the manipulability ofthe mechanism during the tasks. Here, we will use the ratio ofthe smallest singular value ofthe 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 ofthe manipulator Jacobian corresponding to the wrist joints, and the orientation ofthe tool. Fig. 6 shows the distribution ofthe 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.

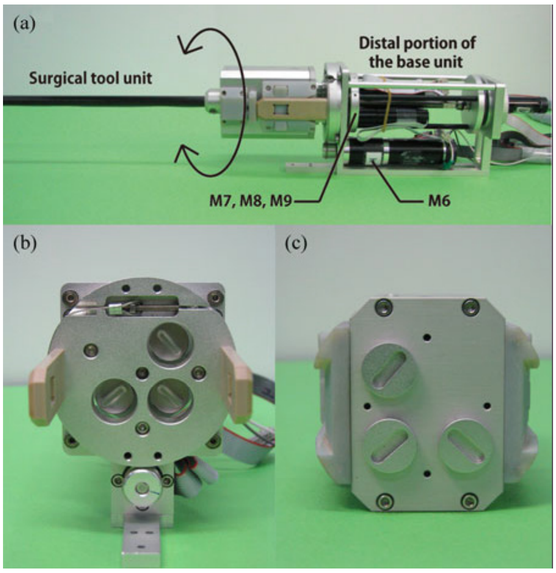


Fig. 3. (a) Surgical tool unit attached to the distal portion of the base unit. (b) Three driving pulleys coupled to the motors at the distal portion of the base unit. (c) Three driven pulleys of the surgical tool unitExperimental System

The control equipment is illustrated in Fig. 11. The PHANTOM device with 6 DOF plus two buttons is used as a master manipulator. The master manipulator is connected to the computer by IEEE 1394 communication and its encoder signals are delivered to the computer. The computer is connected to themotor amplifier amp 1 by a USB port. All the motor amplifiersare MAXON EPOS2 and they are connected to each other by controller area network communication. Then the encoder signals of the master manipulator are delivered to all the motor amplifiers. The motor amplifiers are also connected to the dc motors. The encoder signals of the dc motors can be delivered to the computer via motor amplifiers. We set the overall control rate at 20 Hz. The round-trip latency was about 150 ms. The latency can be reduced by upgrading the computing power

4.DISCUSSION:

Performance issues of the proposed manipulator are discussed in this section. The specification of the manipulator is listed.The performance of the proposed manipulator was compared with published results from the da Vinci system, the RAVEN system, and the system of the University of Hawaii [37].

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The results of the two FLS tasks are listed in Table V. We can reduce the task completion time if the precision of the surgical manipulator is improved and the force feedback is usedIt is also important to note that this method cannot evaluate ifthe system will have the complete dexterity necessary, since it looks at the problem from a purely kinematic point ofview, and dexterity includes the dynamical properties ofthe 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 ofthe 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.

5. Concluding Remarks:

In this paper, a quantitative method to evaluate kinematic properties ofrobotic 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 ofthe system to perform suturing and knot tying tasks in minimally invasive setting, it might be desirable to segment the critical and non-critical parts ofthe recorded open surgical motion, especially to remove the segments corresponding to the parts ofthe 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 ifthe system will have the complete dexterity necessary, since it looks at the problem from a purely kinematic point ofview, and dexterity includes the dynamical properties ofthe 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 ofthe 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

6. Experimental Results:

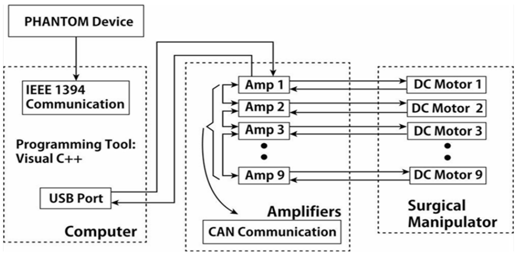

Fig. 4. Control equipment

•Gripper has an equivalent force of about 4.22 N.
•The maximum tip force is 23.5N.
•The maximum lifting force of the pitching joint was 4.41 N.

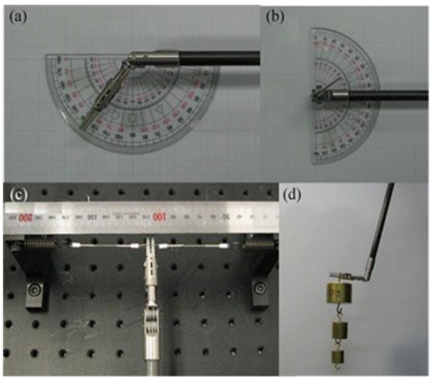

Fig. 6. (a) Measurement of the actual angle of the pitching joint. Measurement of the actual angle of the distal rolling joint. Measurement of the gripper force. Measurement of the lifting force

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