Design and control of a robotic assistant for laparoscopic surgery

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Abstract. This paper presents a robotic assistant for helping surgeons in minimally invasive surgery. The system provides the direct control of the camera positioning inside the abdominal cavity, by both surgeon voice commands and remote teleoperation. This work is based on a previous experience with a system designed around an industrial robot arm. The new system keeps all the capabilities of the previous one, but incorporates a specially designed arm for this application. This prototype does not require any modification of a standard operation theatre (furniture or surgery tools) for its installation and its putting into operation. The system has been tested by using patient simulators, and in vitro tissues.

During last years, a new field has gained the interest of robotic researchers. Minimally invasive techniques, such as laparoscopy, have grown as a very suitable domain for robotic systems. In these procedures, the surgeon only uses the visual feedback information provided by a camera attached to the endoscope. Thus, the surgeon manoeuvres the laparoscope and video camera within the abdominal cavity to explore the anatomical structures and their pathologies. Since these procedures can last up to two (or even more) hours, the camera image can suffer a significant loss of stability. The centring on the point of interest can be worse, as well. In this scenery, a robotic aid, able of moving the laparoscopic camera according to surgeon's voice commands (allowing him or her to use both hands in the surgical procedure itself), would become a very helpful tool in the operating room.

1. Problem Statement.

Laparoscopic techniques involve the use of long stem instruments through small incisions in the abdominal wall of the patient. A special camera, whose optic penetrates as well into the abdomen, helps the surgeon to manoeuvre the instruments in order to complete the procedure (Satava, 1998). Thus, we have two possibilities to develop a robotic aid: moving the instruments or moving the camera. Every one of these options follow a different target: robotized instruments can help us to achieve telesurgery, moving the surgeon from the operating room to a distant site; a robotic camera, however, can improve coordination and efficiency, and free a second surgeon (the one who moves the camera) to help the main surgeon, or to carry out another procedure in a different operating room.

A review of the literature can show diverse ways of facing the development of a laparoscopic assistant. In 1995 Taylor and others proposed a complete system, including a manipulator, a special end-effector to carry the laparoscopic camera and a new control strategy. The manipulator had 7 degrees-of-freedom (dof) divided into three components: a translation component (3 dof), a remote centre-of-motion component (2 dof) and a distal component (2 dof) that completed the 4 dof that an insertion point offers (roll, pitch, yaw and penetration). Thus the orientation of the camera through the incision was decoupled of its positioning. An interface based on an instrument-mounted joystick, for voice-recognition system were not very capable at that moment.

Green, at SRI International (1995), developed a different concept. The target of this system was to explore the possibility of a telesurgery scheme, appropriate not only for minimally invasive surgery but to open surgery as well. Thus, two manipulators (5 dof) was included in the local subsystem -though the inclusion of 7 dof manipulators was yet planned-, and a complete remote workstation was developed, including stereo video and audio, and two master manipulators with force reflection capabilities. A view of the surgical field was provided by a camera mounted on a third arm. This telesurgery concept was later enhanced and taken to a commercial stage by Intuitive Surgical's Da Vinci system (Guthart, 2000).

The HISAR system (Funda, 1995) presented a new configuration of the manipulator. The proposed one was a 7 dof robot mounted on the ceiling, with 3 dof to position the camera and 4 dof to get the right orientation. Two of these orientation axes were passive to grant free compliance with the port of entry. Since this point acts as a fulcrum, it is necessary to have an accurate knowledge of its position to move the camera with precision. In order to achieve this, a re-estimation procedure of the pivoting point is proposed.

Hurteau (1995) proposed a system based on a 6 dof industrial manipulator, modified by means of an universal joint between the end-effector and the camera holder. This feature permits to position the robot away from the patient since it does not need to be attached to the stretcher. Moreover, the use of passive axes allows a simple way of facing the motion control problem while avoiding the potential application of undesirable forces on the patient.

