On laparoscopic robot design and validation

Instituto Andaluz de Automática Avanzada y Robótica, Universidad de Málaga, Málaga, Spain

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, including teleoperation capabilities. This prototype does not require any modification of a standard operating room for its installation and its application in surgical procedures. The insertion point of the laparoscopic camera constitutes the most important kinematic constraint in laparoscopic techniques. In the proposed design, this has been solved with a passive wrist. A three active degrees of freedom manipulator positions the wrist. In order to demonstrate the robot suitability to develop the tasks it has been designed for, a design validation has been performed. This validation consists of simulations based on the configuration space concept. Finally, trials with alive animals have been carried out in an experimental operating theatre.

1. Introduction

During the last years, a new field has attracted the interest of robotic researchers. Minimally invasive techniques, such as laparoscopy, have grown as a very suitable domain for robotic systems. 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 explore the anatomical structures and their pathologies [15]. Thus, the surgeon only uses the visual feedback information provided by the camera attached to the optic.

Currently, the usual procedure consists in holding the camera by an assistant while the surgeon manoeuvres the surgical tools inside the patient abdomen. This fact requires a high coordination between them. However, in some procedures the surgeon needs more than two instruments at the same time, and a second surgeon, in charge of the camera and a surgical tool, is necessary.

Since these procedures can last up to two (or even more) hours, the camera image can suffer a significant loss of stability due to the tiredness of the surgeon who moves the camera. Focusing the point of interest can also become a difficult task. In this scenery, a robotic aid, being able to move the laparoscopic camera (allowing him or her to use both hands in the surgical procedure itself), would become a very helpful tool in the operating room. A robotic camera could improve coordination and efficiency, and release the assistant or the 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 different ways of facing the development of a laparoscopic assistant. In 1995 Taylor et al. [16] proposed a complete system, including a manipulator, a special end-effector to carry the laparoscopic camera and a new control strategy. In this design, as in most of the robot manipulators, the orientation of the camera through the incision was decoupled of its positioning. The interface was based on an instrument-mounted joystick, since voice-recognition system were not very capable at that moment.

Green, at SRI International [8], developed a different concept. The target of this system was to explore the possibility of a telesurgery scheme, not only suitable for minimally invasive surgery but also to open surgery as well. This telesurgery concept was later enhanced and taken to a commercial stage by Intuitive Surgical’s Da Vinci system [9].
The HISAR system [6] presented a new configuration of the manipulator. The proposed one was a 7 degrees of freedom (dof) robot mounted on the ceiling. Two of the orientation axes were passive, to grant free compliance with the entry port. 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 geometrical re-estimation procedure of the pivoting point is proposed.

A different approach consists in a modification of a standard industrial manipulator. For instance, Hurteau [11] proposed a system based on an industrial manipulator, modified by means of an universal joint. The system of the Universitat Politècnica de Catalunya [1] goes a step beyond and shows a motion control system able of moving the camera following the movements of the instruments. 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 clear 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. In a further development, a specific robot was designed [2].

The Computer Motion AESOP [17] 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 arm attached to the stretcher, and presents an end-effector with three axes (two passive and one active). Many surgical procedures have been completed using this system, and it has received the FDA-approval.

Another commercial device is the EndoAssist [3] by EndoSista. The orientation is obtained thanks to a remote centre of rotation scheme. The robot has to be placed over the patient in such a way that its center of rotation coincides exactly with the insertion point. Though it is a commercial system, not much data has been released.

This paper deals with the principles and considerations prior to the development of a laparoscopic robot, called WLR, as a part of the whole ERM system. Section 2 states the requirements to design such a system. Section 3 describes the several types of kinematic constraints that the manipulator has to comply with. Section 4 faces the design according to the previous principles. Section 5 presents a kinematic validation of a manipulator design. Section 6 introduces the main characteristics of the ERM system. Finally, Sections 7 and 8 are devoted to the experiments and conclusions.

2. Requirements for a laparoscopic manipulator

Laparoscopic techniques involve the use of special 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 surgeons to manoeuvre the instruments in order to complete the procedure [15]. The entry points of the instruments in the abdomen only allow them four degrees of freedom: two rotations around the entry point, one rotation around the tool axis and one displacement throughout this axis. The characteristics of these degrees of freedom imply the following drawbacks:

1. Inversion of the movement. The entry point acts like a fulcrum in such a way that the camera pivots around it (except in movements of penetration or extraction). Thus, when the surgeon moves the hand to the right, it is translated in a left movement of the tool tip.

