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# Lightweight Hand-held Robot for Laparoscopic Surgery

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*Abstract*— **Some phases of laparoscopic interventions, such as suturing, require precise and dexterous movements that are difficult to perform by means of rigid instruments. Multi-DOF hand-held instruments and teleoperated systems have been developed to increase movement dexterity. In this paper, we present the design of a novel hand-held robotic instrument that can be operated by the surgeon with one hand only, while standing at the operating table and acting on a traditional laparoscopic instrument with the other hand. Its main advantages are the low weight, achieved by dislocating the motors and using a flexible transmission, and the possibility to switch end-effector, changing the instrument type according to the phase of the intervention. The instrument can be used easily and rapidly, since it does not require long or complex set-up procedures. We describe the instrument design, the development of the first prototype and compare it to rigid instruments in the ability to approach sutures at various angles.**

## I. INTRODUCTION

Minimally invasive surgery (MIS) interventions bring numerous benefits to the patient, but severely hinder the surgeon due to the keyhole accesses. Since MIS instruments are rigid or only limitedly flexible, some anatomical regions are not accessible. The insertion point acts as fulcrum constraint on the long, stiff instruments, causing non-intuitive effects on the tip movements, like movement inversion and velocity scaling. The use of endoscopes, necessary to look at the operated regions, causes loss of color and depth perception and increase the difficulty of identifying and handling the tissues and the risk of tissue damage. Direct manipulation and palpation of tissues are prevented by the keyhole accesses; friction and leverage that arise from the use of stiff instruments reduce or distort force and tactile feedback.

Technology can provide many different instruments and devices aimed at restoring – and possibly augmenting – the reduced surgeons' perception and motor skills. This work focuses on laparoscopic procedures and presents a novel hand-held robotic instrument with additional degrees of freedom (DOF) at the instrument tip, that can be readily used by the surgeons during specific phases of the intervention, when they need additional dexterity, such as for suturing.

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## II. BACKGROUND

To perform intra-corporeal suturing the surgeon needs to perform precise movements both for stitching and knotting. Most commercially available laparoscopic instruments are long and stiff and allow only the opening and closing of the forceps by means of a scissor-like handle and the adjustment of the roll angle by means of a knob. This roll angle adjustment, however, is meant only for ergonomics and does not introduce a new DOF. Therefore, laparoscopy performed with stiff instruments is limited to 4 DOF. This allows to easily stitch only cuts that are aligned with the instrument shaft, while stitching cuts that are at a 90 degrees angle with the instrument shaft is much more difficult.

Research aimed at enhancing dexterity for laparoscopic procedures has led mainly to three categories of instruments, namely purely mechanical hand-held instruments, mechatronic hand-held instruments, and teleoperated systems, which will be briefly described in the following. This classification is not exhaustive but is useful in order to describe works related to our project.

### A. Mechanical Hand-held Instruments

Besides traditional, rigid instruments for laparoscopy like forceps, dissectors, clip appliers, etc., some instruments are available commercially that allow a manual control of the tip orientation, such as linear cutters and clip appliers. However, changing the orientation of the tip is often achieved by rotating an additional knob that requires the use of the other hand. Examples of this type of instruments are of the ETHICON family, like the ENDOPATH ETS Compact-Flex45 Linear Cutter that has a steerable head or the LIGACLIP ERCA Endoscopic Rotating Multiple Clip Applier.

Recently, a few mechanical instruments have been presented as research results. In [1], an instrument is presented in which the knob that controls the roll angle in traditional tools is replaced by a hinged ring that can be used to steer 2 DOF of tip deflection. However, a precise movement of the ring requires 2 or 3 fingers and it is unclear how the surgeon can simultaneously open/close the gripper with the scissor-like handle. In [2] a cutter with an alternative handle is presented in which 1 DOF of tip deflection can be steered by a 2 DOF hinged lever that is used also for opening and closing the gripper. The direction of the cut can be therefore be selected freely, at the cost of giving up the knob for adjusting the roll angle, thus leading to a less ergonomic instrument, and of mixing the commands for gripper opening and orienting on the same lever, which could lead to confusion. The Radius Surgical System is a commercially-available manual manipulator that allows precise and controlled needle guidance in endoscopic suturing [3], [4]. The instrument has a lever to control the tip orientation, a knob to control the gripper roll angle, and a lever for the gripper closing. The instrument allows smooth and precise movements, however the controls are not very intuitive and training is required to achieve a good dexterity.

