Pivoting motion control for a laparoscopic assistant robot and human clinical trials

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Abstract—This paper presents a compliant motion control method for the robotic assistant ERM (Endoscopic Robotic Manipulator), designed and developed by the authors for handling the camera in laparoscopic surgery. Since the robot has a passive wrist and it is not fixed to the operating table, the relative position between the robot camera holder and the insertion point is unknown. In this way, the proposed approach keeps the camera orientation according to the motion references in spite of this uncertainty and compensates for other unexpected disturbances about the relative robot–patient position. This system has been tested with live animals as well as in clinical trials on humans.

Keywords: Surgical robotics; Cartesian robot control; risk analysis; computer-assisted surgery; laparoscopic surgery.

1. INTRODUCTION

Laparoscopic techniques are an efficient alternative to conventional open surgery in order to treat several kinds of diseases. The foremost advantage is that the patient needs less time to recover after the operation. However, the surgeon’s practice is more complicated because of the natural constraints of this kind of procedures. In particular, the fact of accessing the abdominal cavity with special long instruments through little incisions in the skin. 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. These factors produce movement limitations, loss of touch and three-dimensional perception, and hand–eye coordination problems [1]. The development of robotic assistants, in

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order to handle surgical tools or laparoscopic cameras, tries to mitigate the above issues. Thus, when developing a robotic aid, we have two possibilities: moving the instruments or moving the camera. Every one of these options follows 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 release 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.

In this way, automated positioners are a category of these types of robotic assistants specialized in the accurate placement of the surgical instrument tip inside of the abdominal cavity [1]. They describe globe-shaped movements of the tool at the port of entry (fulcrum point) on the abdomen and this is the reason why they are endowed with spherical wrists [2].

A robotic assistant based on a passive wrist guarantees that no forces are exerted at the port of entry, since its mechanical structure allows free compliance with this. However, any uncertainty in the relative position between the automated positioner and the fulcrum point decreases the accuracy in placing the instrument tip. This fact is an intrinsic health hazard by itself for the patient, so this kind of wrist is usually employed in non-critical positioning tasks, like camera navigation movements. Indeed, in such actions, the risk is reduced to a bad centering of the camera field with regard to the desired target.

Actuated wrists avoid the precision positioning difficulty mentioned above by means of special mechanical structures. They are designed in such a way that they have a remote rotation center, which would be positioned to coincide with the fulcrum point [3], in order to avoid exerting dangerous forces in the patient body. The pivot point is perfectly located and, in this way, the accuracy of the spherical movement of the tool is assured. Common schemes are based on four parallel linkages models like LARS [3] or the robotic extender configuration [1]. Other approaches use semicircular arc linkages for the same aim [4].

In any case, it is necessary to consider a Cartesian control strategy for achieving the spherical movements of the surgical tool around the fulcrum point. The classical schemes are based on the indirect control of the spherical coordinates by means of introducing kinematic information in the joint feedback loop. For example, the generalization of the extended Jacobian technique [5] computes the generalized joint variables from the Cartesian movement references. This method takes into account the motion in constrained workspaces, and it makes the space conversion for both kinematically redundant and deficiently robotic systems. Other schemes consider a Cartesian velocity control loop in order to follow a trajectory commanded through a haptic input device [6]. Finally, as already mentioned, the uncertainty in the position of the fulcrum point has a strong influence on the kinematics of the passive wrist robotic systems. In this way, its control strategy usually includes an on-line geometrical estimation algorithm in order to minimize the location error of this one [6, 7].
This work describes a compliant camera orientation approach for the surgical robotic cameraman endowed with a passive two-joint wrist. In contrast to the classical methods cited above, the proposed strategy carries out the direct control of the Cartesian coordinates and it assures a desired dynamic behavior during the movements in spite of the fulcrum point uncertainty. Thus, Section 2 details the kinematic model of the task and the effect of the fulcrum point uncertainty from the trajectory planning point of view. Section 3 describes the proposed control scheme. Finally, Sections 4 and 5 describe the implementation and the experiments using the ERM (Endoscopic Robotic Manipulator), fully developed in the University of Malaga. The final section is devoted to the conclusions.