2. Scaling. The tool amplifies or attenuates the surgeon’s movement depending on the penetration: a value over a threshold produces an amplification, whereas a value below it causes the opposite effect. The applied efforts are also scaled.

3. Loss of touch. The tissue texture and the efforts, which gives a useful information to the surgeon in open surgery procedures, are transmitted poorly in laparoscopic techniques. Moreover, the fulcrum effect and the trocar friction adds errors to the little information the surgeon gets.

In a laparoscopic procedure different instruments are used, and must be manoeuvred coordinately with the camera movements. In general, the main surgeon handles the tools while an assistant moves the camera. This cooperation between both presents three fundamental problems:

1. The surgeon must inform the assistant whatever he wants in every instant. So, problems derived from the verbal communication appears, and the assistant could misunderstand the surgeon orders.

2. As the camera is held by the assistant, the image is not totally stable, and it is affected by his/her strength of wrist. This effect rises during the surgical procedure.

3. The assistant works in an uncomfortable position to move the camera accurately, specially when the fatigue appears. This makes the camera to rub tissues, soiling itself and obliging the assistant to extract and clean it. This problem increases the procedure duration, and so the risks for the patient.
To solve or to attenuate some of these problems, the use of manipulator robots has been suggested. The main purpose of the proposed system is to help surgeons by moving the camera through their commands. No instruments are intended to be robotized at this stage. A surgical robot has to accomplish a set of requirements for its successful integration in a laparoscopic operating theatre. According with the scenery where it has to work, a set of requirements has been defined:

1. To allow the accomplishment of habitual laparoscopic techniques. In other words, it should be located in different modes according to the procedure necessities, and it should have the same capacity to move the camera as a human assistant.
2. It should involve an improvement of the laparoscopic technique. It means that it should solve or attenuate some of the problems of laparoscopic techniques.
3. Easy integration in a conventional laparoscopic operating room. Needing special installations or cares is not advisable.
4. To be multipurpose, if possible, so that it takes part in several kinds of procedures. It allows an increase of the features of the system improving its amortization.
5. It must work safely and the risk of damages to the patient or to the surgical team must be minimized, even in a wrong use of the system.

These desired characteristics for a robot assistant in laparoscopic procedures can be translated in a set of specifications that helps to define its design. These requirements will also permit a first validation of the proposed design. Thus, a laparoscopic robot should comply with the following points:

1. Positioning independent of the operating table, in such a way that it could be located in different places around the surgical field relative to the applied procedure.
2. Multiple workspace configurations to perform the system positioning with respect to the operating table and the rest of the surgical equipment.
3. Enough workspace without interfering with the surgeon or the rest of the surgical team.
4. It should not be bulky.
5. Minimum number of degrees of freedom and actuators.
6. Compatible with the constraints that the laparoscopic technique requires (kinematic constraints of the surgical tool insertion point).
7. Easy procedure conversion to either open surgery or conventional laparoscopic surgery (i.e. without robot).
8. Ability to work with the available equipment in a conventional laparoscopic operating theatre, without any new system such as compressed air or trifasic electric supply.
9. Autoclavable and easy cleaning.
10. Regarding the operation, the attention needed by the surgeon should be minimum.
11. It should be safe for the patient as well as for the medical team.

Requirements 1 to 6 affect in a special way to the kinematic design of the robot. However, all the specifications must be taken into account in every stage of the design. For instance, a favourable kinematic structure could present dangerous movements for the staff even if the surgical tool is operated safely inside the patient body.

3. The task model

In order to develop a robotic system that handles a surgical tool, the way a human uses it must be studied. In this case, the tool is a laparoscopic camera. Nevertheless, most of the general conclusions can also be applied to other surgical instruments. Therefore, a task model has been established.