Overall, multi-DOF mechanical instruments often have a non-intuitive interface because the transmission needs to respect mechanical constraints and cannot be designed freely.

### *B. Mechatronic Hand-held Instruments*

To overcome limitations in designing the mechanical transmission, mechatronic hand-held instruments have been developed. As with traditional laparoscopic instruments, these instruments allow the surgeon to stand at the operating table near the patient. One hand is used to operate the mechatronic instrument, while the other hand can be used for a traditional laparoscopic instrument. Currently, none of the mechatronic instruments is commercially available. Many research works in this field lead to hand-held robotic instruments that have an end effector actuated by one or more motors that are located in the handle of the instrument. This results in a heavy and therefore poorly ergonomic instrument. Four examples of this approach are the instruments presented in [5], [6], [7] and [8]. A different approach lead to the multi-DOF forceps manipulator system presented in [9]. In order to reduce the weight of the instrument, the motors are not located on the instrument and a flexible transmission is used to steer the 2 DOF of the instrument tip.

One major drawback of all the cited systems is that the instrument tip is an integral part of the instrument, whereas in laparoscopy it would be desirable to be able to change the instrument type from grasper to forceps to dissector, etc., according to the phase of the intervention.

### *C. Teleoperated Systems*

Telerobotics is the most natural way to restore dexterous movements in MIS. Indeed, with respect to mechanical instruments, robotic devices allows to physically decouple the master and slave parts. This allows to overcome the fulcrum constraint at the insertion point and therefore to develop a more natural and ergonomic interface. The surgical instrument can so be replaced with robotic instruments that are under direct control of the surgeon through teleoperation.

Surgical telerobotics has reached a mature, commercial stage, and the forefront is represented by the da Vinci® Surgical System [10], together with the Zeus [11], which was developed first but is not sold any more. In teleoperated systems, the surgeon stays at a console (master system) while the robot arms (slave system) that mount the surgical instruments are located at the surgical table and operate on the patient. The movements of the surgeon at the console are replicated by the slave robot, which eliminates the fulcrum effect and allows further enhancements such as tremor compensation and movement scaling. In addition, a wide selection of interchangeable surgical instruments is available for the da Vinci and Zeus. However, telerobotic systems force the surgeon to move away from the patient, which is felt as a drawback by many surgeons. The robot is the only actor at the operating table and the surgical routine is completely modified. Moreover, the long setup times force the surgeons to use the teleoperated system throughout the whole procedure and not only for the phases that require enhanced dexterity. Additional drawbacks are represented by the cost of those systems, by the additional space occupied in the already cramped operating room and by the reduced interaction of the surgeon with his team. Furthermore, commercial telerobotic systems have not yet implemented force feedback, but this issue is addressed in several recent research works, such as [12]. Moreover, other competitor systems such as [13] are being developed.

Another interesting approach is the Minimally Invasive Manipulator (MIM) [14]. This system is a purely mechanical telemanipulator: the system is fixed at the operating table and the slave part mechanically replicates the movement of the master, controlled by the surgeon by means of ergonomic handles. With respect to robotic teleoperation system, the MIM is smaller, less complicated and allows the surgeon to stay closer to the operating table. However, also in this case, the surgeon cannot use a traditional laparoscopic instrument while he/she is at the manipulator.

## III. SYSTEM REQUIREMENTS AND OVERVIEW

In this work we present a novel multi-DOF hand-held mechatronic instrument for laparoscopic procedures. In its design we have taken into account the major drawbacks of currently available instruments and research prototypes, aiming at developing an instrument that allows the surgeon to perform dexterous movements while still being ergonomic and easy to set-up and use.

