A New Robot for Minimally Invasive Surgery

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Abstract. Minimally invasive surgery (MIS) challenges the surgeon's skills due to his separation from the operation area which can be reached with long instruments only. To overcome the drawbacks of manual MIS minimally invasive robotic surgery (MIRS) plays an important role. This paper takes a close look at the requirements on a MIRS system and describes the new DLR robot for MIS. This includes a discussion of the robotic arm, of appropriate control laws, as well as of actuated and sensorized instruments.

1 Introduction and Motivation

Minimally invasive surgery (MIS) is an operation technique established in the 1980s. It differs from open surgery in that the surgeon works with long instruments through small incisions (typically smaller than 10 mm) and that he has no direct access to the operating field as in open surgery. The main advantages of MIS compared to open surgery are: small incisions, which reduce pain and trauma, shorter hospital stays, shorter rehabilitation time, and cosmetic advantages. Of course, MIS has disadvantages as well: Direct hand-eye coordination as in open surgery is lost [1], as the long instruments (approx. 30 cm) have to be moved around an invariant point (entry point or fulcrum point) on the patient's body. The friction in the trocar reduces the sensation of contact forces between instrument and tissue. Palpation of tissue is not possible because the surgeon does not have direct access to the operating field. Only four degrees of freedom (DoFs) remain inside the body, due to the kinematic restrictions at the entry point. Therefore, the surgeon cannot reach any point in the work space at an arbitrary orientation. This is a main drawback of MIS, which makes complex tasks like knot tying very time consuming and requires intensive training [2,3]. As a consequence of these drawbacks MIS did not prevail as desired by patients and surgeons. Only cholecystectomies (gall-bladder removals) are performed in 95% or more cases using minimally invasive procedures.

Key technologies to overcome the drawbacks of manual MIS are robotic and mechatronic systems, which help the surgeon to regain virtually direct access to the operating field. These technologies applied to minimally invasive surgery in combination with telepresence and telemanipulation approaches lead to minimally invasive robotic surgery (MIRS).

MIRS telepresence systems help the surgeon to overcome barriers, such as the patient's chest or abdominal wall, which separate him from the operating area and cause the drawbacks mentioned before: With appropriate control algorithms the undesired reverse hand motion can be avoided. The downscaling of the surgeon's hand motion before it is transmitted to the robot is another benefit: movements of instruments become more accurate than in open surgery. Additionally, the surgeon's tremor can be reduced using low-pass filters. Actuated instruments with two additional DoFs give back full dexterity inside the human body to the surgeon. Small force/torque sensors adjusted near the instrument tip allow for the measurement of manipulation forces/torques [4] which can be displayed to the surgeon, thus providing kinesthetic feedback. Furthermore, MIRS systems can allow for the realization of autonomous functions (such as motion compensation of the beating heart [5,6,7]) and enable surgeons to perform new operation techniques like endoscopic minimally invasive bypass surgery at the beating heart [8].

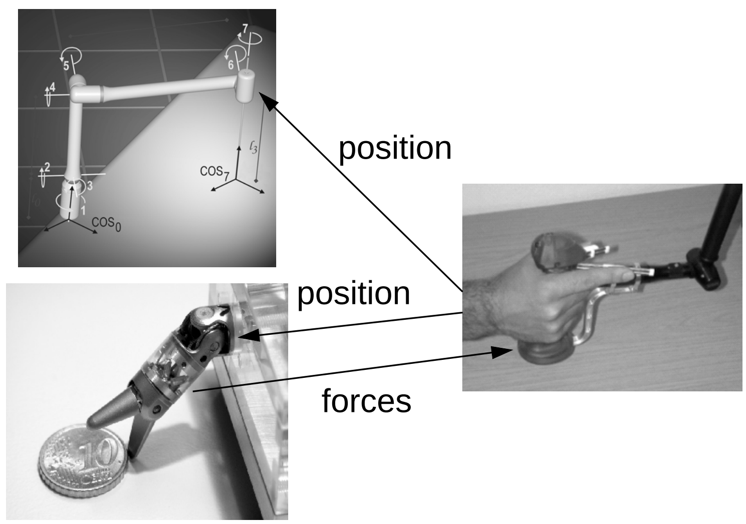

Fig. 1. Main components of DLR MIRS system

The main components of the DLR MIRS setup are given in figure 1: The slave (left part of figure 1) consists of a surgical robot (being currently assembled) together with an actuated and sensorized pair of forceps. The master (right part of figure 1) consists of a stereo video screen (not shown) and a kinesthetic feedback device for the grasping forces which is attached to the stylus of the PHANToM. The presentation in this paper focuses on the slave components robotic arm and sensorized instruments. It is expected that these crucial parts of a MIRS system help to avoid the before mentioned disadvantages and allow patients and surgeons to benefit from the advantages of MIS.