Two reference systems have been defined, one in the entry point \( \{ F \} \), and the other one in the camera \( \{ C \} \) (Fig. 1). The camera position and orientation is defined through the transformation. This transformation is composed by a rotation and a displacement, as it can be observed in the following equation:

\[
F_{TC} = \begin{bmatrix} F_{RC} & F_{PC} \\ 0 & 1 \end{bmatrix}
\]

where \( F_{RC} \) is defined by the ZYZ Euler angles:

\[
F_{RC} = R_z(\varphi) \cdot R_y(\theta) \cdot R_z(\psi)
\]

The orientation can be decomposed in three angles:

- \( \varphi \), around \( Z \) axis of the \( \{ F \} \) system, in such a way that the \( X' \) axis of the rotated \( \{ C \} \) system points to the working area.
- \( \theta \), around \( Y' \) axis of the rotated \( \{ C \} \) system, in such a way that the \( Z'' \) of the transformed \( \{ C \} \) system (and therefore the optic of the camera) is pointed to the target zone.
- \( \psi \), around \( Z'' \) axis of the resultant \( \{ C \} \) system of the latter transformation.
When the three angles are null, the system \{C\} matches to the \{F\} one.

In the proposed system, only zero degree optics have been considered. Thus the \{C\} system is linked to the camera and not to the optic. This model could be applied to optics with angle if the reference system were linked to the optic. In this case, the $\psi$ angle would be a latter rotation to get the desired image.

The characteristics of the laparoscopic camera movement are defined by two main factors: insertion point and orientation.

### 3.1. Insertion point

The entry point to the patient abdomen imposes a set of constraints to the laparoscopic tool movement, including the camera. It prevents the lateral displacement so that the available degrees of freedom are reduced to four: three rotations and one translation (Fig. 2). Two of these rotations pivot around the entry point of the camera according to two perpendicular axes, both contained in the same plane as the patient abdomen. The third one turns around the camera longitudinal axis, and the last degree of freedom is a longitudinal displacement along the latter axis.

These four cartesian degrees of freedom are also restricted. The first two are limited according to the nature of the surgical technique and, mainly, to the patient characteristics. The tools penetrates into the patient body through the trocar, which is inserted in the abdomen approximately at 45°. The instrument movements involve forcing the elasticity of the abdominal tissues, which are a composition of four types: skin, fat, muscle and soft tissues. This elements have a limited elasticity and it depends on the corpulence of the patient. The thinner the abdominal wall, the less efforts are applied on the patient. Certain authors [4] report a maximum deflection angle with respect to the tool axis at $+75°/-75°$ (Fig. 3). According to the task model, this limit can be set by a range of the angle $\theta$:

$$105° \leq \theta \leq 255°$$

The third rotational degree of freedom is related to the camera orientation and is detailed in the next section. The last degree of freedom is a displacement along the camera axis, called penetration. The maximum penetration that can be reached is determined by the maximum instrument length and the external trocar length. The former is the segment length that can be inserted into the abdomen, that is to say, the distance along the optic from its tip until the position where its diameter cannot be introduced into the trocar. Regarding the trocar length out of the patient, it is a variable magnitude as well as the total size of the trocar is.

According to the task model, the penetration restriction can be expressed as follows:

$$L_{ET} \leq p \leq L_{Lap}$$

where:

- $L_{ET}$ is the external trocar length.
3.2. Orientation

The camera orientation is fundamental in a laparoscopic procedure since the monitor image depends on it. In particular, a rotation along the longitudinal axis will produce the same rotation in the image.

The proper laparoscopic camera movement consists of parallel translations to the generatrixes of an inverted cone trunk. In such a way, the upper side of the camera always points to the vertical axis of the above-mentioned cone. Different positions of the camera are shown in Fig. 4, where the internal and external workspaces are represented. The camera cannot be located in any position in the external workspace, but its upper side must be always pointing to the inside. This movement causes a rotation in the monitor image, but this rotation is easily assumed by the surgeon, since the image that he perceives is the same image he would see if he was placed instead of the camera position (Fig. 5).

According to the task model, this orientation constraint is expressed as $\psi = 0$.

4. Kinematic design

4.1. Orientation

As in general robotics, in laparoscopic applications the problem of orientation and the problem of positioning are usually decoupled. It allows to resolve both questions through the inverse kinematic model. Also, the design and the construction of the robot mechanical structure are facilitated.

