

Simulation for Optimal Design of Hand-Held Surgical Robots

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Abstract—Hand-held surgical robots are manipulators with dexterous effectors to be used by surgeons in minimally invasive surgery and especially in laparoscopy. Mechanical manipulators for laparoscopy have appeared on the markets in recent years with various interfaces and dexterities. 2 examples are RealHandTM and Laparo-AngleTM. The question of which interface and control mode is the best has not been answered yet. Also, the effector kinematics has not been studied much. We have made a simulator to study the robot's interface, control mode and kinematics to design a hand-held surgical robot for laparoscopic surgery. We asked test subjects to use the simulator and try to make sutures in a virtual environment. Users opinion is that a joystick as interface is easier to use, compared to a jointed interface translating hand's orientation to that of the effector. It appears that a 6 DOF effector coupled to the shaft is necessary and dexterous enough to make sutures in different angles.

I. INTRODUCTION

Minimally invasive surgery (MIS) is a type of surgical operation in which a surgeon inserts surgical instruments inside a patient's body through small incisions. Each instrument passes through a trocar, a cylinder with a sharply pointed end, inserted in the patient's body to make an incision. It is common to insert 2 instruments and an endoscope at a time, through 3 incisions made on the vertices of a triangle. In single-port MIS, the 2 instruments and the endoscope are inserted through a single incision to reduce the trauma. In natural orifice transluminal endoscopic surgery (NOTES), no incision is made. The instruments and the endoscope pass through natural body openings. Conventional surgical instruments used in MIS are hand-held instruments with long shafts, an effector (a grasper, a cutter etc.) at one end and a handle at the other. In these instruments, the effector is rigidly connected to the shaft.

Certain motions are very difficult or impossible to make using conventional instruments, especially in single-port and NOTES surgical operations. Because, the instrument passes through a port and is effectively constrained by the pivot point. So its motion is constrained to 4 degrees of freedom (DOF) [1]. The 4 DOF are: (1) translation along the shaft of the instrument, (2) rotation around the translational axis and (3) and (4) limited inclination of the shaft pivoted around the incision point [2].

A surgical robot could facilitate difficult motions. A hand-held surgical robot for MIS has an effector jointed to its shaft. The joint gives the effector additional DOF compared to the conventional effector. How the surgeon controls the

effector is a major issue in the design of a hand-held surgical robot [3]. The way the DOF of the handle are mapped to the DOF of the effector is called the control mode [2]. A non-intuitive control mode leads to long learning curves, longer operation times and more importantly, additional burden on the surgeon. The surgeon has to do a cognitive remapping to resolve the incompatibility of the viewpoint presented by the endoscope and his spatio-motor expectations [2]. A non-intuitive control makes this remapping more complicated. Another major issue in the design of such robot, is its effector's kinematics. The question is how many additional DOF for the effector are required to make it suitable for every needed motion in MIS.

The hand-held surgical robot falls into a broader category of robots that we call series comanipulators. These are hand-held robots that extend human hand's dexterity to manipulate objects the hand can not manipulate directly. Such comanipulator, if held by hand and viewed directly by eyes can be controlled easily using already known motor skills, as its movements correspond to the user's visuomotor expectations. But in MIS, the comanipulator is constrained by the pivot point. As a result, its inclinations around this point result in inverse movements. Moreover, the vision from the endoscope is different from a direct view, as the endoscope's line of sight is different from the surgeon's eyes' line of sight. So the user has to learn new motor skills to manipulate objects using the robot.

II. SIMULATION FOR ROBOT DESIGN

A few hand-held mechanical manipulators for laparoscopic surgery have appeared on the market in recent years [4], [5], [6], [7], [8] and there is ongoing work for developing mechatronic devices [9], [10]. These devices use different interfaces, control modes and effector kinematics. Although some of them have achieved good results [11], none of them has been proven to be the best choice.

We have made a virtual reality (VR) simulator to study different interfaces, control modes and effector kinematics of series comanipulators for laparoscopic surgery. The Simulator is a platform allowing an operator to perform certain surgical tasks in a VR environment, using a surgical instrument. The simulator is composed of a laparoscopic training box, a Polaris tracking system, a surgical instrument, a monitor and a PC with the software control unit. Fig. 2, shows the simulator. The control unit uses tracking information from