2. CAMERA NAVIGATION ON PASSIVE WRIST-BASED ROBOTS

The laparoscopic navigation task is defined as camera positioning in order to aim the optic device to the desired anatomical structure inside the abdominal cavity. The robot wrist describes globe-shaped movements centered at the fulcrum point, which introduces the holonomic motion constraint. The passive wrist accommodates this limitation in such a way that the location of the optic tip is just determined by the relative position of the camera with respect to this port of entry [2]. Figure 1 shows the above situation, where the fulcrum point has a task frame attached in order to specify the camera’s relative location by the spherical coordinates $\alpha$ (orientation

![Figure 1. Spherical coordinates for camera navigation.](image-url)
angle), $\beta$ (altitude angle) and $\rho$ (outside penetration, defined as the distance from the passive wrist to the fulcrum along the optic) [2].

The camera and the fulcrum frame absolute locations with respect to the robot base must be known for trajectory planning purposes. The camera is hold on to by the passive wrist and, therefore, its location is given by the robot forward kinematics. However, the fulcrum frame is not affixed to any robot element. It is placed at the trocar inserted in the patient’s body and, therefore, its absolute position is a random magnitude. This situation has a strong influence on the precision for reaching a desired spherical coordinate. A wrong fulcrum frame location implies a camera positioning inaccuracy, which can be directly evaluated by the orientation and altitude spherical coordinate elements. Hence, the motion control software uses an outside penetration estimator algorithm in such a way that the current estimation error produces the undesired planning effects detailed in Fig. 2.

The schemes included in Fig. 2 show a single camera movement for modifying the altitude angle $\beta$ by means of a movement from the starting coordinate A to the ending coordinate B with a null orientation angle $\alpha$. Let $\rho$ be the estimated outside penetration and let $\rho'$ be the actual one, in such a way that $\rho_c$ represents the estimation error, which verifies the relationship $\rho' = \rho + \rho_c$. The left side scheme (Fig. 2a) considers a positive value for $\rho_c$ and the right side scheme (Fig. 2b) presents the negative case. In both cases, the system computes a wrong circular arc-shaped trajectory for the camera, by using $\rho$ as the estimated turning radius, around the inaccurate absolute position of the fulcrum point F (solid line). Nevertheless,
its real location is placed at $F'$, corresponding to the actual outside penetration $\rho'$ which produces the ideal camera movement for reaching the coordinate $B'$ (dashed line).

Therefore, this outside penetration error $\rho_e$ causes two undesired camera positioning inaccuracies: (i) an altitude error $\phi_\beta$, defined as the difference between the measured altitude angle $\beta'$ and the desired one $\beta$, and (ii) either an optic tip over-penetration (Fig. 2a) or under-penetration (Fig. 2b) due to the deviation from the ideal trajectory at the end of the movement (Euclidean distance from $B$ to $B'$).

The Cartesian coordinates of both goal points $B$ and $B'$, with respect to the reference system placed at the real fulcrum point position $F'$, are defined by (1) for a given altitude displacement $\beta$:

$$ B = (x_B, z_B) = (\rho \sin \beta, \rho_e + \rho \cos \beta), $$
$$ B' = (x'_B, z'_B) = ((\rho_e + \rho) \sin \beta', (\rho_e + \rho) \cos \beta'), $$

where the measured altitude angle $\beta'$ is defined as:

$$ \beta' = \tan^{-1}(\frac{x_B}{z_B}) = \tan^{-1}\left(\frac{\rho \sin \beta}{\rho_e + \rho \cos \beta}\right). $$

(2)

By tacking into account the above considerations, the altitude error $\phi_\beta$ is defined as:

$$ \phi_\beta = \tan^{-1}\left(\frac{\sin(\beta - \beta')}{\cos(\beta - \beta')}\right) = \tan^{-1}\left(\frac{\rho_e \cdot \sin \beta}{\rho + \rho_e \cdot \cos \beta}\right). $$

(3)

Figure 3 represents the altitude error behaviour as a set of isolines determined by the variation of both the altitude angle $\beta$ (from 0 to 90° in the horizontal axis) and the outside penetration $\rho$ (from 130 to 280 mm in the vertical axis). The contour lines are labeled with their associate altitude error level in degrees, in such a way that the solid isolines relate to an outside penetration error equal to 20 mm and the dashed lines are used for $\rho_e$ equal to 50 mm.