The system of the Universitat Politèctica de Catalunya (Casals, 1996) goes a step beyond and shows a motion control system able of moving the camera following the movements of the instruments, thus permitting the surgeon to forget the problem of controlling the camera and allowing he or she to concentrate on the surgical procedure itself. This system is based on a SCARA industrial manipulator modified with an universal joint in the end effector. An extension of this device permits to free space near the stretcher since the robot does not need to be placed right beside it. The control of the camera is achieved through a computer vision system that tracks special marks on the instruments.

The Computer Motion Aesop (Wang, 1996) is a commercial system intended to move the camera according to the commands of the surgeon, first through a pedal and after through a speech recognition system. It is a 4 dof robot attached to the stretcher, and presents an end-effector with three axes (two passive and one active). The passive ones guarantee the compliance between the camera and the insertion point, and the active one rotates the camera around its longitudinal axis. Many surgical procedures have been completed using this system, and it has received the FDA-approval.

Another commercial device is the Laparobot (Dowler, 1996) by EndoSista. This system suffered different modifications from an experimental setup to finally reach a definitive configuration. It is based on a 3 dof positioner that holds 3 dof to orientate the camera. An additional axis gives the possibility of working with angled endoscopes. No passive axes are included to secure the compliance between the camera and the abdominal wall; instead of it, the orientation subsystem is design to move the camera around a remote centre of rotation. The robot has to be placed over the patient in such a way that its centre of rotation coincides exactly with the insertion point.

The Black Falcon (Madhani, 1998) presents a different scope. It is intended to hold an instrument, not the camera. Thus, the system has an 8 dof slave manipulator and a 7 dof master manipulator (including force reflection in three of its axes). The slave manipulator separates a 4 dof stage, to move the instrument according to the constraints at the insertion point, and a 4 dof wrist to work inside the patient. To guarantee that no harm will be caused on the insertion point, the mechanical structure of the four implied axes is designed to necessary comply with the constraints.

2. Robot kinematic design.

The main purpose of the proposed system is helping surgeons by moving the camera according to his or her commands. No instruments are intended to be robotized at this stage. Moreover, completion of this target should accomplish the next requirements in order to be a useful solution:

1. The resulting system should avoid (or at least minimize) modifications on a standard operating room.
2. It should not be bulky.
3. It should be safe.
4. Surgeons should command the movements easily.

According to this requirements, the first step was to choose a kinematic configuration. As can be seen in the literature, most of the systems -if not all- separate the problem of positioning from the problem of orientation. This way, we consider two different problems:

1. Vertical motion of the wrist movement plane by keeping this plane parallel to the stretcher (translation along the Z axis of the global robot coordinate frame)
2. Motion along the wrist movement plane (combined translations along the local X_c and Y_c wrist axis).

In order to accomplish the motion in the horizontal XY plane by keeping the camera orientation, we conclude that the standard RR planar manipulator is appropriate. This arm is mounted on a monocarrier platform as it is shown in Figure 1. A double parallelogram structure would have been another possibility for the RR part of the robot. However, it would have added weight and less accuracy (Taylor, 1995). The only advantage of the parallelogram design (the availability of more room for encoders and other sensors) can be easily compensated in the RR manipulator through a proper design of its joints.

The length of the two elements of the RR manipulator have been computed by studying the camera workspace outside of the abdominal cavity when the optic is inserted through the trocar. Figure 2 shows the camera positioning outside limits, defined by a minimal insertion length of the optic through the trocar with the maximal deflection angle of 75º. Therefore, the cartesian workspace of the camera is defined as an inverted cone with a base radius of *a*. If we assume a camera optic length of 360 mm from the distal end (d) to camera holder grasping point (g), the value of the arm elements length (L_1, L_2) is computed from expression $L_1 \cdot L_2 = 278750\text{mm}$. This equation has been obtained considering that the arm should reach any point of a 40 cm-size square, which contains the base of the inverted cone, and by taking into account that, since the robot is not attached to the stretcher, this square could be located in an asymmetrical position from the arm. If we choose to have both elements with the same length, which has been our selection in order to make easier storage and operation, we come to an element length defined by: $L_1 = L_2 \cong 530mm$.