In laparoscopic applications, the orientation must be achieved complying with the task constraints. The tool the robot moves can be modified only by means of three rotations around the entry point. This implies that any design that tries to separate the problem of orientation and the problem of positioning will only achieve it relatively, because any change in the wrist orientation must involve a displacement too, unless it is located indeed in the entry point. This is not possible because the tool is inserted in the abdomen through a rigid trocar. Moreover, a piece of the tool must stay outside. Nevertheless, there are three ways to obtain the proper laparoscopic tool orientation while complying with the kinematic constrains of the insertion point:
Remote centre-of-motion. The kinematic structure of the robot is designed in such a way that it forces the end effector to rotate around a centre of motion. Since this one is not located at any manipulator joint axis, it is denominated remote centre. This concept can be achieved by several ways. One possibility consists in using curved rails and to move the instrument along them. Another way is to make the mechanism with spherical links between consecutive joints of a standard manipulator. Maybe the most common option is a four bar linkage. Combining two of this structures, the two rotations contained in the same plane as the abdominal wall are obtained. The main disadvantage
of this strategy is the final volume of the mechanical structure. It is used by Intuitive Surgical’s Da Vinci [9,12].

– Active control of the pivoting point. The insertion point constraints are imposed by means of the robot joints control. That is, transforming mechanical constraints to software constraints. This possibility only makes sense if the robot has more than four degrees of freedom, so it is not a way to minimize the number of actuators in a surgical robot.

– Passive joints. The tool orientation is controlled through the positioning of the external tip. Via passive joints, the carried tool complies with the entry point constraints. In fact, the own patient body imposes the movement limitations. In addition to this security advantage, others can be enumerated:

1. The required actuators are as much in number as the degrees of freedom.
2. The resulting system dimensions are reduced in comparison with the robots based on remote centre-of-motion.
3. The robot will not mechanically force the patient’s tissues at the direction of the passive degrees of freedom.

One of its disadvantages can be a less ability for the orientation control, but it can be eliminated through a proper design of the manipulator and its motion control.

There are multiple possibilities in number and configuration for passive joints. The following are the most logical ones: to set out the axes according to the degrees of freedom in the abdominal wall (Figs 6a and 6b, the latter adopted by Computer Motion’s AESOP [17]); or to arrange the passive axes in such a way that the camera movements that a human carries out, are reproduced (two passive joints in a perpendicular plane to the abdominal wall, see Figs 7a and 7b).

The two configurations that allow a conical camera movement are similar in a kinematic way. Both configurations present a singularity at axis – Z. Since the incision is always made in angle, this problem does not appear actually. In addition to its easy design and construction, configuration c) shows another important advantage. Whereas the other passive wrists need that the orientation of its origin is ensured, in this one, the first passive axis disposition eliminates this restriction. It allows to simplify the design of the rest of the robot, because only a proper positioning of the wrist must be achieved. No actuated axes are thus required to obtain the desired orientation, and they are only used to solve the position problem. Therefore, it has been adopted in the WLR (Wireless Laparoscopic Robot) robot whose description is detailed later.

4.2. Positioning

The specifications 1 to 8 exposed in Section 2 concern the surgical robot positioning. Also, the system should be a statically balanced mechanism; in other words, the performance of the motors is not needed for maintaining the robot in a certain position.

Requirements 5 and 6 set the number of degrees of freedom to the minimum, that is, three, due to the chosen passive wrist. Requirements 1, 7 and 8 eliminate the mechanisms mounted in the ground or clamped to the operating table, because they force modifying the operating room, and they make difficult to withdraw the robot of the surgical field in case of a conversion of the procedure to open surgery or conventional laparoscopic surgery (i.e., without robots).

Thus, there are several possibilities, presented in Fig. 8. The configuration chosen for the WLR robot positioning is the showed in Fig. 8c.

The last point to define is the length of the elements. The length of the two elements of the RR manipulator have been computed by studying the most unfavourable case of the camera workspace outside of the abdominal cavity when the optic is inserted through the trocar. Figure 9 shows the outside limits of the camera position, defined by a minimal insertion length of the optic through the trocar with the maximal deflection angle of 75°. 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 the camera holder grasping point (g), the value of the arm elements length \( L_1, L_2 \) is computed from expression \( L_1 \cdot L_2 = 278750 \text{ mm}^2 \). This equation has been obtained considering that the arm should reach any point of a 550 mm-size square, which contains the base of the inverted cone. 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: \( L_1 = L_2 \approx 530 \text{ mm} \).

The prismatic degree of freedom must supply a vertical displacement equal to the depth of a human abdomen. Since this one is a very variable amount, and a greater linear displacement does not increase the total volume that the whole system needs in an operating room, large dimensions has been chosen. In the real-
ization of the prototype, a linear monocarrier with a displacement of 700 mm has been arranged.

Figure 10 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.

