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A minimally invasive surgery robotic assistant for HALS–SILS techniques

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ABSTRACT

This paper is focused in the design and implementation of a robotic surgical motion controller. The proposed control scheme addresses the issues related to the application of a robot assistant in novel surgical scenario, which combines hand assisted laparoscopic surgery (HALS) with the single incision laparoscopic surgery (SILS) techniques. It is designed for collaborating with the surgeon in a natural way, by performing autonomous movements, in order to assist the surgeon during a surgical maneuver. In this way, it is implemented a hierarchical architecture which includes an upper auto-guide velocity planner connected to a low-level force feedback controller. The first one, based on a behavior approach, computes a collision free trajectory of the surgical instrument tip, held by the robot, for reaching a goal location inside of the abdominal cavity. On the other hand, the force feedback controller uses this trajectory for performing the instrument displacement by taking into account the holonomic movement constraints introduced by the fulcrum point. The aim of this controller is positioning the surgical instrument by minimizing the forces exerted over the abdominal wall due to the fulcrum location uncertainty. The overall system has been integrated in the control architecture of the surgical assistant CISOBOT, designed and developed at the University of Malaga. The whole architecture performance has been tested by means of in vitro trials.

1. Introduction

Minimally invasive surgery (MIS) has become one of the most important surgical techniques in the last twenty years due to its capability of reducing the number of incisions that are practiced on patients, with the aim of shortening postoperative convalescence, whereas diminishing any other complications. This shortening involves several social and economic consequences as, for example, minimizing the time that patient stays at hospital. The current trends in surgery are moving towards two different approaches: transumbilical single incision laparoscopic surgery (SILS) and hand-assisted laparoscopic surgery (HALS).

The first one implies even less invasive techniques with associated advantages as cosmetics or less incisional pain. Despite this technique represents a less invasive approach compared to standard multiport laparoscopic surgery, it may

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also present some drawbacks. In first place the surgeon must use special modified instruments, in such a way that the movement is not so natural. In addition to this, as all the instruments are inserted through a single incision, it can be common in the learning phase that the instruments clash against each other and the laparoscope during the surgical intervention. In this way SILS has a longer learning curve than standard laparoscopic procedures and it requires a strong coordination between the surgeon and the camera holder assistant [1].

The second technique mentioned above allows the surgeon to insert a hand through a small incision via a pressurized sleeve. In this way the surgeon can use his non-dominant hand intra-abdominally while he can operate a surgical instrument with the other hand. With this technique the surgeon gains control over the operation, sense of depth and tactile feedback in comparison with a conventional laparoscopic surgical technique while still being a minimally invasive surgery (MIS) technique. This strategy has been proved as a good option in certain kind of interventions as, for example, colorectal cancer surgery [2] where the patients presented a significantly lower blood loss, operative time and stance in the intensive care unit and a more adequate lymph node harvest. Similar results have been obtained for colon cancer surgical interventions [3].

In this way, although HALS is more aggressive for the patient, it is useful for performing more complex surgical procedures, which cannot be addressed by using conventional minimally invasive surgery. Thus, some surgeons apply SILS techniques for reducing the number of instrumental input ports in order to reduce the impact on the patient's body [4]. In this situation, we speak about a combined HALS–SILS scenario.

The main drawback of this new kind of interventions is the fact that the surgeon needs assistance for handling all required surgical instruments. In particular, while the surgeon holds the organ with one hand and a surgical instrument with the other one, the assistant has to manage the laparoscopic camera as well as an additional surgical instrument. In this scenario, the assistant may be only replaced by a sophisticated robot system capable of taking autonomous decisions (i.e. automation of surgical maneuvers). The conventional systems (like ZEUS by Computer Motion and DaVinci by Intuitive Surgical) were not designed to satisfy the above issue on MIS and present the disadvantage of being bulky making the performance of a single-port approach challenging [5].

The automation of surgical maneuvers by using the robot co-worker concept allows surgeons to concentrate on the surgical procedures while the robot assistant automatically helps in a collaborative way. Such systems are easier to handle and require less training period as surgeons collaborate with the robots like human assistants. Visual Servoing techniques are defined as the most common methodology for designing automated tasks and it is used in surgical applications like safe movements of the endoscope on cardiac surgery [6]. Other works based on the automation of surgical maneuvers are devoted to actively assist the surgeon during the intervention, for example: by performing autonomous stitching and knot tying procedures [7]; by automatically guiding the flexible endoscope tip in colonoscopy diagnosis [8]; by providing automatic conversion of a robot assistant behavior from laparoscopic navigation to open-surgery motion [9]; or by giving autonomous decisions on teleoperation with high communication latency or low bandwidth [10].

The EndoPAR robotic system [11] is a paradigm of this kind of robotic assistants. It is able to automate a knot tying procedure in heart surgery, and allows the surgeon to operate as if there was no heartbeat. Furthermore, there are also studies for human–machine skill transfer on robot assistants in order to perform automatic knot tying procedures, or an automatic navigation on cholecystechtomy without pre-operative information [12].

In any case, for performing these automatic movements, the robot has to adapt the instrumental displacements to the holonomic constraints imposed by the fulcrum point. For this question, there are many solutions based on remote rotation center [13] but all these approaches can cause muscle abdominal wall tears. Indeed, an undesired movement of the patient body during the intervention causes the displacements of the input instrumental ports from position where the robot was calibrated. In this way, the remote rotation center does not fix the new position of the fulcrum point, and therefore, unwanted forces appears on the abdominal wall, a situation that it is intensified if SILS techniques are used [14]. Therefore, a continuous force control during the intervention is needed in order to avoid this problem.

This paper proposes a robotic assistant designed for the HALS–SILS combined scenario which has the previously mentioned capabilities of both automation of surgical maneuvers and continuous force control for instrument displacements. This robotic system is equipped with two arms, one for holding the endoscope and the other for carrying an additional instrument. In particular, this work is focused on the surgical instrument auto-guided velocity planner (in advance, the auto-guide system) and a low-level force feedback controller (in advance, the low-level controller). The arm which carries the instrument must avoid the collision with the surgeon's instrument and the organs inside the abdominal cavity during its navigation, whereas the low-level controller shrinks the forces exerted on the abdominal wall. The future of this work is oriented to replace the surgeon assistant in the referred laparoscopic surgery scenario. For this reason, authors eventually propose a control architecture for performing automated tasks, which adapts the movements to the surgeon actions.

The structure of this article is divided into six sections. After this introduction, Section 2 states the HALS–SILS scenario and presents the two problems related with the named scenario: the generation of auto-guide movements and the navigation problem of the laparoscopic tools. Section 3 details the low-level controller scheme while Section 4 explains the proposed methodology for auto-guided movements. In this way, Section 5 presents the in vitro experiments with CISOBOT system related to the theoretical contribution stated in previous sections. Finally, Section 6 is devoted to final conclusions and future works.

2. Problem statement: scenario definition

Fig. 1 shows the surgical HALS–SILS scenario described in the introduction which includes the robot assistance to the