Towards the Development of a Hand-Held Surgical Robot for Laparoscopy

Ali Hassan Zahraee, *Student Member, IEEE,* Jamie Kyujin Paik, Jrome Szewcyzk, *Member, IEEE,*
and Guillaume Morel *Member, IEEE,*

***Abstract*—A minimally invasive surgery (MIS) which typically involves endoscopic camera and laparoscopic instruments may seem to be the ideal surgical procedure for its apparent benefits. However, in comparison to open surgeries, the spatial and mechanical tool limitations posed on surgeons are so high that often MIS is foregone for complex cases and even when it is possible, the procedure requires a high dexterity, calibre and experience from the surgeon. Particularly, suturing procedure through MIS is known to be extremely challenging. We are working towards the development of a robotic hand-held surgical device for laparoscopic interventions that enhances the surgeons' dexterity. The instrument produces two independent DOF which is sufficient for enabling MIS suturing procedure in vivo. The end effector's orientation is controlled by an intuitive and ergonomic controller and its position is controlled directly by the surgeon. Different control modes, handles and end effector kinematics are primarily evaluated using a virtual reality simulator before choosing the best combination. A proof-of-concept prototype of the device has been developed.**

***Index Terms*—Medical Robotics, Surgery, Manipulators.**

I. INTRODUCTION

MINIMALLY invasive surgery (MIS) or laparoscopy typically involves use of special surgical instruments with an observation of the surgical field through an endoscope. Each instrument passes through a trocar, a cylinder with a pointed blade end, inserted in the patient's body to make an incision. It is common to insert two instruments and an endoscope at a time through three incisions made on the vertices of a triangle. In single-access MIS, the instruments and the endoscope are inserted through a single incision. MIS causes less operative trauma for the patient than an equivalent invasive procedure (open surgery). It leaves patients with less pain and scarring, speeds recovery, and reduces the incidence of post-surgical complications. Conventional instruments used in MIS are hand-held instruments with long shafts, an end effector (needle holder, dissector etc.) at one end and a handle at the other. The instrument passes through the trocar and is effectively constrained by a pivot point. At the pivot point, the instrument motion is constrained to 4 degrees of freedom (DOF) with a reduced range of motion [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 trough the incision [2]. Some gestures are very difficult or impossible to make using the non-dexterous conventional instruments. Besides, the view from the endoscope being along a different axis than the axis of vision of the surgeon, and the inclinations of the shaft being mirrored, make the eye-hand coordination much more difficult for the surgeon. An instrument with a jointed end effector can facilitate difficult gestures. The joint adds one or more DOF to the end effector and makes the instrument more dexterous. Thanks to these additional DOF, the surgeon can make sutures or cuts which are either hard or impossible to do with a conventional instrument. The end effector must have 6 DOF to allow the surgeon choose the orientation and position of the end effector arbitrarily and perform all surgical tasks which are otherwise impossible or difficult to perform with a 4 DOF end effector. The DOF added to the end-effector could be actuated manually, pneumatically or electrically. The latter gives a mechatronic (robotic) hand-held instrument. Key needs and applications of micromechatronics in MIS are identified in [3], and relevant technologies, methods, and systems issues in mechatronics are also discussed. Hand-held robotic instruments for MIS fall into the broader category of hand-held robotic manipulators also referred to as serial comanipulators. A simple drill is an example of a serial comanipulator. Several serial comanipulators have been developed for surgery. [4] for example, presents a novel hand-held drilling tool devoted to orthopedic surgery. [5] presents a hand-held, motorized device that actuates the needle base to produce a desired steering direction and magnitude at the tip in minimally invasive percutaneous medical procedures. A major issue in the design of a hand-held robotic surgical device is how the surgeon controls the end effector and how his hands' DOF are mapped to the end effector's DOF [6]. One approach is to control the end effector using buttons, dials or joysticks integrated in the handle as in [7], [8] and [9]. We call this type of handle a finger-operated handle as the controllers mentioned are placed under fingers and controlled by them. Another approach is to have an articulated handle. The additional DOF of the articulation between the handle and the shaft can be mapped to the DOF added to the end effector. Literature suggests that this kind of handle is not optimal, because it is hard to do precise operations with it [10]. However, we could not find any quantitative evaluation results on this subject. Most dexterous laparoscopic instruments commercialized in the past few years use articulated handles, to avoid using electrical actuators. The most famous ones are RealHand^{TM} [11] from Novare Surgical Systems,

A. H. Zahraee, J. Szewczyk and G. Morel are with Institut des Systems Intelligents et de Robotique, Université Pierre et Marie Curie - Paris VI, 4, place Jussieu, 75005, Paris, France (emails: zahraee, sz, morel@isir.upmc.fr). J. K. Paik is with Microrobtics Laboratory, Harvard University, Cambridge MA. Corresponding author: zahraee@isir.upmc.fr.

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Radius^{TM} from Tuebingen Scientific Surgical Products [12], Laparo-angle^{TM} from Cambridge Endoscopic Devices [13] and Roticulator from Covidien [14]. Our study results suggest that the best kind of interface for controlling the end effector is a finger operated handle. The way the DOF of the handle are mapped to the DOF of the end effector is called its control mode. In laparoscopy, 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 mode makes this remapping more difficult, leading to long learning curves, longer operation times and additional burden on the surgeon. We compared 3 different control modes for articulated handles to find the most intuitive one. An intuitive control mode for finger-operated handles has been the one used in video game consoles since many years ago. Making a dexterous instrument in miniature dimensions (the device's shaft should be 5 mm thick) with a mechanical force transmission system that can provide for the requirements in MIS, is difficult and costly. So, choosing the simplest kinematics for the added DOF that allows performing all needed movements is critical. In RealHand for example, the end-effector can yaw or pitch while the surgeon can roll the instrument's shaft using his thumb. Laparo-angle has an end-effector that can yaw, pitch and roll, but its shaft's rotation is manual and thus limited. Table I shows dexterous instruments available on the market and major differences between them in terms of kinematics and controls. These instruments have all been successfully tested in laparoscopic interventions [15], [16], [17],[18], especially in single-access laparoscopy where the need for dexterous instruments is even greater. While they all claim to be intuitive and dexterous, most surgeons still prefer using classic instruments.