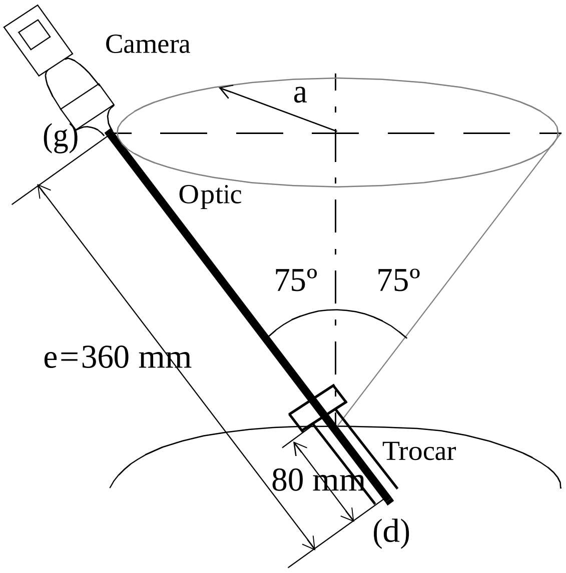


Figure 1. Optic workspace.

The orientation problem can be solved in two ways: through passive axes and through mechanically constrained joints. The last solution, though is intrinsically safe, implies a usually bulky structure that has to be placed over the patient. This way, it can restrict the surgeon's freedom of movement, so this possibility was discarded in an early stage of the design (Muñoz and others, 2000). Thus, our proposed system achieves a proper orientation of the camera through passive axes. The first of these axes is disposed parallel to the actuated joints (rotation around the Z axis), allowing the camera to turn around the axis of the inverted cone of its cartesian workspace. The second passive joint (rotation around the X axis) completes the degrees-of-freedom that the camera needs to comply with the required workspace. Figure 2 shows a horizontal movement of the robot arm from point A to B. In this situation, the optic pivots at the trocar insertion point C thanks to the holder Z rotation. Similarly, the vertical movement of the arm is possible thanks to the X rotation of the holder.

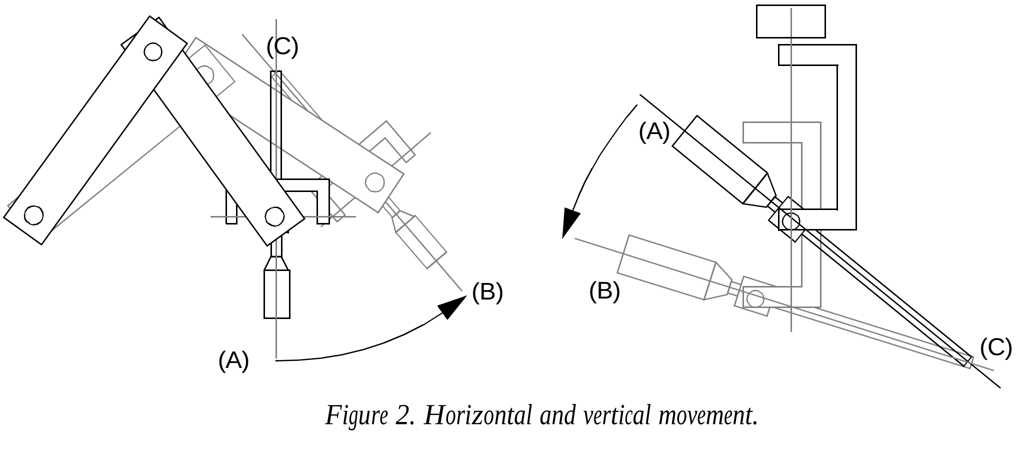


Figure 2. Horizontal and vertical movement.

Figure 3 shows the cartesian workspace of the camera related to the resulting workspace of the robot arm. It can be noticed that the workspace of the camera can be located in a wide range of positions inside the robot workspace, thus allowing the system to be placed according to the necessities of every case.