A preliminary study of (3) concludes that the relationship between $\rho$ and $\rho_e$ has a strong influence on the altitude error. In particular, as the quotient $\rho_e/\rho$ increases, this last magnitude grows faster. In this way, Fig. 3 shows that the isolines are closer to each other when the outside penetration takes its minimum value ($\rho$ is equal to 130 mm).

On the other hand, the over/under-penetration error $e_\beta$ due to the deviation from the ideal trajectory is defined as the difference between the actual outside penetration $\rho'$ and the goal point $B$ module:

$$ e_\beta = \rho' - \|B\| = \rho + \rho_e - \sqrt{(\rho \sin \beta)^2 + (\rho_e + \rho \cos \beta)^2}. $$

(4)

Figure 4 also uses the isoline representation in order to characterize the over/under-penetration error. The range of variation of $\beta$ and $\rho$, the values for $\rho_e$, and the isoline styles are the same as the described in Fig. 3. The associated labels show the over/under-penetration absolute value expressed in millimetres.
Figure 3. Altitude error $\phi_\beta$ for $\rho_e$ equal to 20 and 50 mm.

Figure 4. Over/under-penetration error $e_\beta$ for $\rho_e$ equal to 20 and 50 mm.
Unlike the altitude error, this effect does not have a substantial influence of the outside penetration error \( \rho_e \), and it can be considered as a function of the altitude angle increment and the current outside penetration error. However, it is a source of more potential hazards than the altitude error, since over-penetration implies an uncontrolled optic tip displacement which could harm an internal organ. On the other hand, an altitude error only produces a bad centring of the desired target.

Expressions (3) and (4) prove every orientation angle as well as any altitude increment. Moreover, the orientation and outside penetration error analysis (named \( \phi_\alpha \) and \( e_\alpha \)), for modifying only the orientation angle \( \alpha \), also verifies these two expressions where \( \alpha \) takes the place of \( \beta \).

Finally, the outside penetration error produces a coupling effect between the orientation and the altitude angles. An orientation movement causes an undesired altitude change. Figure 5 illustrates this situation and describes an orientation displacement from location A to B. The left-hand scheme (Fig. 5a) shows the top view of the mentioned motion (XF–YF plane), where F and F’ keep their previous meaning. On the other hand, \( \eta \) and \( \eta' \) are the projections of \( \rho \) and \( \rho' \) in the XF–YF plane. This scheme has the same interpretation as Fig. 2, i.e. the camera movement starts at location A, and the trajectory planner uses \( \eta \) and F for computing the goal orientation B. Nevertheless, the trajectory deflection \( e_\alpha \) from the ideal goal location B’ produces the altitude change \( \gamma \) which is shown in Fig. 5b.

In this way, the described altitude change is defined, from a geometrical point of view, as a function of the trajectory deflection \( e_\alpha \), the altitude angle \( \beta \) in point A and

\[ \gamma = \text{function of } e_\alpha, \beta, \rho_e \]
the new one $\beta'$ measured after the orientation movement in the goal location $B$:

$$\gamma = \tan^{-1}\left(\frac{\sin(\beta - \beta')}{\cos(\beta - \beta')}\right) = \tan^{-1}\left(\frac{e_{\alpha} \cdot \cos \beta}{\rho + \rho_{c} - e_{\alpha} \cdot \sin \beta}\right).$$

(5)

A study of (5) shows that the coupling effect is negligible even in the worst situation. An increase of $60^\circ$ in orientation is necessary for a shift of $1^\circ$ in altitude. The geometrical analysis developed in this section concludes that the outside penetration error has a significant influence in the orientation and altitude error. However, it has of minor importance for the coupling effect. Therefore, a decoupled Cartesian controller can be designed: one for eliminating the orientation error and the other for the altitude imprecision.