TABLE I
DIFFERENCES BETWEEN 4 DEXTEROUS INSTRUMENTS

	RealHand	Laparo-Angle	Roticulator	Radius
Kinematics	Y-P	Y-P-R	Y-R	Y-P
Controllers	articulated handle	articulated handle,knob	knobs	articulated handle
End-effector lock	No	Yes	Yes	No
Needs use of the other hand	No	For lock	For yaw	No
Shaft rotation	by a shaft screw	by rotating the handle	by rotating the handle	by a shaft screw

In this paper we explain our efforts towards the development of a robotic dexterous hand-held instrument for laparoscopy. We did a series of tests and evaluations with a simulator to choose between an articulated and a finger-operated handle, an intuitive control mode and an optimal kinematics. Then we explain the design of the mechanical transmission system for a proof-of-concept prototype.

II. SIMULATION

To evaluate and compare different handles, control modes and kinematics, we made a virtual reality (VR) simulator. The Simulator is a platform allowing an operator to perform certain preprogrammed surgical tasks in a VR environment, using a hand-held instrument with a virtual end effector. It 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. 1(a) show the simulator.

Polaris is a motion tracking system by Northern Digital Inc. It can keep track of the position and the orientation of several targets in 3D space with a precision of 0.3 and a

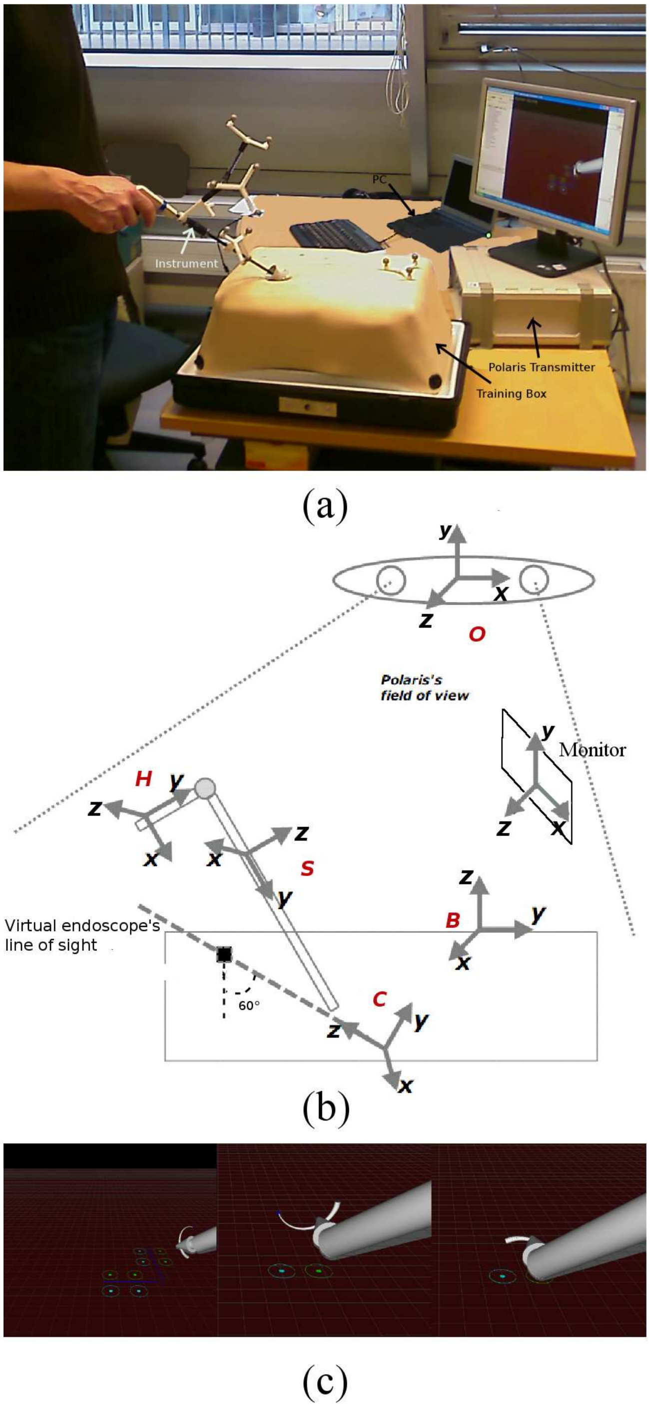

Fig. 1. (a) Simulator in use, (b) Local coordinate systems of the simulator, (c) From left to right: snapshots from the simulated scene showing a suture