In particular we aimed at developing a hand-held dexterous instrument, that can be operated by the surgeon with one hand only while standing at the operating table and acting on a traditional laparoscopic instrument with the other hand. The instrument must be readily available and must not require long or complex set-up procedures: it must be possible to use the instrument only during some phases of the intervention and then to revert rapidly to traditional instruments when the additional DOF are not needed. The instrument must be lightweight in order to hold down the surgeon's fatigue during long interventions. The instrument must have enough DOF to allow the surgeon to perform complex tasks, like stitching and knot tying, at all angles with respect to the instrument shaft. The commands to drive the DOF at the instrument tip must be intuitive and natural at all orientations of the instrument and must not require too much training to be mastered. It must be possible to easily switch the end-effectors of the instrument so that only one robot is needed in the operating room. Available end-effectors should include scissors, graspers, needle holders, dissectors, etc. The separation between instrument and end-effector also has the additional benefit of allowing different sterilization procedures and the disposal of the end-effector.

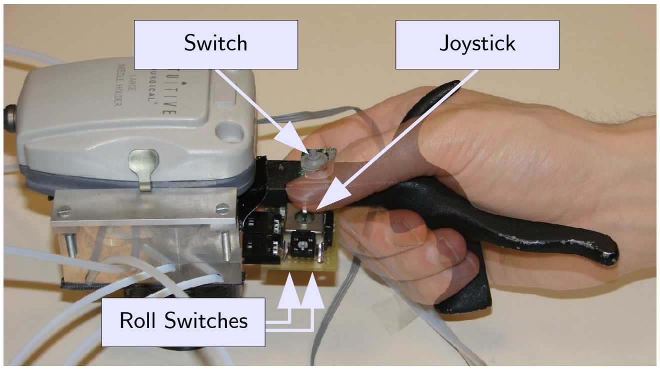


Fig. 1. Instrument handle with joystick.

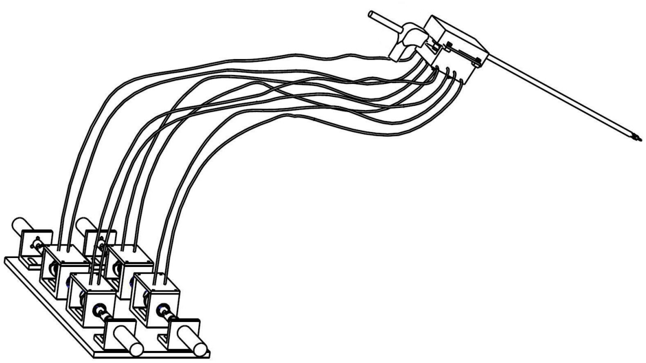

Fig. 2. Concept drawing of the lightweight hand-held laparoscopic robot.

We therefore designed and fabricated an instrument that has an ergonomic handle and allows to mount the instruments of the da Vinci EndoWrist® family. The motors used to steer the tip are dislocated from the handle by using flexible transmissions. The master part has a joystick that allows the surgeon to control the DOF of the end-effector. We decided to use a foil grip, because it is a very comfortable handle and there are many sizes that can be matched to the surgeon's hand. The joystick is mounted on this foil grip, as shown in Fig. 1. The system has four motors and allows yaw, pitch, grasp and roll movements. Figure 2 shows a concept drawing of the instrument.