### 3. ADAPTIVE PI CARTESIAN CONTROLLER

In most of the cases, control strategies for compensating for both the penetration and orientation errors due to the fulcrum point position uncertainty are based on a geometrical approach in order to determine the outside penetration $\rho$ [6, 8]. Specifically, the aim is to compute the distance between two consecutive optic axis orientation vectors. It is assumed that the fulcrum point is located at the middle point of this segment and the next set of camera movement data are used for updating the present entry point estimation. However, this approach does not compensate for the fulcrum location imprecisions during the current motion. These imprecisions originate from factors like the on-board sensor noise or entry point slow displacement.

The proposed control scheme has been designed in order to compensate for the orientation and penetration errors described in the previous section. It uses a Cartesian trajectory planner, which takes care of the robot wrist to perform the planned spherical movement, following a first-order system temporal response. In other words, if $\sigma_{d}$ represents the goal spherical coordinate ($\alpha$ or $\beta$), the trajectory generator imposes to the actual optic location $\sigma(t)$ the behaviour detailed as:

$$\sigma(t + T) = e^{-T/\tau} \sigma(t) + K (1 - e^{-T/\tau}) \sigma_{d}.$$  

(6)

In the above expression, $\tau$ and $K$ are the time constant and the static gain of the first-order system. $T$ specifies the sample time.

This trajectory generator is detailed in Fig. 6 and it computes the robot joint references $[\theta(t), \dot{\theta}(t)]$, which assure the behaviour presented in (6), by taking into account a reference goal $\sigma_{r}(t)$, expressed in spherical coordinates.

In this way, the state generator computes a planned spherical position and velocity for the camera optic. Then, the path generator and speed profile, using the estimated outside penetration $\rho$, transform the named spherical references into Cartesian end-effector positions and velocities $[X(t), \dot{X}(t)]$. Finally, the inverse kinematics computes the required joint vectors.
The proposed trajectory generator, attached to the low-level robot joint controller in an open loop configuration, is able to set the time constant $\tau$ for the given displacement. This action is possible by tuning the joint controller parameters and selecting a suitable value for $\tau$ which does not saturate the robot actuators. However, this question does not guarantee reaching the goal spherical coordinate, since the static gain $K$ is unknown. In fact, it depends on the quotient between $\rho$ and $\rho'$. In other words, the goal location will only be reached with a null outside penetration estimation error:

$$K = \frac{\rho}{\rho'} = \frac{\rho}{\rho + \rho_e} = 1.$$  \hspace{1cm} (7)

Therefore, an adaptive PI control law is added to the Cartesian control scheme as shown in Fig. 7.

The above Cartesian controller, by using the desired optic location, generates a smooth spherical trajectory which is used as the adaptive PI control law reference. The control loop feeds back the actual optic location for computing the required optic spherical trajectory, which eliminates the location error due to the outside penetration uncertainty.
Figure 8 shows altitude angle compensation by means of the proposed control strategy. The camera movement starts at point A and B is computed as the camera goal position for reaching the desired altitude angle $\beta$. However, this is a wrong computation since it is made by taking into account the estimated fulcrum position $F$ instead of the actual one $F'$. At this point, the controller determines the required angle $\Delta \beta$ which is used in order to calculate the new camera position $C$ where, finally, the desired altitude angle $\beta$ is reached.

As shown in Fig. 8, the following expression is proved at camera position $C$:

$$\rho \sin(\beta + \Delta \beta) = \rho' \sin \beta. \quad (8)$$

Therefore, the lower expression finds a geometrical estimation of the actual outside penetration as a function of the desired altitude angle and the required one:

$$\rho' = \rho \left( \cos \beta \cdot \frac{\sin \Delta \beta}{\sin \beta} + \cos \Delta \beta \right). \quad (9)$$

This geometrical estimator is included in Fig. 7 at the upper right-hand corner. The job of this estimator is divided into two issues: (i) tuning the PI control law for keeping the control specifications and (ii) updating the outside penetration estimation $\rho$ used by the trajectory generator. The performance of this control scheme and the geometrical estimator accuracy will be studied in the next section.
4. FAIL-SAFE IMPLEMENTATION

The proposed Cartesian control scheme has been included in the motion control architecture of the ERM [9] (see Fig. 9). This robot has been fully designed and built in the University of Malaga in order to assist in laparoscopic surgery by moving the camera. It has 5 d.o.f. divided in two components: 3 active d.o.f. with a classical PRR configuration for camera positioning, and a passive wrist consisting of two joints perpendicular to each other for camera orientation. The human–machine interface allows two ways of communication: voice commands and joystick movements.