maximum update rate of 60 Hz. A local coordinate system is associated to each target and Polaris provides for the position and orientation of every target in a global coordinate system. A Polaris target is attached to each rigid body in the scene. Fig. 1(b) shows different coordinate systems present in the scene. The laparoscopic training box is a box covered with a skin-like cover, representing the abdomen of the patient. A Polaris target on the box gives its position and its orientation. The surgical instrument consists of a shaft and a handle. The handle of instrument is interchangeable between an articulated one and a finger-operated one. For the articulated handle, we used the handle of a conventional laparoscopic surgical instrument. It was attached to the shaft using a 3 DOF knee joint, enabling it to pitch, yaw and roll. For the finger-operated handle, we used a Nunchuck^{TM}, a handle made by Nintendo for its video game console Wii. It has an ergonomic design and connects easily to a PC through Bluetooth. It has a 2 DOF joystick under the thumb and 2 buttons under the index finger. A Polaris target is attached to the instrument's shaft and another one to the articulated handle. The control mode and the kinematics of the instrument's virtual end-effector can be programmed in the simulator. A 19" LCD monitor is used to show the simulated endoscopic image of the inside of the training box. It is positioned 1m away from the operator and deviated 45° from his line of sight to resemble the situation in an operation room. The control program runs on a PC, receiving tracking data from Polaris through a 115200 bps serial connection. The simulator program filters the measurement noise of the tracking data by an exponentially weighted moving average filter. Equation (1) shows the output of such a filter for an input sequence x_k (n is length of the window).

$$\bar{x}_k = \alpha \bar{x}_{k-1} + (1-\alpha) x_k \tag{1}$$

$$\alpha = \frac{n}{n+1} \tag{2}$$

The filter introduces a lag in the simulation. There's a trade-off between the noise still left on the output and the lag. We tested different degrees of filtering (α) from 0.5 to 0.91 ($1 < n < 10$) and $\alpha = 0.75$ ($n = 3$) seemed to give the strongest filter that didn't introduce a perceivable lag, while filtering enough noise to give a steady pose for a stationary target. The pose of each body is calculated in the virtual endoscope's coordinate system. This virtual endoscope's position on the training box, its line of sight and its scope can be chosen arbitrarily. We chose a triangle with 10 cm sides to place the instrument and endoscope, a line of sight inclined 60° from vertical and a 75° scope which are typical values in laparoscopic interventions such as cholecystectomy. The image of the inside of the box is finally rendered. There is no force feedback, but a visual feedback that indicates collisions between the needle and the working surface. The frame rate of the graphical simulation is 60 FPS. A higher frame rate will be actually useless as the refresh rate of generic LCD monitors is 60 Hz. The image is rendered using OpenGL 2.0, GLU and GLUT libraries. OpenGL has methods for drawing basic geometric shapes (points, lines and polygons). GLU adds methods for drawing such shapes as cylinders, circles and spheres. GLUT is used for window management. For coloring, the light is supposed to be coming from the endoscope's position. The image shows the instrument with its end effector holding a needle, and a working surface with a grid and suturing points identified by different colors. Fig. 1(c) shows the simulated scene. Evaluations are based on subject performance in making sutures. Suturing is one of the most frequent, yet difficult tasks in laparoscopy. It needs a certain level of prior training. One of the main advantages of a dexterous surgical device is considered to be its ability to make sutures in difficult angles e.g. sagittal sutures. Our simulated suturing task includes putting the needle in the right orientation so as to insert it in the working surface with the right angle, reaching the suture point and turning the needle to bring it out of the exit point. This is considered the end of the gesture. Grabbing or releasing the needle are not simulated. This series of motions (orient, reach, orient) was chosen based on previous studies done on decomposition of laparoscopic tasks [19], [20].

A. *Evaluation of Articulated and Finger-operated Handles*

Our first objective was to compare an articulated handle with a finger-operated one in terms of precision and choose the better one. Plus, we wanted to choose the most intuitive control mode for coupling the handle's DOF to the end effector's DOF. For the articulated handle we tested 3 different control modes:

- Mode 1: when the handle makes a yaw or pitch, the end effector makes a yaw or pitch but in the inverse direction. When the handle rolls, the end effector rolls in the same direction. This makes the user to see the end effector move in the same direction as his hand. The end effector's yaw and pitch angles can be locked in this mode. When locked, the end effector can only roll according to the handle's rolling. Locking the end effector is integrated in the simulator using a vocal command.
- Mode 2: the end effector's movements are similar to mode 1 in this mode. But the end effector's yaw and pitch angles can not be locked. Thus, the subject has to maintain both position and orientation of the end-effector while rolling it.
- Mode 3: This mode is the opposite of mode 1. As a result the end-effector is always along the same axis as the handle. But its movements are the inverse of the handle's from the user's point of view.

For the finger-operated handle, we used the one control mode always used in video game consoles i.e. right-left and up-down movements of the joystick make a right-left and up-down movements of the end-effector respectively. It has proven to be the most intuitive one for this kind of handle over the years. There is evidence that this control mode is also the most intuitive one for a finger-operated handle of a surgical instrument [21]. The finger-operated controllers on the handle control the speed of rotation of end effector joints, as their range of movement is limited and can not effectively control the end effector's position. Fig. 2 shows instruments with articulated and finger-operated handles, as well as yaw,