## IV. DETAILED SYSTEM DESCRIPTION

Motors are placed away from the tool handle and connected to it by means of a flexible transmission. A prototype has been built using a 4-DOF EndoWrist® instrument by Intuitive Surgical Inc. [15], that we connected to the motors using tendon-sheath transmissions, the same kind of transmission used in robotic hands. Cables are used to transmit movement from the motors to the tool, and sheaths are used in order to have a flexible transmission, while maintaining the cable in tension. The system is composed by 4 DC motors mounted on a frame and attached to the driving pulleys (see Fig. 2). For each of the driving pulleys a stainless steel cable is fixed with both ends and is also wound on a driven pulley . Each driving pulley is split in two parts that can counterrotate allowing the cable to be pretensioned, as in [16]. Then these

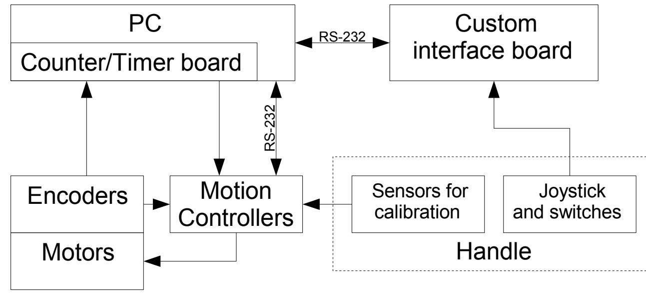


Fig. 3. System control scheme.

two parts are connected together after the device has been assembled. Another support was built for the driven pulleys and attached to the laparoscopic tool, where other 4 wheels are located, each connected to a driven pulley.

The design of the interface between the support and the tool tip is based on [17]. There are four driven pulleys, one for each driven pulley of the EndoWrist. The sheaths, two for each pulley, are attached to both supports and the cables slide inside them. The tendon-sheath driving system allows the tool to be moved independently from the position of the motors: these remain fixed to the base. The weight of the prototype in aluminum of the hand-held instrument is about 300 g, which is lower than the weight of several other robotic devices in previous literature. An analog joystick is used to control the movement of the end-effector of the tool.

### A. Motors

The DC motors are manufactured by Faulhaber, model 2342018CR coupled with a gear reduction, series 23/1, ratio 43:1. We decided to use this model after a rough calculation, by considering the order of magnitude of the forces applied to the laparoscopic instrument handles like reported in [18] and in [19]. We first decided the gear reduction ratio on the basis of the maximum required output torque of about 350 mNm for the grasping function and on the basis of the maximum output speed of about 360 deg/s. We found the gear reduction ratio by dividing the maximum allowable speed for the gear reduction by the maximum speed required for the load and we decided for the precautionary value of 43:1 of the 23/1 series. Then we found that the output power required to the motor is about 30 W for continuous operation. However, for our instrument continuous operation is not required, therefore we decided for the 19 W motors, series 2342, powered with 18 V.

### B. Control Part

The control part is formed by a Windows PC, four PI controllers and drivers for the motors. Inside the PC there is a dedicated PCI Counter-Timer board in order to generate the velocity commands or the position commands for the motors. This board is a NI-PCI 6624 manufactured by National Instruments, it has 8 counter-timer modules and offers channel-channel isolation and a $\pm 48$ VDC voltage range on inputs and outputs. Typical applications include quadrature encoder measurement, edge detection, frequency measurement, pulse-train and pulse-width-modulated (PWM) signal generation. The motor drivers include the PI motion controllers and these are manufactured by Faulhaber, series MCDC2805. The input signals originate from the handle part of the instrument where a two-axes potentiometer joystick with a momentary switch and two other switches are located. The joystick signals are used to orient the tip of the EndoWrist, one for the pitch, one for the yaw movement and the switch present on the joystick is used for the grasping function. The other two switches are used for activating the roll movement of the stem: one switch is used to rotate in one direction and the other for the opposite direction. These last two buttons are located in the lower part of the handle. All these handle signals are processed by a custom interface board that sends commands to the PC through a RS-232 connection. The control scheme is shown in Fig. 3. These informations are related to the position of the joystick and the state of the switches and the software that runs on the PC will calculate the correct values for the velocity commands to send to the motor drivers on the basis of the received informations. Software has been developed in C++ language with Microsoft Visual Studio .NET 2003 and QT3 by Trolltech for the graphical user interface. The velocity commands are sent to the drivers with PWM signals, one for each motor, generated by four counter-timer channels of the PCI board. The position of the motors is read by the PC with the remaining four counter-timer channels connected directly to the encoders. Moreover the motion controllers are connected to the PC with a RS-232 connection. With this configuration the time critical tasks are carried out by the motion controllers that perform the velocity control, also taking into account the range of motion of each motor, while the generation of the command signals for the motors, that is a less time critical task, is left to the software. The problem is to generate signals for the four motors to move the end effector correctly. We calculated the kinematics of the EndoWrist by moving each pulleys in a micrometric slide and photographing the tip position. Using an image analysis software we found the relationship between the EndoWrist pulleys and the parts that are in the tip. Figure 4 shows the internal view of the EndoWrist highlights the pulleys involved in the tip movement [20]. The relationships between the angles of the pulleys ($\vartheta_{130}$, $\vartheta_{132}$, $\vartheta_{136}$, $\vartheta_{134}$) and the angles of each part of the tip ($\vartheta_{154}$, $\vartheta_{52}$, $\vartheta_{581}$, $\vartheta_{582}$) are represented by the transmission ratio matrix (1).