5. Kinematic validation

Each laparoscopic procedure demands a particular disposition of the surgical instruments regarding the surgical field (the patient). This internal disposition determines the external layout (surgical team and equipment arrangement required to carry out the operation). It should be noticed that a robot carrying a surgical instrument must achieve two goals: to move the camera to the desired point and not to interfere with the surgical team. Both objectives are closely related to the surgical procedure, so it has to be studied in order to obtain: first, a viable position for the robot; and second, a validation of the system compatibility with each procedure. A certain position of the robot is feasible only if it allows accessing the surgical field, and the physical structure of the robot does not interfere with
the movement of the surgeon and his assistant, and does not impede the monitor visualization. In every kind of intervention, several alternatives can be chosen, and it will be discussed later.

The validation of the system compatibility with each procedure can be done carrying out simulated operations in an experimental operating room. In this way, the construction of a prototype is required. Nevertheless, when a new design consideration is taken into account, another prototype must be constructed. Thus, the development stage may be improved by means of a simulation tool which permits checking design compatibility with the task and robot environment.

Among the several mathematical and simulation
tools used in robotics, the configuration space has been chosen to develop a validation procedure for surgical manipulators.

5.1. Configuration space

A robot configuration $q$ is defined as a vector whose components contain information about the current state of the robot. The vector providing this information is given, firstly, with two components: the position $p$ and the orientation $\theta$. Then, the configuration can be defined as follows:

$$q = (p, \theta) = (x, y, z, \alpha, \beta, \gamma)$$

It can be also defined, once the kinematic structure of the manipulator is set, as:

$$q = (q_1, q_2, q_3, \ldots, q_n)$$

where $n$ represents a degree of freedom of the robot.

The configuration space $C$ of the robot $R$ consists of all the configurations $q$ that the robot can reach within its workspace. $T(q)$ is the subset of $C$ which permits to perform a given task, and $B(q)$ is the subset of $C$ formed by the configurations occupied by obstacles [13].

Thus, the compatibility of a robot task with its environment is proved if the configurations set required to complete the task does not share any element with the configurations set defined by the obstacles. So that, a compatibility test is designed to define the configurations set of the task $T(q)$ and the obstacles set $B(q)$, and to check that the intersection of both is the empty set.

5.1.1. Obstacles in the configuration space

The first step to verify the compatibility based on the configuration space is to obtain the above mentioned sets $T(q)$ and $B(q)$.

The process to create the task configurations, $T(q)$, consists in defining the set of points and orientations the end effector should adopt in the workspace to reach every goal (usually in cartesian coordinates). These points are translated to the joint space of the robot through its inverse kinematic model. Then, it is obtained a set of points of the configuration space constituting $T(q)$.

However, defining $B(q)$ is more difficult since not only the end effector must be studied, but also the robot intermediate segments: if the inverse kinematic model is used to transform the obstacles around the robot from cartesian space to configuration space, only the
collisions of the end effector are studied, and the robot intermediate structure is ignored. Thus, a collision test has been developed, providing useful information about the compatibility of the whole manipulator structure with its surrounding obstacles.

5.2. Kinematic validation of the wlr robot

The proposed robot is a manipulator with three degrees of freedom. Therefore, its configuration space is given by means of:

\[ q = (q_1, q_2, q_3) \]

In order to establish the \( T(q) \) subset that a robot has to adopt in a surgical procedure, the task workspace for each case has been defined. This has been made by taking into account the anatomical region of interest, the entry point of the instrument and the position of the robot. A specification of every task has been made based on spherical coordinates with respect to the camera reference system. Then, the resulting set of positions of the end effector -in spherical coordinates- has been translated into a set of cartesian positions of the robot wrist. Finally, these points are translated into the joint space through the inverse kinematic model of the robot.

5.2.1. Obstacles in the operating theatre

In order to define the \( B(q) \) subset, the same strategy that in the case of \( T(q) \) can not be adopted, because all the possible incompatibilities are not covered. A collision test has been developed to verify the configurations of the robot which are incompatible with the considered obstacles. The study has been restricted to possible collisions with the surgeon and/or his assistant. Both have been modelled as cylinders with a diameter of 500 mm, and located in several positions according to the procedure that is being analysed. Thus, a set of boundary configurations of the robot is obtained, and can be represented in the configuration space together with the task \( T(q) \). In this representation, the compatibility of the robot with the considered procedure can be verified by visual inspection.