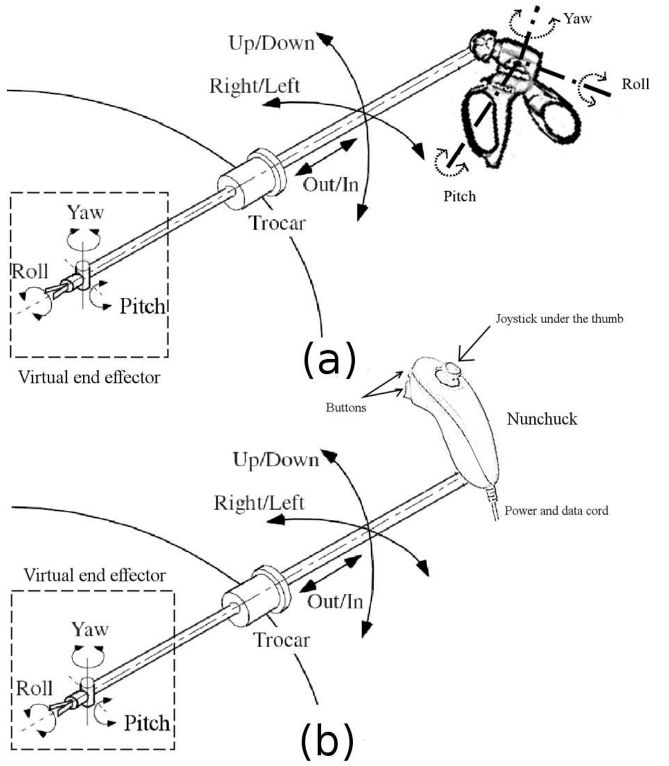

Fig. 2. (a) Instrument with articulated handle, (b) Instrument with finger-operated handle

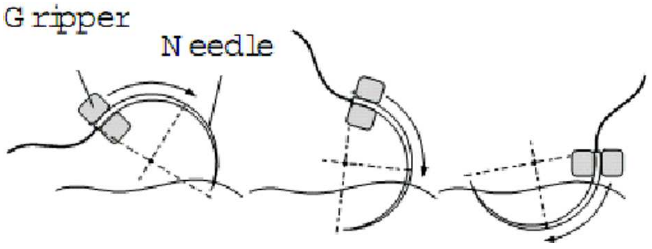

Fig. 3. Perfect suture [10]

pitch and roll movements of handle and end effector with respect to shaft.

For each evaluation, we asked test subjects to do frontal and sagittal sutures on a horizontal virtual working surface inside the training box. The suture points were identified by different colors. Each subject had 10 tries for frontal and 10 tries for sagittal sutures for each handle and control mode (40 frontal and 40 sagittal sutures in total for each subject). In a perfect suture, needle is inserted in the tissue on the start point of the suture and comes out of the end point while it follows its curve, avoiding applying any side forces on the tissue. Such a suture is made by rolling the needle, around an axis of rotation that passes through the center of the circle of which the needle is a part (we consider half circle needles here). Fig. 3 shows such a suture. However, rolling the end effector rotates the needle around the longitudinal axis of the end effector. The needle deviates from the desired path and undesired side forces are applied on the tissue. The surgeon needs to compensate for the resulting deviation by pivoting the shaft. He has to coordinate his hand and arm movements with his visual, and a non-intuitive control makes this more difficult. So the metric we use is the ability of the test subject to follow the needle's curve and stay in a certain vicinity of the insertion point to limit the side forces. Some deviation from the perfect suturing path is inevitable due to unintentional movements of hand and arm. The amount of acceptable side forces applied on the tissue, and thus the vicinity in which the needle has to stay for a successful suture, depends on mechanical properties of the soft tissue on which the suture is done. For example, muscle tissue is more elastic than liver, prostate or kidney and can resist greater side forces without being damages. After consulting surgeons and taking into account measurements of mechanical properties of soft tissues from [22], [23] and [24], we established a simplified metric as follows: For the simulated needle with a 1 mm radius (normalized dimensions), we defined 4 levels of tissue elasticity, with 2, 3, 4 or 5 mm criteria to pass. A suture may pass the 5 mm criterion, but not the 3 mm one, meaning that it's an acceptable suture on muscle tissue, but not on kidney.

For our tests, taking into account the fact that the subjects were not expert laparoscopic surgeons, we chose the 5 mm criterion. The needle has to stay in a 5 mm vicinity of the suture's start point and come out in a 5 mm vicinity of the end point for the suture to be successful. The subjects were engineering students with no experience in laparoscopy. 15 subjects evaluated an articulated handle and a finger-operated handle. Literature suggests that expert laparoscopic surgeons are significantly different from surgical novices in terms of applied forces and torques [25], [26], patterns of movement [27], task completion times [25], [26], [28],[27], trajectory length [27] and number of errors [29]. However, these studies that are mostly done for the purpose of modeling surgical gestures in laparoscopy and providing metrics for objective assessment of skills in virtual reality simulators, are done using either conventional laparoscopic instruments with 4 DOF or the da Vinci surgical system. When it comes to instruments with novel human-robot interfaces and different kinematics, expert surgeons are probably not greatly different from novices. In fact, the additional DOF and the method of controlling them may be as new to them as it is to the novices. As a result, surgeons and novices will both use their basic visumotor skills to execute the new tasks. This strongly suggests that the results of our studies would be the same, had we used expert surgeons as subjects. This has of course to be proven with experimental data in a separate study using expert surgeons as subjects. Besides, it is not even sure that expert surgeons do better than novices with these novel instruments as they do with conventional instruments or the da Vinci. For example, there is evidence that playing video games could improve surgical skills in minimally invasive surgery [30], [31]. Younger subjects though surgically novice, have generally more experience with video games and the joysticks used to play them than middle age expert surgeons. Fig. 4 shows the percentage of successful frontal and sagittal sutures done by all subjects using an articulated handle with 3 different control modes and a finger-operated handle.