$$\begin{pmatrix} \vartheta_{154} \\ \vartheta_{52} \\ \vartheta_{581} \\ \vartheta_{582} \end{pmatrix} = \begin{pmatrix} 0 & 0 & 0 & 1.54 \\ 0 & 0 & 1.03 & 0 \\ 0 & 1.15 & 0.743 & 0 \\ 1.15 & 0 & 0.743 & 0 \end{pmatrix} * \begin{pmatrix} \vartheta_{134} \\ \vartheta_{136} \\ \vartheta_{132} \\ \vartheta_{130} \end{pmatrix} \quad (1)$$

With this rough estimation we have implemented the correct movement of the tip. It is possible to move the $\vartheta_{52}$ without changing $\vartheta_{581}$ and $\vartheta_{582}$ and this corresponds to the pitch movement if the tweezers are oriented horizontally. This movement is performed with three motors because of

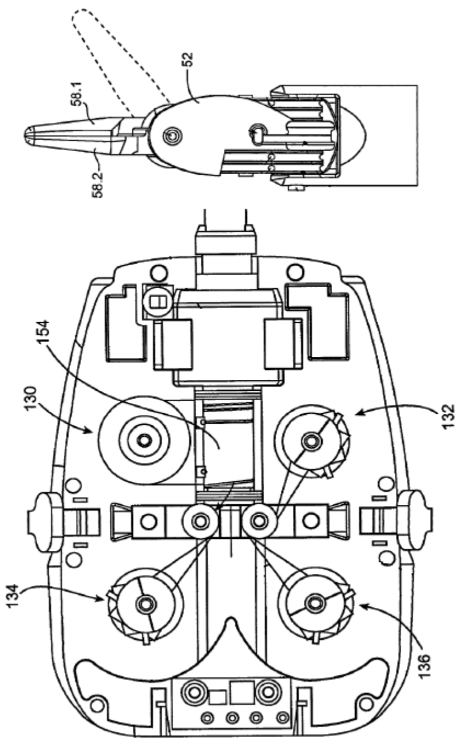


Fig. 4. EndoWrist schematics (from [15]).