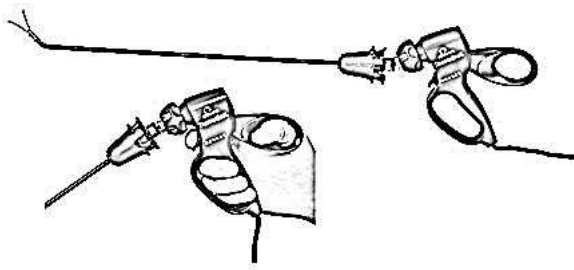


Fig. 1. RealHand™, a mechanical instrument with a jointed effector

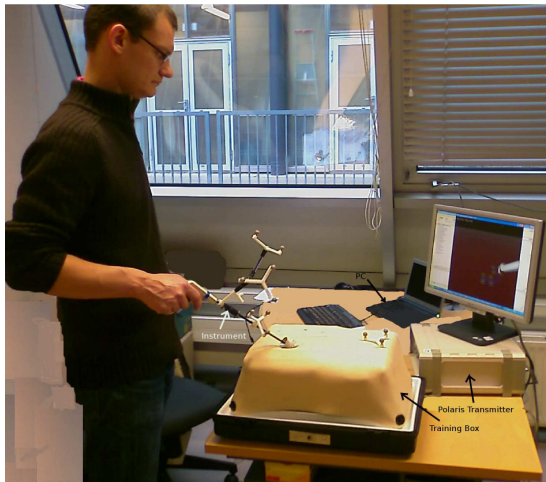


Fig. 2. Operator using the simulator

Polaris to determine the position and the orientation of the instrument and its handle (in the case of a jointed handle). It maps the control signals from the interface to the orientation of the effector, according to the programmed control mode. The image of the inside of the training box is then simulated, as if there were a real endoscope looking inside.

The interface of the instrument is held by the surgeon to control the simulated effector. We studied 2 approaches for the interface: one approach is to control the effector using buttons, dials or joysticks integrated in the interface as in [10]. Another approach is to put an articulation between the interface and the shaft and map the DOF of the handle to the DOF of the effector as in [4] (Fig. 1). The surgical instrument used in the simulator can have an articulated interface or a Wii Nunchuck interface.

The effector could have several DOF. In the simulator, the effector's articulation can be simulated to have the desired number of DOF from 1 to 3. The mapping between these DOF and the handle's DOF can be programmed as well. Our simulations show that it becomes more difficult to learn how to control the effector as its dexterity increases. On the other hand, the effector must have enough DOF to enable the surgeon make all necessary motions. Fig. 3 shows an instrument simulated with a 7 DOF effector.

III. RESULTS

Using our simulator we asked users with no experience in MIS to do sutures on a horizontal plane. Different motions a

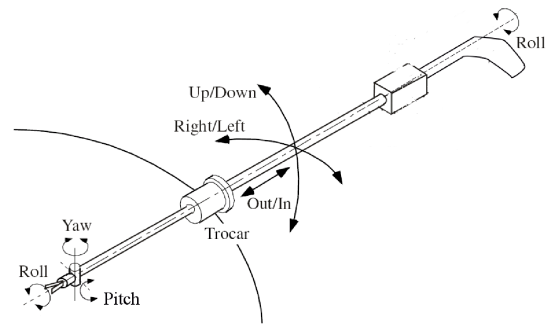


Fig. 3. A simulated robot with a 7 DOF effector

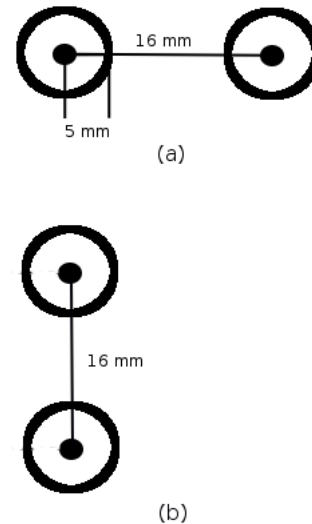


Fig. 4. (a) Frontal and (b) sagittal suturing tasks

surgeon makes during a laparoscopic operation are identified to be one of these 5 basic motions: reach and orient, grasp and hold/cut, push, pull and release [12]. A suturing task was chosen because it includes all these motions. Fig. 4 shows frontal and sagittal suturing tasks. Fig. 5 and Fig. 6 show how a suture is made with the simulator. The results presented here are more qualitative than quantitative. We plan to do more tests and provide more results in the near future.

A. Effector

In making the hand-held robot, an effector jointed to the shaft with a knee-joint can have up to 3 additional DOF, compared to an effector rigidly connected. However, constructing a 3 DOF joint for this application is costly. A 2 or 1 DOF joint would be easier to make.

To make sutures in angles, like sagittal sutures which are in 90° angles, the user has to orient the effector and the needle, and then roll it. Based on this principle, the effector needs at least to yaw or pitch and to roll. These 2 DOF plus the 4 DOF that exist already, make the robot a 6 DOF manipulator. Simulation results show that such robot configuration enables the surgeon to suture in different angles, even if the angle of the working surface changes as well. A 150° roll is needed to make a complete suture.