In order to achieve the clinical trials, a risk analysis of this system must be developed. Thus, a failure mode and effects analysis (FMEA) has been used in order to implement the ERM control system. In this way, the robotic assistant is considered as a set of functional modules. The analysis requires identifying a set of failure modes for each module, its effect on the overall system and the possible hazards to the patient. By taking into account the probability of failure occurrence and the severity of the hazard to the patient, an index risk has been established [10].

Figure 10 shows the above-mentioned modules and their relationship. These modules are described below:

- Supply module. This module powers the motors and the control electronics, and it is placed in the robot base.

![Figure 9. The ERM.](image-url)
- Servocontroller arm. It follows a classical PRR configuration, and includes the mechanical structure, motors, encoders and joint low-level control.
- Passive wrist. It adds passive freedom in two axes at right angles to one another that allow the optic to pivot freely on the abdominal musculature, but without distorting pressure.
- Supervisor module. This component manages the overall device functions. It is a micro-controller-based system, which receives motion commands and plans the servocontroller arm trajectory.
- Communication system. This is the human–machine interface which allows two different communication modes: *via* voice commands and by means of a joystick.

As an example, Table 1 details the failure mode risk analysis of the servocontroller arm module. From Table 1, the following controls have been applied for each one of the possible failure modes.

(i) If the affected joint is blocked, the joint low-level controller detects the failure and reports this situation to the supervisor module. This supervisor module stops the movement and puts it into the fail state. In the fail state, the robot motion controller waits for a manual restart using the control panel. In this situation no voice or joystick command is allowed.
(ii) The joint low-level controller detects an excessive position error in the affected joint when it tries to carry out the desired trajectory. Thus, it stops the
Table 1.
FMEA for the servocontroller arm functional module

<table>
<thead>
<tr>
<th>Failure mode</th>
<th>Effect on the system</th>
<th>Possible hazards</th>
<th>Risk index</th>
</tr>
</thead>
<tbody>
<tr>
<td>Actuator, gear or transmission failure in the rotational joints</td>
<td>the affected joint stops its movement and the arm performs a wrong trajectory, without effort exerted on the patient’s body due to the passive wrist compliance</td>
<td>the servocontroller arm does not perform the desired trajectory, therefore the optic movement inside the abdominal cavity is different from the expected one; thus, it can touch a tissue</td>
<td>occasional and marginal harm (2)</td>
</tr>
<tr>
<td>Encoder failure in any of the three actuators, due to mechanical failure or electronic failure</td>
<td>the arm begins to carry out a wrong trajectory</td>
<td>the optic movement inside the abdominal cavity is different from the expected one; thus, it can touch a tissue</td>
<td>remote and critical harm (2)</td>
</tr>
<tr>
<td>Joint low-level controller failure</td>
<td>the arm begins to carry out a wrong trajectory</td>
<td>the optic movement inside the abdominal cavity is different from the expected one; thus, it can touch a tissue</td>
<td>remote and critical harm (2)</td>
</tr>
</tbody>
</table>

movement and reports this question to the supervisor, and then this module detains the movement.

(iii) The controller cannot respond to the supervisor in an appropriate way, therefore the supervisor turns off the motor power supply and puts it into the fail state.

These control actions has been programmed in the low-level control firmware and in the supervisor module. A similar analysis must be developed for the rest of the modules in order to complete the applicable control actions for reducing the risks of the overall system.

5. EXPERIMENTS

Three kinds of experiments have been carried out in order to test the system: laboratory experiments, live animal procedures and, finally, human clinical surgery.