the correlation between the parts of the tip. A problem that arises with the use of the joystick is that when there the stem roll angle is non-zero, the joystick vertical and horizontal movements do not correspond to the tip vertical and horizontal movements. We decided to calculate the tip direction considering the stem roll angle and the joystick values in order to maintain the correspondence between the horizontal and vertical movement of the joystick and the tip. Each time the system is powered on an initial calibration is performed because the tip position is unknown. For this purpose there are four omnipolar hall-effect digital switches, one for each handle driven pulley. These sensors are fixed to the EndoWrist support. On the driven pulleys there are four permanent magnets, one for each pulley. Initially, each motor goes to its limit position that is reached when the magnet stands in front of the hall-effect sensor; afterward, each motor goes to the position represented by the middle of his maximum range; then the system is ready to operate. We know every motor range because we measured it from the EndoWrist pulleys. The speed of the motors that command $\vartheta_{134}$ and $\vartheta_{136}$ (that move the two parts forming the tweezer, angles $\vartheta_{582}$ and $\vartheta_{581}$) is lower than the speed of the other two angles, in fact $\vartheta_{582}$ and $\vartheta_{581}$ depend respectively from $\vartheta_{136}$ and $\vartheta_{134}$ and both depend also from $\vartheta_{132}$, therefore for these angles the maximum position limits are reached when $\vartheta_{132}$ is already at the limit switch. This particular procedure has been studied for the use of the EndoWrist and it is implemented directly in the motion controllers. This calibration procedure can be carried out every time that the instrument loses the coordination, in fact tendon-sheath drive systems are affected by friction and compliance and they introduce a hysteresis nonlinearity between the joint torque output and the actuator displacement, as reported in [21]. When the system is running, the calibration procedure can be called through the PC software that has a graphical user interface showing the main features like position and current consumption for each motors and permits also to set directly the parameters like tip velocity, motor enable or disable and to call the calibration procedure (see Fig. 6).

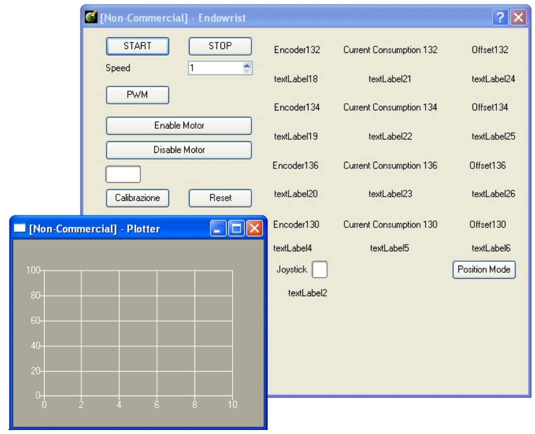


Fig. 6. Graphical User Interface.

## V. PRELIMINARY TESTS

With respect to mechanical instruments our system offers a more natural mapping of the degrees of freedom, by allowing to use a 2-DOF joystick to orient the tool tip. The use of a joystick allows to map the orientation of the stick to the orientation of the tool tip, which seemed to be a natural and intuitive mapping. Moreover, the surgeon can decide if a forward movement of the joystick tip corresponds to an upward or downward movement of the end effector according to his own preferences and previous training. As previously discussed, purely mechanical tools usually require two separate controls for orienting the tool tip (e.g. two knobs or a knob and a lever), since a mechanical transmission connecting a multi-DOF handle to the tip would be too complex. Current mechatronic systems adopting the joystick solution have the motors mounted on the instrument. By dislocating the motors, our system is more lightweight and ergonomic.

We asked two expert surgeons to use our first prototype (shown in Fig. 5) to approach a suture from different angles, particularly 0, 45 and 90 degrees, and then to perform the same task with a traditional instrument (see Fig. 7). With our instrument, the surgeons can grab the needle in the correct way at all angles, while approaching the suture at 90 degrees with the traditional instrument is much more difficult. The opinions of the surgeons are encouraging, because they found it very interesting to have many more DOF than with a traditional instrument, while standing near the operating table and also the possibility to change end-effector in a rapid way was appreciated. On the other hand, the surgeons did not agree with the use of a joystick to control this instrument, in fact they felt this control mode is not very intuitive because they were unable to control both DOFs of the tip orientation simultaneously and ended up controlling only one DOF at a time. It is worth noting, however, that the surgeons started using the instrument with no previous training at all and still managed to perform the sutures correctly.