5.2.2. Problem statement

The collision test can not be developed without a previous definition of the robot position relative to the surgical field. The purpose is not eliminating the assistant, but releasing him of manoeuvring the camera. This fact maintains the possibility of placing the assistant in his usual position. In this way, the incorporation of a robot does not involve a dramatic change in the mode the surgical team works.

Almost every surgical procedure can be performed through minimally invasive techniques. Nevertheless, in abdominal surgery only in six of them laparoscopy has been accepted as the “gold standard”:

- Cholecystectomy
- Nissen funduplicature
- Inguino-femoral hernia
- Adrenalectomy
- Splenectomy
- Diagnostic laparoscopy for the acute abdomen

Some of these procedures share the same staff distribution around the operating theatre and can be grouped. Thus, in each set of procedures, several positions for the robot can be proposed (Fig. 11). The selected locations are marked with a thick line. The criteria to discard a place or another was to keep the robot as far from humans as possible, to minimize the possibility of interferences, while keeping the assistant in the usual position adopted in every procedure. The only one exception was taken in the cholecystectomy, where the robot is located in place of the assistant, while this one is moved to the other side of the patient (the assistant’s new position is not shown in the figure). The reason for this is the experience during the experiments with a previous system based on an industrial manipulator [14], where the surgical staff preferred such an arrangement. To compare the performances of both systems (the old one and the new one), this layout has been maintained.

Every procedure demands a particular disposition of the entry point, zone of interest and robot position. In order to place these points of interest relative to the surgical field, a reference system has been defined in the horizontal plane which the entry point of the camera belongs to. As it has been described before, the manipulator should be able to reach any point of a 550 mm-size square centred in the insertion point. This square is the base of the aforementioned reference system, whose origin is fixed on the bottom left corner (Fig. 12).

The surgeon and the assistant, modelled as cylinders with a diameter of 500 mm, are the obstacles considered for the collision test. They are placed according to the operating theatre disposition showed in Fig. 11. The values for all the positions and the workspace size are, of course, approximated.
5.2.3. Results

Since the results obtained for each surgical procedure are similar, only one case is detailed: right inguino-femoral hernia repair.

In this procedure, the surgeon is located at the patient side opposite to the affected inguinal region, and the assistant at the opposite side of the surgeon. The monitor and the instruments are placed at the bottom of the patient (Fig. 13).

Only three entry points are made, one of them for the laparoscopic camera insertion. The work area is located at the lower abdomen. The required internal workspace is a cone with elliptical base. Its dimensions mainly depend on anthropometric characteristics of the patient, but a base of $150 \times 100$ mm and a maximum penetration of 180 mm can be reasonable values. A $45^\circ$ inclination of the cone axis from the vertical, and a $225^\circ$ rotation around the vertical axis are considered. Figure 14 shows the camera workspace in this procedure, in cartesian coordinates.

The robot position is $(-300,0)$ respect to the reference system mentioned above. The surgeon and the assistant positions are respectively $(1150,850)$ and $(0,550)$ with regard to the robot.

Figure 15 shows the results obtained for right elbow configuration. The configurations set that the robot adopts during the intervention and the circles that model the surgeon and the assistant can be observed in Fig. 15a. Also, the robot configuration limit prior to a collision, is displayed (in this case with the assistant). Fig. 15b represents the problem in the configuration space. The prismatic degree of freedom is represented by the vertical axis. Here the constraints take the shape of two planes limiting a forbidden region. Each plane represents the maximum angular value in a rotational joint in such a way that there is no collision neither with the surgeon nor with the assistant.

In left elbow configuration, a collision with the assistant appears. This is represented in Fig. 16, where numerous positions of the robot are superposed to the space reserved for the assistant. In the configuration...
space, this collision is translated in several points located beyond the limit of the first rotational joint.

As it has been seen, the process of kinematic validation gives useful information in order to position the robot in the appropriate place. The study, that has been extended to all the above mentioned surgical procedures, demonstrates that the system is able to work in everyone. Moreover, it has allowed to select the best configuration (right or left elbow) for each procedure.