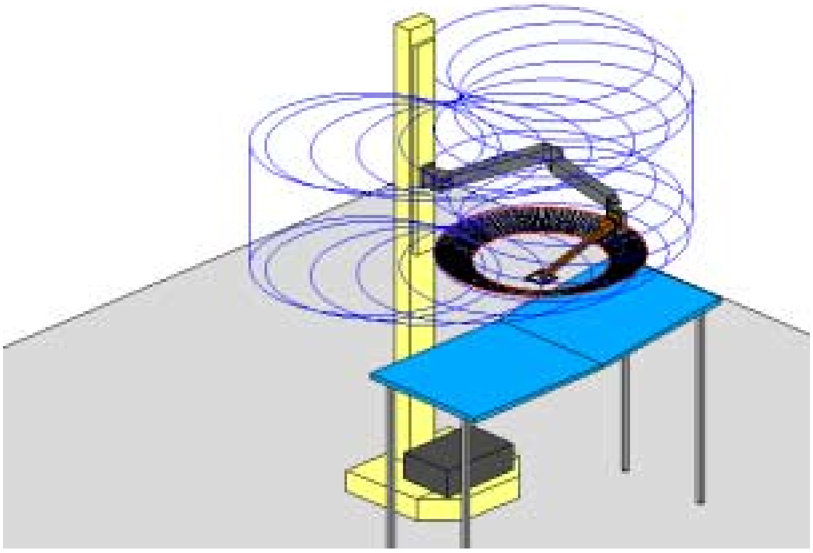


Figure 3. Workspace of the camera related to the workspace of the arm.

3. The Local-Remote Control System.

The overall scheme of the shared control system of the robotic assistant is shown in Figure 4. A shown, the robot arm can be commanded both local and remotely by means of high level basic camera movement instructions. The local user (surgeon) interface allows spoken commands. The remote user (experienced/mentor surgeon) can see the endoscopic video image and interact with the local surgeon by means of an overlaid graphical annotation system. Also a video-conference channel is available for a more natural communication.

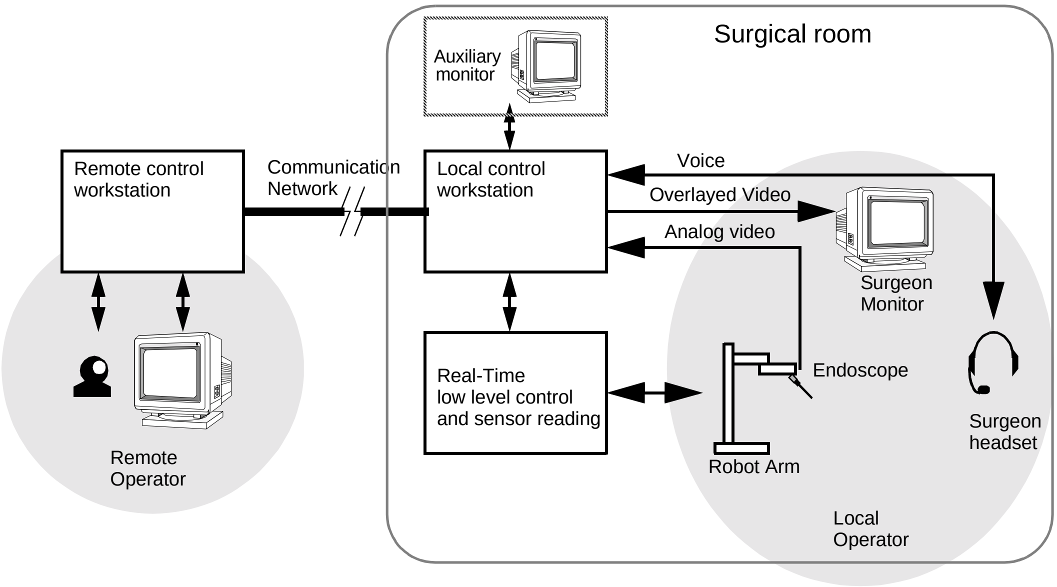


Figure 4. Overview of the local-remote control architecture.

This system purpose is to go beyond the limits of the telemedicine and teleassistance applications. In this sense the first step is to control the camera position inside the patient's body for helping the local operator to find the interest area and showing him the suggested procedure. As the robot trajectory generation and feedback control loop are local, the remote system teleoperation is stable (Gómez-de-Gabriel, 1999) under remote supervisory commands.