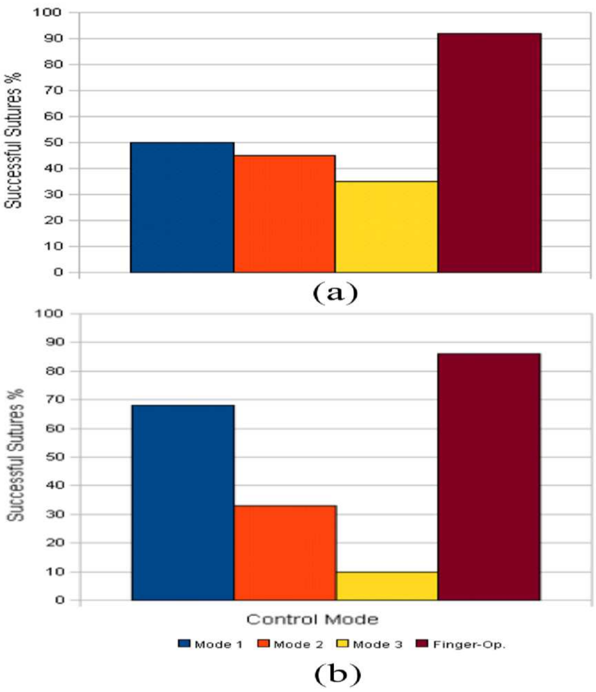

Fig. 4. Percentage of successful sutures with an articulated and a finger-operated handle, (a) Frontal sutures, (b) Sagittal sutures

The results of this test show that mode 1, a control mode like the one used in RealHand and Laparo-angle is more intuitive than mode 3 and more efficient than mode 2. The possibility of locking the orientation of the end-effector would improve the dexterity. A finger-operated handle has a higher precision than an articulated handle. The major reason for this, according to the subjects is that with an articulated handle, it's difficult to keep the position of the end-effector steady, while changing its orientation (for example rolling it). Moreover, they were complaining about the excessive fatigue it causes. [32] confirms that an ergonomic finger-operated handle reduces fatigue compared to a conventional handle. These results suggest that a finger-operated handle is a better choice for a dexterous hand-held instrument and we are going to use this handle from now on.

B. Evaluation of different Kinematics for the End-effector

Our second objective was to compare different kinematics for the end effector and choose the optimal one. Surgeons need to be able to suture in different angles (frontal/sagittal). As a result they need 6 DOF needle holders. The question we are studying here is which 6 DOF kinematics is the best one for a hand-held laparoscopic instrument, knowing that 4 DOF are already defined as a result of the instrument being constrained by the pivot point. The kinematics we used for the end effector in the tests in the previous section was a yaw-pitch-roll kinematics allowing 6 DOF manipulation. But it's very difficult to realize such an instrument in miniature dimensions taking into account the force and torque requirements in MIS. Keeping the already existing 4 DOF, we should add 2 more DOF to the end effector to make it 6 DOF. The 2 DOF we want to add, are those of a 2 DOF wrist added to the end-effector. Without loss of generality, we suppose that the 2 revolute joints of the wrist have concurrent axes. For 2 revolute joints with concurrent axes, 6 combinations of rotational axes are possible. These combinations are: pitch-yaw, pitch-roll, yaw-pitch, yaw-roll, roll-pitch and roll-yaw. But pitch-yaw is the same as yaw-pitch if we only turn the shaft 90°. Pitch-roll and yaw-roll are also the same. Roll-pitch and roll-yaw are singular combinations. This leaves us with 2 possible combinations: yaw-roll (YR) and yaw-pitch (YP). The rotation of the instrument around its longitudinal axis is normally manual. Surgeons have to rotate their whole arm to rotate the instrument and still, the rotation is limited. We decided to make this rotation automatic as well, giving subjects the ability to rotate the shaft clockwise and counter clockwise using 2 buttons. Another possibility we thought about was to add another DOF to the wrist to make it a 3 DOF wrist (like Laparo-Angle, see Table I). Again, there are 6 possible combinations of 3 concurrent rotational axes. 2 of them are singular (RYP and RPY). The other 4 are the same from the operator's point of view and are equivalent to a YPR kinematics. A 3 DOF wrist makes the total number of DOF 7, with 3 of them controlled by fingers. The rotation of shaft stays manual. Fig. 5 shows the 3 tested kinematics.

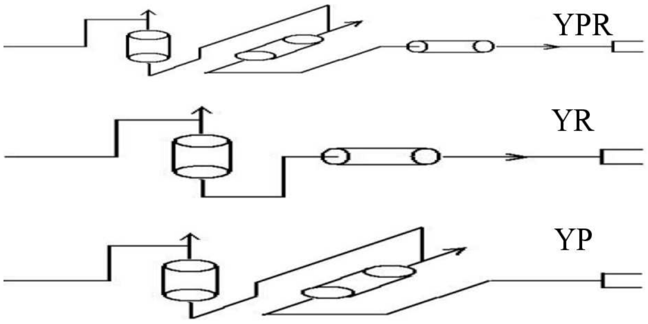

Fig. 5. 3 kinematics for end effector wrist

Using more than 6 DOF makes the task of visumotor control more difficult for the operator. It would not be possible to control the end-effector in its working space either, as 4 of the DOF are exclusively controlled manually. We saw in the previous section that the finger-operated handle let the subjects have a high score of correct sutures (92% for frontal and 86% for sagittal sutures). As we are using a finger-operated handle to evaluate different kinematics, in order to be able to see the difference between the 3 kinematics, we chose a new metric: time to completion of task (TCT). [33] states that the TCT is a practical, easy and valid objective tool for assessing acquired technical skills of urology trainees in a laparoscopic simulated environment. It is also used for comparing different surgical instruments for laparoscopy [34]. Each user made 5 frontal and 5 sagittal sutures using each of the kinematics and his average TCT for 1 suture was calculated. Fig. 6 shows the average TCT for each of the 15 subjects. Table II shows the mean TCT of all subjects for each of the 3 kinematics tested.