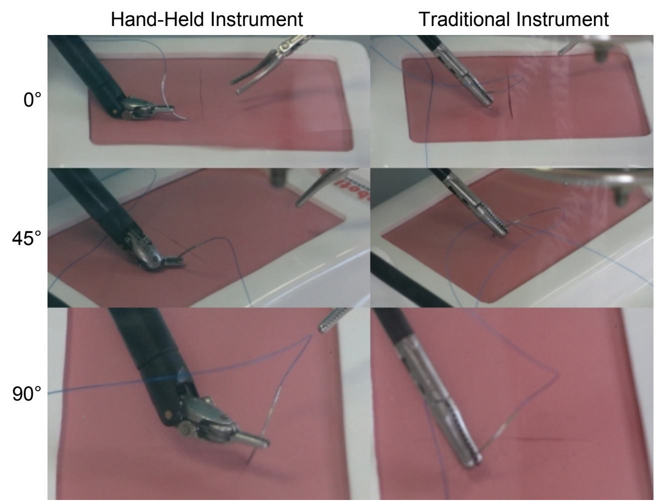


Fig. 7. The different angles at which the suture was approached.

## VI. CONCLUSIONS

We developed a hand-held robotic instrument for laparoscopic surgery that allows to reach all positions of the operating space with 6 DOF (+1 for opening/closing the gripper). The main advantages are the low weight, achieved by dislocating the motors and using a flexible transmission, and the possibility to change end-effector, since the mechanical interface between handle and end-effector can accommodate all instruments of the EndoWrist® family. According to expert surgeons' opinions, this hand-held instrument has great effectiveness and potential. One major issue is the interface to control this instrument. For this first prototype we used a joystick for orienting the tip and two switches for the roll movement; this does not seems to be the optimal way to control it. In [22] we have performed an interface study for the hand-held instrument and assessed the performance of several control modes. By combining these results with the surgeons' opinions, we are now developing a more intuitive interface. The idea behind this new interface is to give the surgeon the possibility to orient the tip directly in a more natural way. We will design a handle that will allow a direct mapping between the position of the handle and the position of the tip. For this purpose, a tweezer-like handle will be studied, the motors will be position-controlled, thus a given handle configuration will directly correspond to a given tip configuration. We will also reduce the size and weight of the interface part between the handle and the end-effector. The final prototype will have the desired features of lightness and intuitiveness and its performance will be assessed by means

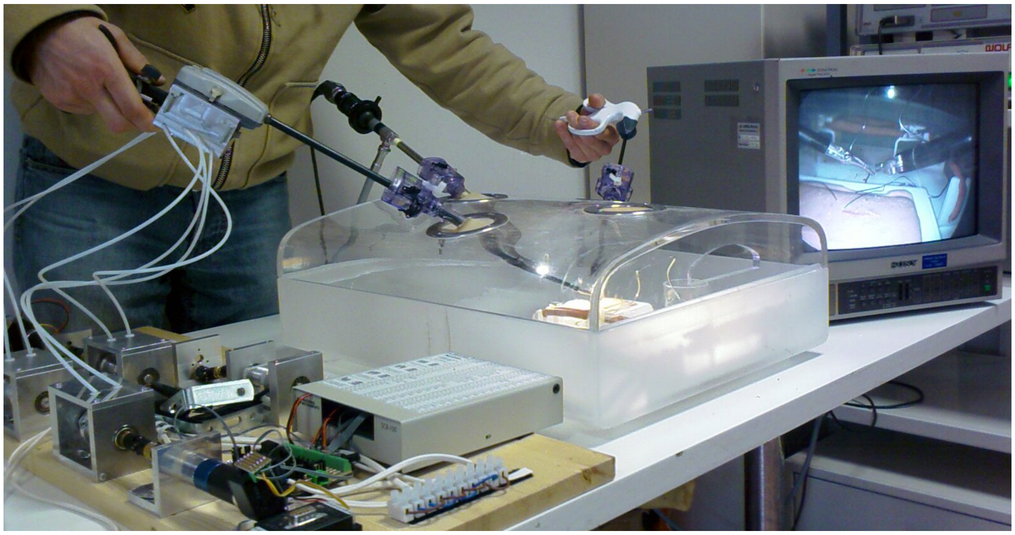

Fig. 5. The first prototype used in a laparoscopic bench box.

of in vitro and in vivo experiments.

## VII. ACKNOWLEDGMENTS

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