6. The ERM system

Once the validation process was completed, and since it presented a positive result for the considered set of laparoscopic operations with the proposed kinematic design, the WLR prototype has been finally constructed as a part of the whole ERM system. This system has been designed to assist in laparoscopic surgery by moving the camera both locally (by the use of verbal commands) and remotely. It is a very simple system, intended to provide a low-cost exploitation and easy management. Teleoperation features have been added to make available telecollaboration schemes, such as telementoring (an expert teaches a novice), teleproctoring (a remote person supervises a procedure) or telediagnosis (a remote physician identifies a disease). To obtain the capability of moving the camera from a remote workstation, a telerobotic architecture has been designed. This architecture is based in the one pro-
posed in [5], and detailed in [7]. It allows local au-
tonomy in the controlled robot, and since the trajectory
generation and feedback control loop are local, the re-
 mote system teleoperation is stable under remote su-
pervisory commands. The goal is to control the robot
through standard TCP/IP networks. This way, a wider
range of applications is possible, since a larger number
of possible remote sites is available.

Some of the main characteristics of this system are its
hardware and software modularity (for a configuration
adapted to the application) and its wireless operation,
what allows it to be moved manually and at any time, as
well as to operate in practically any standard operating
room, since it does not have to be plug to the power
supply network. The system also includes wireless
voice/data communication media.

Special efforts have been made to simplify the local
surgeon (or auxiliary staff) user interface, in such a way
that its set-up is automatically made just by turning
the system on. The fulcrum position in the patient ac-
cording to his coordinates system is automatically and
continuously obtained, to ensure a proper and precise
movement of the surgical tool and to maintain the de-
sired orientation and penetration, even in the presence
of disturbances.

The ERM system has three main modules: the Wire-
less Laparoscopic Robot, the Teleoperation Module and
the Extended Capabilities Module. Each one of those
units provides one or some functionalities and they can,
in principle, be used separately or jointly. The Wireless
Laparoscopic Robot moves the camera in response to
the surgeon commands; the Teleoperation Module al-
lows a remote surgeon to collaborate in, or supervise,
the operation; and the Extended Capabilities Module
provides the connection of the system to the exterior,
both with other manufactures’ equipments and with
external databases.

The three different modules of the system plus the
local surgeon interface are described below.

6.1. The laparoscopic robot

This is the main element of the system. It has been
designed as a three active degrees of freedom manip-
ulator in a PRR configuration. The prismatic degree
of freedom is implemented via a monocarrier platform
that gives the linear displacement through a endless
screw powered by an electrical motor. The RR seg-
ment is constituted by two rectangular elements with
square section moved by electrical motors. In the first
rotational joint, the motor actuation is applied directly
on the axis. The movement is driven to the second joint
by a transmission chain.

As stated above, the orientation problem has been
solved by a passive wrist which consists of two joints
perpendicular to each other (Fig. 17). The first axis is
parallel to the actuated joint (a rotation around Z axis),
while the second one is located in a horizontal plane.
Fig. 15. a) Robot positions (right elbow) during a right inguino-femoral hernia repair procedure. The circles represent the surgeon and the assistant. b) Positions in the configuration workspace.

(a rotation around X axis). The Fig. 18 shows the a general view of the robot.

The controller is integrated in the robot base and, by its side, there are two batteries providing the power supply to the set. The surgeon has a wireless microphone to send his commands to a local interface sub-module, usually a speech recognition system integrated as well in the robot base. However, a joystick, a pedal or another means can be used to substitute or to complement the voice interface.

The robot has been designed to occupy a small volume and not to need clamping to the operating table. Those facts, together with the battery supply and the wireless microphone, make the system to be a wireless system, thus facilitating the integration into the operating theatre.

6.2. Teleoperation module

This module allows telecollaboration between two surgeons, so that an expert may guide or supervise the
operation performed by the surgeon present at the operating theatre. To facilitate this work scheme, the remote surgeon receives the laparoscopic image, on which he can make marks and comments. That information is sent to the operating room, where it is showed overlaid on the laparoscopic image on the video monitor. The remote surgeon can as well take the control of the robot for the camera to show a region of interest. Besides, a video conference channel allows communication between both surgeons.

The implementation of this module consists of two parts: a component within the operating room and a remote workstation. The first element communicates with the rest of the operating room equipment via a wireless communication network, and with the remote workstation via another communication network, which may be a conventional one. That is, one of its purposes is to act as a bridge between the operating room network and the exterior. Another purpose of this component is to overlay the marks in the laparo-
The remote workstation consists of a standard PC, thus permitting a wide range of possible points for remote operation of the system. As input interface, the surgeon may use a standard mouse, but some other media, such as a master manipulator or a Spaceball can be used as well.