The results show that the YR kinematics is slightly better than the YPR kinematics, and both of them are largely better

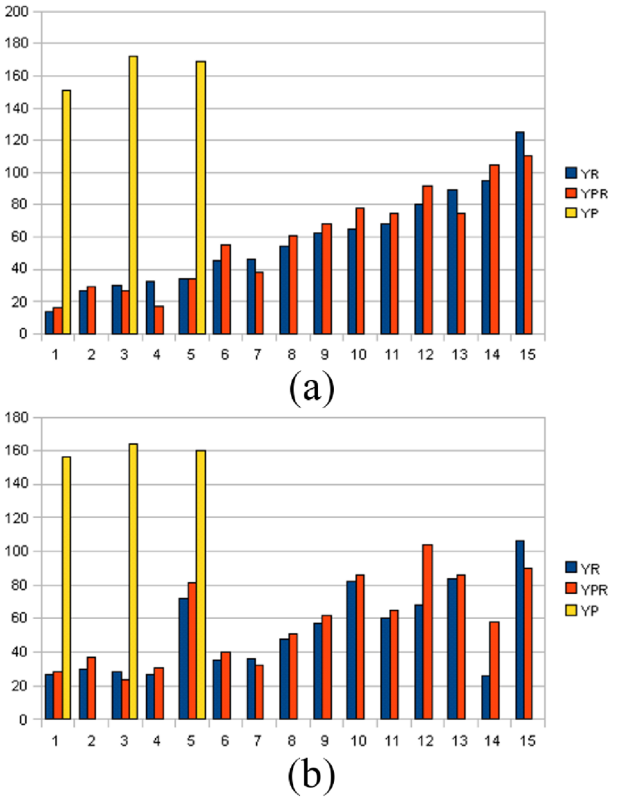

Fig. 6. Average TCT in seconds for 15 subjects using 3 different end effector wrist kinematics

TABLE II
MEAN TIME TO COMPLETION FOR YR, YP AND YPR KINEMATICS

	Frontal	Sagittal
YR	57.73	58.67
YPR	52.4	58.33
YP	$>>YR,YPR$	$>>YR,YPR$

than the YP kinematics, in terms of TCT. Only 3 out of 15 subjects were able to make sutures with the YP kinematics in the 3 minute per suture time limit.

To conclude this section, the tests and evaluations and their final results are summarized in Table III.

1) Discussion: The first remarkable point is the low level of successful sutures using the articulated handle. Another important point is that decoupling hand's movements from the end effector's deflections (this is done using a locking mechanism in control mode 1) makes it easier to roll the end effector to do a suture. On the other hand, subjects had remarkably higher scores using a finger-operated handle. These results showed that an articulated handle is not suitable for precise sutures. As a result, we decided to choose a finger-operated handle for our hand-held instrument. From the evaluation results of different kinematics for the end effector, we could see that an end effector able to yaw and roll results in the least TCT for suturing. Technologically, it is much more affordable to make a 2 DOF mesoscale wrist than a 3 DOF one. At the same time, it is dexterous enough to allow suturing in different angles. The YR kinematics of the end-effector plus finger-operated rotation of the shaft, give surgeons 6 DOF instruments with an intuitive control.

TABLE III
SUMMARY OF TESTS AND EVALUATIONS

Handle	Wrist Kin.	Ctrl. Modes	Metrics	Result
Articulated	YPR	3 Modes	% success	Hi. Mode 1
Finger Op.	YPR	1 Mode	% success	Highest
Finger Op.	YR,YPR,YP	1 Mode	TCT	Least: YR

III. MECHANICAL DESIGN

A. Mechanical characteristics of the developed system

Our third objective was to design the force transmission system and make a proof-of-concept prototype for the chosen type of handle, control mode and kinematics. The essential DOF required for the instrument pincer tip during a suturing procedure is in two independent rotational axis movements as shown in roll (Fig. 7(a)) and roll and yaw (Fig. 7(b)). While it is crucial to execute the full range rotations in required orientation, it is also important to maintain the position in the proposed configuration with a high stiffness and rigidity: unlike endoscopic cameras, a surgical instrument, during an operation, the tip is bound to experience high force load along the length of the instrument as well as on its tip. This mechanical property is crucial when the instrument is used as a needle holder, which has a tight and thin-mouthed pincer designed to hold thin needle ends usually in the shape of a semi circle to facilitate piercing tissues. The mechanical design challenge lies in developing an instrument in thin (5mm) cylindrical shape that produces two independent rotational movements with robustness (Fig. 7) : here we introduce two prototypes that can produce two independent and simultaneous orthogonal rotations amid the constraints imposed by practical usage in operating rooms.