The communication media between both sites depend on the distance, and varies from low bandwidth internet networks, to dedicated ATM high bandwidth channels. Shortest distances allow different physical connections for low cost analog video, data and voice channels.

4. The Remote Operator Interface.

The remote user interface (see Figure 5) is intended for instruction and supervision purposes. In this way, this operator is able to aim the lasparoscopic camera and to advise to the local surgeon by means of a set of overlaid marks. These marks, hand-drawn by the remote operator over the endoscopic image, are displayed both in the local and remote workstations. Moreover, a videoconference link is available between both surgeons.

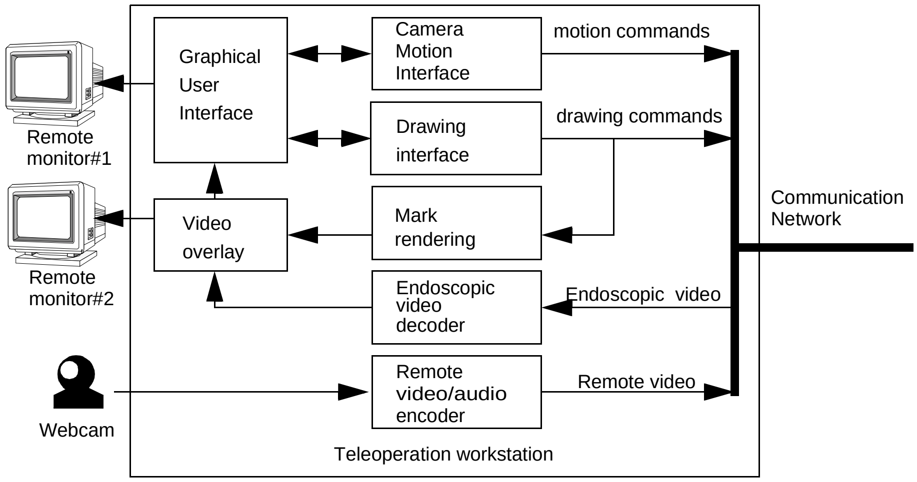


Figure 5. Remote workstation architecture.

The dual monitor workstation (See fig. 6) is a *Pentium III* PC with 128 Mb RAM, a *dualhead* AGP video card from *Matrox*, running under *Microsoft's Windows 98*. The main application has been written (designed) in *Delphi-4* standard, (*Borland*). External devices include a *Phillips* USB webcam and the *SpaceBall* manual controller (force/torque sensor). Also the *NetMeeting* application is used for videoconferencing.

Figure 6. The dual remote workstation display.

The tested video overlay system is based on the inexpensive *Brooktree* bt878 PCI video capture chip in a 768x576 pixels size 15 bit deep with overlay mode, giving a frame rate of 25 fps (PAL TV system) so slow image acquisition/processing is no longer needed.

The mouse input device gave the best results due to its easy of use and integration with the operating systems's GUI. So it is used for graphic annotation and for sending robot motion commands. These commands can be issued by means of a single mouse click over the new aim point. Insertion/extraction commands are issued by using the now standard mouse wheel. It is also possible to select special robot commands from a context-sensitive menu, or by using the keyboard. The use of standard devices and computers makes possible to have a teleoperation station in almost any available networked computer.

5. The Local Control Workstation

The local control workstation (see Figure 7) comprises the surgeon interface and the robot control. The first one includes the video and graphical engine as well as the speech recognition and synthesis components. The high level robot motion control translates camera motion commands into joint coordinates as the references for the low level real-time joint controller.