### 6.3. Extended capabilities module

The main component of this module is the Presentation Server. This element communicates with the local interface, which the local surgeon can use to demand information, such as previous patient’s explorations or documentation on the procedure in progress. Additionally, if the operating room has surgical equipments prepared for centralized operation, such as those of Storz™ or Stryker™, the surgeon can also control them via the local interface. In this case, and until a standard on communication of that kind of equipments is not adopted, it is necessary to incorporate an adaptation module.

### 6.4. Local surgeon interface

Like most of the robotic surgical assistants, speech recognition has been chosen to provide the command input. It allows a simple way of controlling the robot, avoiding to use hands or feet for this purpose. In addition, this method improves sterilization since it avoids physical contact.

An off-the-shelf speech recognition hardware module (from Sensory Inc.) has been used, and it is trained to recognize a small set of intuitive commands like “Move Up”, “Move Left”, “Move Out”, . . . These commands must be trained with the surgeon voice. The selected module has the capability to play oral messages to confirm to the operator that the instruction has been recognized and that it is to be executed. The module is programmable in C-like language, so it is also in charge of the local interface control, carried out in a very compact and simple way without the need of a PC computer.
7. Experiments

The project is currently undergoing the certification stage by the Spanish Health Authorities. An additional advantage of the modular configuration of the system is the possibility of facing this certification separately, so each module follows its own procedure. Thus, the Wireless Laparoscopic Robot, the first module, is completing the last preliminary steps before experiments on humans.

The certification procedure is not completely unified in the European Union. Every category involves different requisites for the placing on the market of a product. The Wireless Laparoscopic Robot fits into one of the categories demanding less requirements, thanks to several aspects of its design, like the passive wrist, the battery supply or the lack of a computer and an operating system. This simplicity, in the design as well as in the certification procedure, diminishes the cost associated to the placing on the market of the system.

As a part of a previous stage, before the clinical trials on humans, several experiments on animals have been carried out. These were performed in local mode, that is, without using the other two modules of the system. One of the tested aspects was the set-up time, measured from the moment the robot is entered into the operating room to the instant it can be commanded by the surgeon. Once the robot is located in the desired point, only a button must be pushed to start working. This action launches the initialisation, as well as the local interface, which is based on speech recognition. If the training has been previously completed, the set-up time is less than two minutes. On the contrary, if it is performed in the operating room, the set-up time reaches six minutes.

The surgeon can decide to withdraw the robot, for any reason (e.g., because of a conversion of the procedure from laparoscopy to laparotomy). Then the required time (withdrawal time) is approximately half a minute: the only required actions are disengaging the laparoscope from the end-effector (without any tool), releasing the wheel brakes and then drawing back the robot.

Up to date, several procedures on experimentation animals have been carried out including cholecystectomies, Nissen funduplicatures and anastomosis (not included in the set of procedures, but similar in disposition and zone of interest to those of the cholecystectomy). The main purpose of the performed experiments is to compare the efficiency between the robot and a human assistant. Nevertheless, obtaining decisive results is difficult since common indices of behaviour for the robot and a human assistant cannot be defined. In particular, the high precision when locating the end of the laparoscopic inside the abdomen is a
remarkable feature of the robot. This magnitude is impossible to acquire when a human assistant operates the camera. In the other hand, some facts, as the surgeons fatigue or their comfort, cannot be estimated because of its subjective nature. However, during these trials the involved surgeons expressed their satisfaction about the system performances. Despite they received no training about the speech recognition interface, more than 90% out of the commands were successfully recognized. During these trials the correspondence between the information obtained through the proposed validation procedure and the actual performance of the Wireless Laparoscopic Robot was confirmed. No interference between the surgical staff and the manipulator was reported, while the movement of the laparoscopic camera fulfilled the expectations.

8. Conclusions

This paper is focused on design and validation of surgical robots. A set of requirements and constrains has been presented. According to it, a robotic assistant has been proposed. The WLR robot has been designed as a three active degrees of freedom manipulator with a passive wrist which consists of two joints perpendicular to each other.

The proposed system has been validated through a simulation tool based on the configuration space. Thus, the results have demonstrated that the WLR robot is appropriate to develop the tasks it has been designed for. In addition, the simulation has permitted choosing the most suitable robot configuration (right elbow, left elbow) for each considered procedure. In the end, several experiments with alive animals has been performed in an experimental operating theatre, which confirms the previous validation process and verify the good response of the WLR robot.

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References