1) Metallic bellow model: In order to transmit the rotational movement of the pincer tip (roll), while the body is in motion (yaw), a metallic bellow is used (Servometer Ltd. see Fig. 7(b)). The bellow is manufactured by an electro-depositing process on an undulated mould that is removed after certain thickness is achieved (0.2mm for this prototype). This inner bellow is completely independent from the outer rings which have chiseled slopes for making the curvature which are 90 deg = fold and 180 deg = tension. Such actuation is carried out by two cables (0.3mm dia. 5kg load multi-stranded steel cable) attached on the sides. A single cable (multi stranded stainless cable 0.75mm dia.) actuated pincer is affixed to the bellow joint which is controlled by the cable actuation of the wedged sleeves to form its yaw angle. The cable is flexible yet robust to take the shape of the outer structure that controls the yaw direction of the end pincer. This pincer assembly rotates freely from the outer shell while maintaining its longitudinal position by a polymer bearing. The wedged sleeve links are formed that the instrument tip operates in either 0 or 90 degrees positions: The rigidity of the instrument is guarded and controlled by the cable tension on the side (Fig. 8(a) shows only the cables in

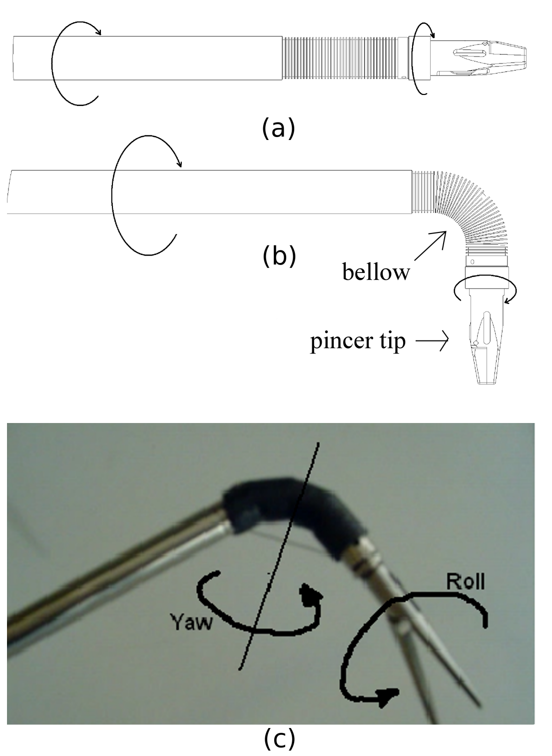

Fig. 7. Continuous roll motion for (a) the yaw angle 0, (b) the yaw angle 90 degrees, (c) Prototype in two rotational axis yaw and roll

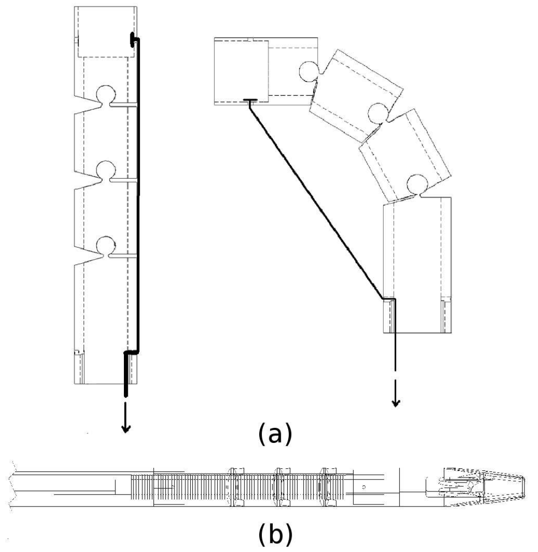

Fig. 8. (a) Metallic bellow model's wedged shell assembly with cable transmission for bending, (b) Metallic bellow model design in assembly with shell unit, bellow tubing and the pincer

tension). The assembly of the pincer and the rotatable metallic bellow joint is displayed in Fig. 8(b). Also, here it can be noted that the assembly configuration can be reversed to have the bellow either on the inside (Fig. 8) or outside (Fig. 7). The actual prototype displays the bellow inside of the links as seen in Fig. 10(b).

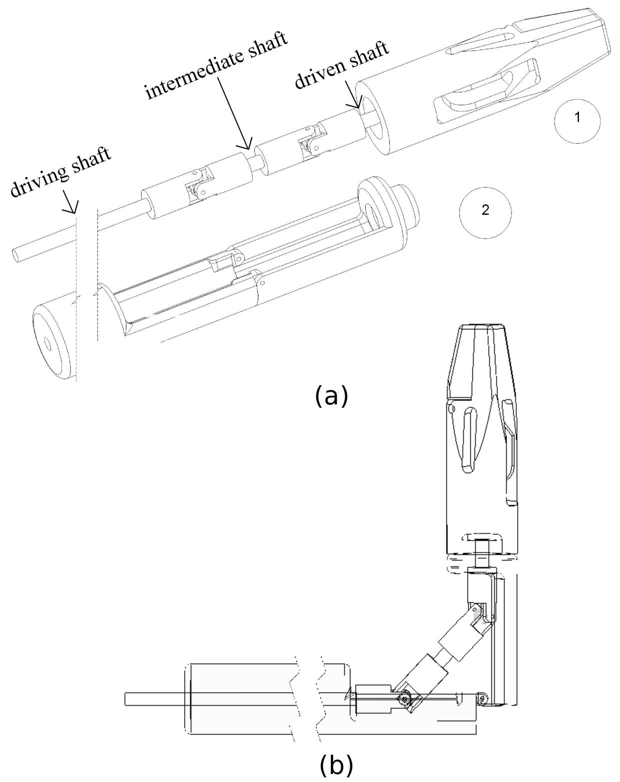

Fig. 9. (a) Universal joint and pincer assembly: (1) double universal joint and pincer assembly (2) shell unit, (b) Instrument in 90 degrees yaw position

2) Universal joint model: The same single cable actuated pincer (needle holder) is used for the second prototype which employs the double universal joints and sliding shell member: the opening and closing of the pincer is operated by a button on the proximal end on the handle. A novel design idea for developing a millimeter-scale actuator for locally actuating the opening and closing of the pincer (5-mm-diameter laparoscopic needle driver) for a robot performing MIS is presented in [35]. This actuator is designed by combining a dc micromotor and a shape memory alloy actuator in series. We envisage making such an electrically actuated pincer for future prototypes.