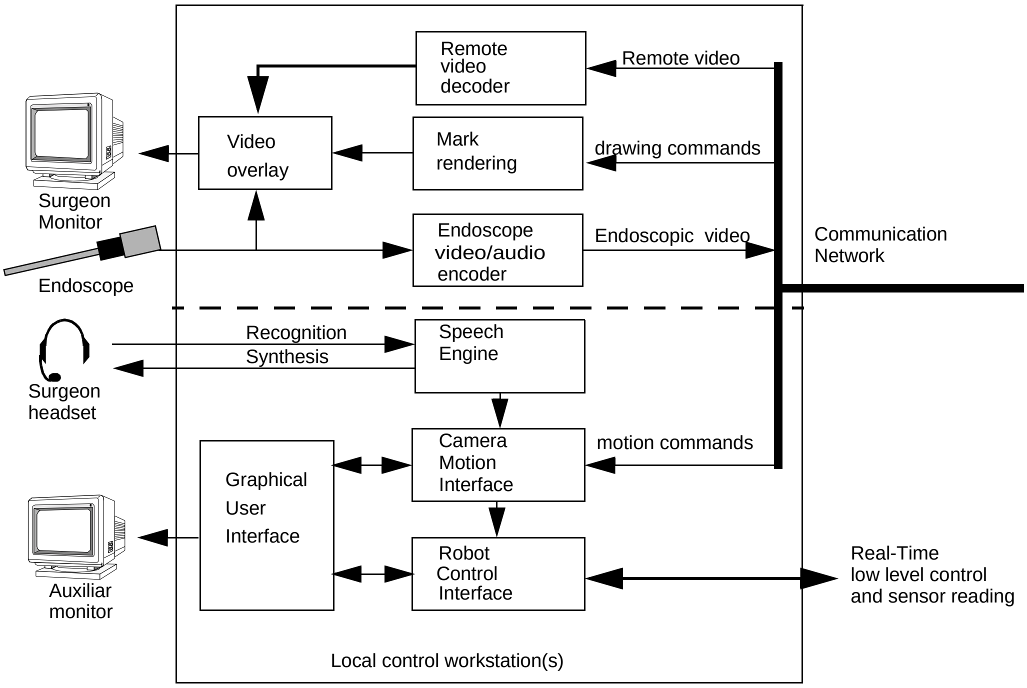


Figure 7. Local workstation architecture.

This computer system is also a Pentium III PC running Windows 98 provided with a dual video system (AGP and PCI Voodoo 3-300). The main display opens a 768x576 pixels overlay surface and draws the remote marks. The second display provides technical information about robot status, position and control at the different control levels, which is mainly used by the engineers during the development stages. Main screen is used also for displaying the low-resolution videoconference system with a view of the remote operator.

A reduced set of intuitive commands relative to the camera coordinate system (“Move Up”, “Move Left”, “Get Out”,...) can be trained for the surgeon voice. The voice recognition system is accomplished by means of the command recognition *ActiveX* component. Also components for voice synthesis have been used in order to provide convenient user information about command completion.

The local video overlay system is implemented by using the above mentioned bt878 PCI analog video-capture chip because most commercial laparoscopic camera system provide analog (S-video/composite) outputs. Other benefits are the low cost and the absence of compress-decompress delay which could difficult the visual feedback control of the surgeon tooltip.

Path generation and tracking is performed by concurrent high priority threads. As this is not a real-time operating system, real-time constraints are soft, and response times are not warranted. For this reason low level joint control of the three active degrees of freedom are performed by external special purpose microcontrollers (LM628) from *National Semiconductor*s which perform PID control with trajectory generation with *on the fly* update of parameters and trajectory. The power amplifier is an H-Bridge (LMD 18200) capable of driving a 3A PWM signal.

For a smart control of the arm movements, a standard parallel port has been used for sending references and control parameters. The PC printer port in EPP mode (bi-directional with automatic handshake control) delivers over 1.5 Mb per second. In fig. 8 a picture of the 8x9 cm single sided circuit board is included.

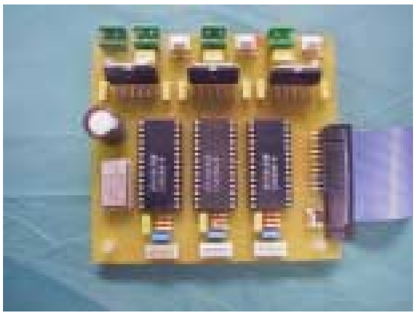


Figure 8. The three-axis low-level control and power system circuit board.