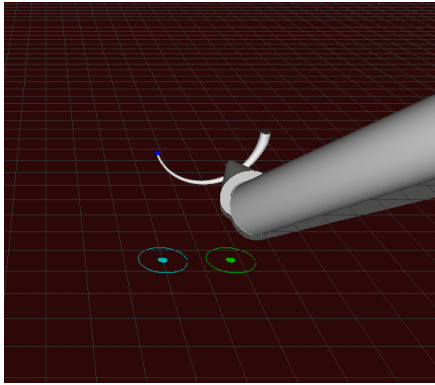


Fig. 5. Orienting the needle for a frontal suture

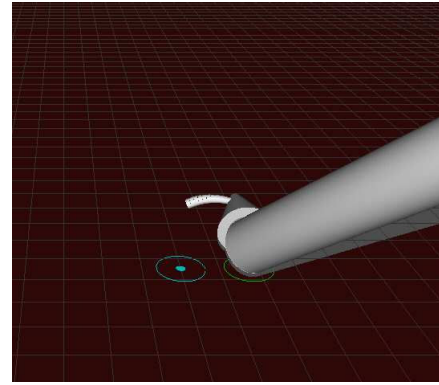


Fig. 6. Touching the right suture point

B. Interface and Control Modes

We used 2 different interfaces to control the effector of our surgical instrument:

- First we used the handle of a conventional laparoscopic instrument and jointed it to a 30 cm shaft using a universal joint (Fig. 7). The orientation of the handle relative to the shaft was used to control the effector. This means we had 3 DOF of the handle we could map to the effector's DOF: roll, yaw and pitch. These DOF were amplified homogeneously and mapped to the 3 DOF of the effector. The amplification factor was set to 3, so that a 30° inclination of the handle causes a 90° inclination of the effector. Users opinion was that learning how to use this interface was easy. Users showed great improvement in performance after little training. However, it is difficult to keep the position of the effector while orienting it. As a result, doing precise movements is very difficult with this type of interface [13].

The mapping between the DOF of the handle and those of the effector affects directly the learning curve and task completion times. We tested 2 different mappings:

- direct mapping, i.e. mapping similar DOF to each other (handle's roll, pitch and yaw to effector's roll, pitch and yaw).
- inverse mapping, i.e. mapping similar DOF to each other, but changing the direction of rotation.

Inverse mapping looks more intuitive and users had better performances with it.

- Next we used a Wii Nunchuck controller and rigidly connected it to the shaft (Fig. 8). The Nunchuck has a 2 DOF joystick and 2 buttons. We used the joystick to control the first 2 and the buttons to control the third DOF of the effector. With this interface however, the rotation speeds of the effector are controlled rather than its rotation angles. Our users tended to get used to this interface very fast. It was much easier to keep the instrument in its position while orienting its effector.

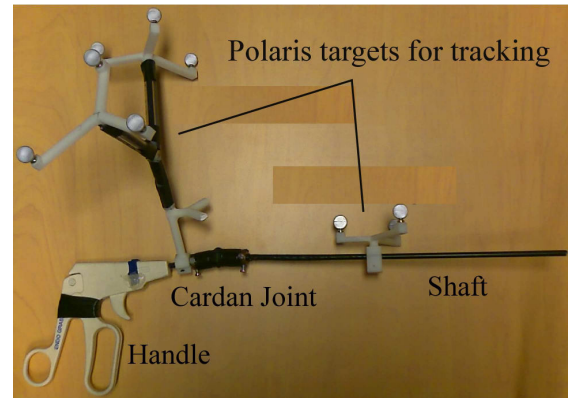


Fig. 7. Instrument with articulated interface

IV. CONCLUSIONS AND FUTURE WORKS

A. Conclusions

A robotic hand-held instrument can help the surgeon suture in angles that are impossible to do using a conventional instrument. For this matter, mechanical hand-held instruments with jointed effectors, like RealHandTM are interesting. The VR simulator is an effective tool to understand the difficulties of MIS and to develop robotic manipulators for it.

A surgeon-robot interface held in the hand and controlling the movements of the effector using a joystick looks promising. Speed control of the tool is necessary using this interface. This interface gives the surgeon a greater precision.

To be able to make complete sutures in every angle, the effector needs to have 6 DOF. With the instrument already having 4 DOF, a 2 DOF joint for the effector would be enough to make a 6 DOF effector. Redundancy makes task completion times longer. Lesser DOF make it impossible to suture in some angles.

B. Future Works

We are going to do systematic tests using novice and expert subjects to test different interfaces and control modes. A series of tests has to be done to study quantitatively, the performance of each interface and control mode. Another series of tests is necessary to study the learning curve. A



Fig. 8. Instrument with Nunchuck interface

comparison between novice and expert users is needed to show if the joystick interface would be as easy to use for the experienced surgeons as it is for novice and younger users who are familiar with video game joysticks. The results will help us choose the best controller for a hand-held robot.

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