However, the bending in yaw direction is actuated by the linear translation of the outer shell (Fig. 9(a)2) with respect to the two universal joints and the pincer assembly (Fig. 9(a)1). Depending on the advancement of the shell unit that can bend maximum 90 degrees from its 0 degree straight position, the universal joint unit can transmit the rotation at the pincer tip. Due to the nature of the universal joint (gimbal adjoining unit fixes two rotating shafts), the rotary transmission experiences jerks and sinusoidal rotational velocity at the driven shaft: at 45 degrees off set of rotating axles, sinusoidal rotational velocity variance is about 40% at the driven shaft. The use of double universal joints minimizes this effect. Therefore, even though the intermediate shaft (Fig 9(a)1) may experience some jerks, the driven shaft of universal joint is directly controllable by the driving shaft in 1:1 ratio while its yaw angle is controlled by the translation of the outer shell (Fig 9(b)).

Fig. 10 shows the designed and manufactured prototypes. They are both 6mm -our primary objective was 5mm- in the diameter and use the same needle holder pincer tips and are

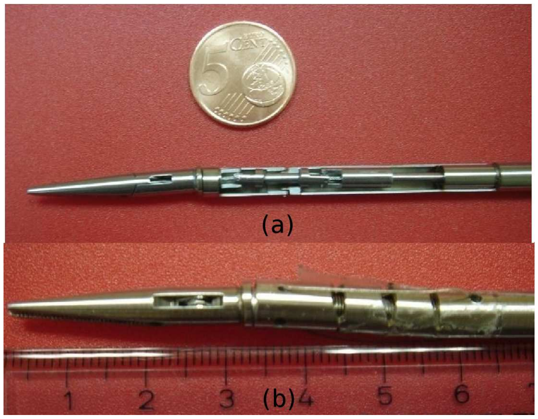

Fig. 10. Prototypes in 6mm diameter: (a) Universal joint model, (b) Metallic bellow model (bellow within the link members)

fabricated in stainless steel. Current prototypes do not have the force/torque requirements for suturing. We are working on 5mm prototypes that satisfy these requirements.

The current instrument prototype (metallic bellow model) is actuated with two rotary DC motors (Maxon motors 118400 with 1024 and 64 reduction gear train) with manual opening and closing of the pincer tip. The handle part of the instrument encases the entire electric component including toggle switches to control 2 DOF rotations. The instrument is adaptable to conventional trocar.

IV. CONCLUSION AND FUTURE WORK

Our methodology of design by simulating first, was successful in the sense that it provided us accurate information as how to design our controller and the robot's kinematics. The simulations showed using our fingers dexterity, results in more precise control of a dexterous end effector. So the best choice of handle for a robotics hand-held surgical device would be a finger operated handle. The most intuitive control mode is a WYSIWYD (What You See Is What You Do) coupling between the movements of the controlling joystick/handle and the movements of the end-effector observed on the screen. It makes the end-effector move on the screen in the same direction as the joystick on the handle. The simulations also showed that to do sutures, the optimal kinematics for the end-effector is a yaw-roll kinematics. 2 proof of concept prototypes were made based on these results. The Wii Nunchuck handle we used in the simulator is not meant to be used in a surgical instrument. We are working on the ergonomic design of a proprietary handle for our next prototype. The force transmission system needs to improve and there is already a new version of it under development.

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Ali Hassan Zahraee received the B.S. degree in electrical engineering from Isfahan University of Technology, Isfahan, Iran in 2005, and the Diplme d'Ingenieur and M.S. degrees respectively from ENSEA and the University of Cergy-Pontoise, both in Cergy, France in 2007. He is currently a Ph.D. candidate at Institut des Systemes Intelligents et de Robotique, University of Pierre et Marie Curie - Paris V1, Paris, France. His research is about finding robotic solutions to the problems associated with laparoscopic surgery.

Jamie Kyujin Paik received the B.Ap.Sci.,and Ph.D. degrees in mechanical engineering from the University of British Columbia, Vancouver, Canada in 2002 and from Seoul National University, Seoul, Korea in 2007 respectively. As a post-doctoral research associate, she had been with Institut des Systemes Intelligents et de Robotique in Paris, France until 2009. Currently she is engaged in post-doctoral research at the Microrobotics Laboratory at Harvard University, Cambridge MA. Her research interests include smart materials, micro robotics and electromechanical designs.

Jerome Szewczyk received a M.S. degree in mechanical engineering from University of Compiegne (France) in 1994 and a PhD degree in robotics at University of Paris VI in 1998. Since 2000, hes assistant professor at Institut des Systemes Intelligents et de Robotique, University of Paris VI. His research activities concern the design of sensors and actuators for meso-robotics based on smart materials and the optimal design of robotic structures for surgical applications.

Guillaume Morel (M′97) received the Ph.D. degree from the University of Pierre & Marie CurieParis 6, Paris, France, in 1994. He is now a Professor of Mechanical Engineering with the University of Pierre & Marie Curie. He was a Postdoctoral Research Assistant with the Department of Mechanical Engineering, Massachusetts Institute of Technology, Cambridge, in 1995–1996, and an Associate Professor with the University of Strasbourg, France, from 1997–2000. After a year spent as a Research Scientist for the French company of electricity (EDF), he joined the Laboratoire de Robotique de Paris (now Institute for Robotics and Intelligent Systems), Paris, France. His research has dealt with sensor-based control of robots, with a particular focus on force-feedback control and visual servoing. Application of these techniques for medical robotics (surgery, rehab) is now the main area of his research.