Laboratory experiments have been used to verify the proposed compliance method. Figure 11 details the robot temporal response for a $\beta$ movement from $-48.1$ to $-43.1^\circ$. The controller parameters have been established in order to reach the reference in 3 s. Some experiments have shown that a time constant of 0.6 is comfortable for the surgeon. The desired spherical trajectory, shown by a dashed line, is the reference generated via a trapezoidal interpolation for reaching the goal altitude from the current camera position. It is the entry of the adaptive
Figure 11. Temporal response for reaching a given altitude angle $\beta$.

PI controller which feeds back the current optic orientation in order to compute the required $\beta$ trajectory (dotted dashed line). Finally, the actual $\beta$ trajectory, obtained via passive wrist encoders readings, is shown as a solid line. As shown, this last trajectory follows the desired one and it reaches the steady state in the $\beta$ goal value. Therefore, the PI adaptive controller eliminates the altitude error in spite of the outside penetration error (50 mm for this experiment).

Figure 12 represents the $\alpha$ coordinate when the altitude movement is carried out. It can be noticed that, at the beginning of the movement, the $\alpha$ coordinate overdamps (with a maximum amplitude of 0.6°). It is due to mechanical imprecision and encoder resolution. Nevertheless, the designed controller compensates for the overdamping and, later, the coordinate keeps its reference value. The geometrical estimator approximates the outside penetration by using the required $\beta$ trajectory and the actual one, during the above movement. Figure 13 shows the proposed estimator performance (dotted dashed line) in comparison with a minimum square estimator (dotted line). The geometrical estimator provides a more accurate outside penetration approximation than the minimum square method. However, the estimation values overdamp at the beginning of the movement. Because of this fact, the geometrical estimator only provides a new estimation to the PI controller and to the trajectory generator when the current movement is finished.

With regard to the animal experiments, several trials have been carried out (see Fig. 14). In order to verify the safety controls, different intentional failures have been introduced during the procedures: blocking the robot links, unplugging the
Figure 12. The $\alpha$ coordinate in an altitude movement.

Figure 13. Outside penetration estimation.
encoders, polarity inversion of the motor supply. All of the above actions were adequately detected and handled without any hazard.

Also, on-line robot–patient displacements were smoothly complied by means of the proposed compliant motion control.

With regard to the clinical trials, a clinical protocol for the validation of the system has been designed. The purpose of the study is to determine the efficacy of the system and obtain the necessary approval for commercial distribution. The clinical trial for laparoscopic cholecystectomy has been designed as follows. Laparoscopic cholecystectomy in two groups of patients will be performed. In the first group, the laparoscopic camera will be handled by the surgeon’s assistant (conventional laparoscopic surgery), whereas in the second one it will be handled by the designed system (by means of the voice interface). Both groups will have 16 patients randomly assigned. Objective data like operating time, number of cleaning operations (number of times that it is necessary to clean the optic), etc., will be collected during the procedure, as well as other subjective data like the surgeon’s tiredness, quality of vision, etc. Currently, nine human cholecystectomy procedures have been carried out for each group (see Fig. 15). In these cases the robot has shown good performance simply by placing the robot near the patient, accommodating the fulcrum point position and perturbations like the patient’s breath. Surgeons have noticed some advantages — the total operating time has been reduced and the movement precision ensures that the optic does not touch any tissue, so it is necessary to clean it only a very few times. Furthermore, due
to the generated trajectory, the procedure field is always centered. Thus, surgeons stated that using the system was comfortable because of both its ease of use and its performance.

6. CONCLUSIONS

This paper has presented an adaptive PI Cartesian controller used to compensate for the laparoscopic orientation errors when a fulcrum position uncertainty exists. First, this work has studied the problem of laparoscopic camera navigation when the robot arm has a passive wrist. This analysis shows that it is possible to design an independent controller for each spherical coordinate: one for controlling the $\alpha$ movements and other for the $\beta$ displacements. These controllers have a common scheme — an adaptive PI controller attached to a trajectory generator. This strategy has been implemented in the ERM control architecture and it is able to eliminate the orientation errors during the current movement.

This robot and the proposed movement controller have been tested by means of animal experimentation. Several kinds of procedures have been carried out and the system response has been satisfactory, with a great accuracy in the camera positioning. Once the system safety has been tested and the certification stage by the Spanish Health Authorities has been finished, clinical trials on humans will have been successfully carried out.
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