6. Experiments and conclusions.

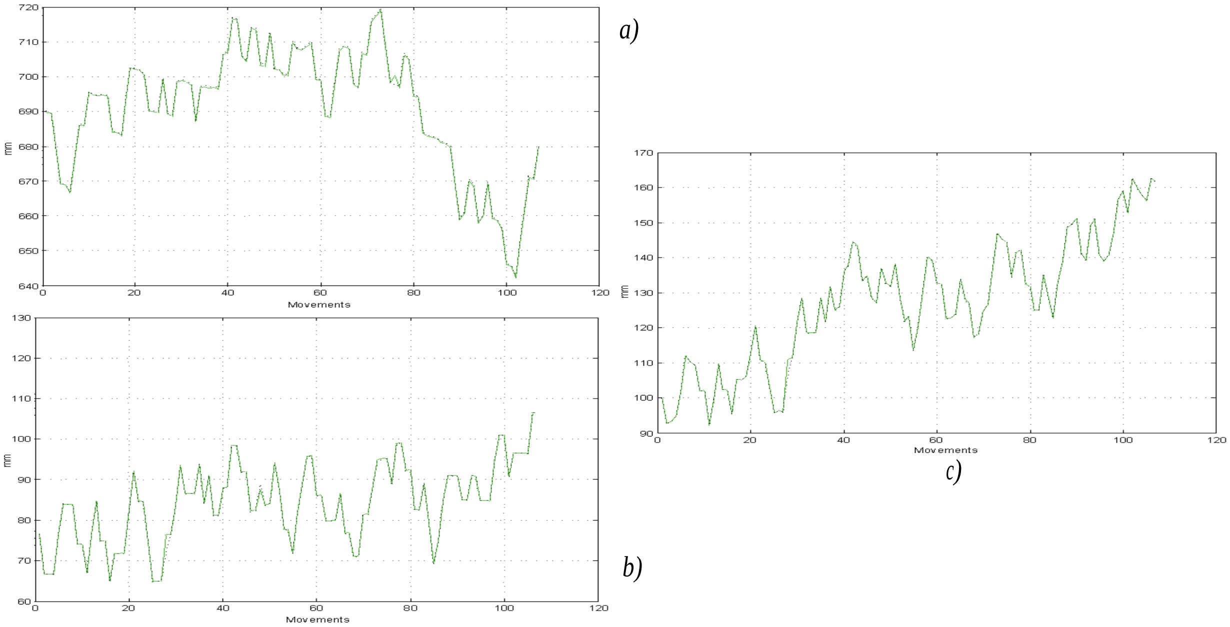
This paper is focused on applications of new technologies to minimally invasive surgery. A robotic assistant has been proposed as a help to surgeons in laparoscopic surgery and telementoring. This design is based on the previous experience with an industrial robot Stäubli RX60 (see Figure 10). This system has been tested by using both patient simulator and experimental animals. When compared with a human assistant, results showed that in short duration operations (about three minutes), like standard "two zeros" sutures, the surgical team employed about 12 more seconds. However, a higher efficiency was obtained in very thin wire sutures. Though surgeons had considered convenient the system during all the experiments, the possibility of completing precision sutures efficiently and comfortably was specially remarkable for them.

The new robotic assistant (see Figure 10) has shown the same motion capabilities than the previous one. Furthermore, we have added teleoperation features through a conventional communication network. Currently, the system has been tested by means of a patient simulator demonstrating the same performances in local mode as well as in remote trials.

Figure 9. The first prototype during a trial.

Quantitative results are shown in Figure 11. Desired position of the end of optic and actual position are compared in cartesian coordinates. As can be seen, no significative errors are present despite the two passive degrees-of-freedom and the compliance of the insertion point.

Figure 10. The new robotic assistant.



a)

c)

b)

Figure 11. Desired position of the end of optic (dotted line) vs. actual position (continuous line) in cartesian coordinates. a) X b) Y c) Z

7. References.

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