The discussion of the slave properties takes place with respect to the two most important commercial MIRS systems available and in clinical use: the ZEUS system from Computer Motion Inc. [9] and the da VINCI system from Intuitive Surgical Inc. [10]. Furthermore, the results are related to the robotic tele-surgical workstation (RTW) for laparoscopy developed by the University of California, Berkeley and the University of California San Francisco [11]. An overview on recent advances in robotic surgery can be found in [12].

In section 2 the properties of the new robot are given in detail. This includes the robot kinematics (section 2.1) and the control laws (section 2.2). Sensorized and actuated instruments developed for robotic surgery are presented in section 3. The last section (section 4) summarizes the results and gives directions for further research and development.

2 Robotic Arm

Current commercially available MIRS systems like da VINCI and ZEUS consist of three robotic arms: two of them hold the surgical instruments, while the laparoscope is attached to the third one [9,10]. Today's MIRS systems are bound by certain limitations: The robotic arms of the da VINCI system are heavy. The ZEUS system possesses arms which are rather light-weight, but only 4 of the 6 joints can be actuated (2 joints are passive). In contrast to ZEUS which utilizes robotic arms in the classical sense both da VINCI and RTW systems exploit four bar linkage designs. Both, ZEUS and RTW need a support at the invariant point. Therefore, they cannot be used in open surgery.

The following sections describe the kinematic requirements from a MIS point of view, possible control laws, and their realization within the described robotic arm.

2.1 Kinematics

In order to be easily mounted or removed by a nurse during an operation, the robotic arm should be compact and light-weight. This is important in emergency situations and also helps to reduce preoperative setup time. Additionally, the robotic arm has to be stiff enough to ensure high precision operation. Unfortunately, this usually contradicts the light-weight design goal.

It is therefore important to determine the link lengths such that the robotic arm performs optimally with respect to dexterity and accuracy in all considered MIS application scenarios but has a compact and light-weight design, too. An analysis of this type was carried out in [13] where the situations of thoracic surgery (see figure 2 right) and abdominal surgery are considered. For these interventions the approximate workspaces were determined taking into account different patient anatomies. The minimal link lengths l_1 and l_2 of the 7 DoFs

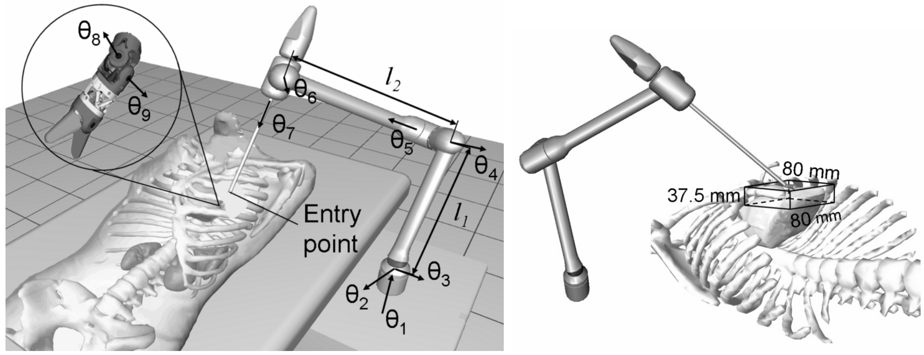

Fig. 2. DLR's surgical robot and workspace for cardiac interventions

robot shown in figure 2 were determined using Genetic Algorithms (GAs). The kinematically redundant robot allows for a more flexible operating room (OR) setup. Two additional DoFs Θ_8 and Θ_9 are added if actuated instruments as described in section 3 are used. Full 6 DoFs remain inside the body due to the kinematic restrictions at the fulcrum point. Using not only one but a variety of possible entry points the result is robust with respect to variations of patient's anatomy and intraoperative registration errors. The GA optimized the link length $l_1 = 259.5$ mm and $l_2 = 327.4$ mm. The optimisation constraints of the GA were used to achieve a desired accuracy of 0.1 mm for translation and $0.5°$ for rotation, respectively. This is considered to be sufficient for the most demanding task with respect to accuracy: suturing blood vessels in cardiac surgery. To provide the surgeon with good manipulability a minimum velocity of 60 mm/s for translation and $30°$/s for rotation is guaranteed. A detailed description of the optimisation procedure and the constraints is given in [13].

The robot is fully actuated to be suitable for open surgery, too. For MIS procedures the fulcrum point position has to be taken into account by the robot's (inverse) kinematics. Possible solutions for online estimation are given in [6,14], additionally, external tracking devices may be used. The robot is currently being assembled.

2.2 Control

Today's MIRS systems offer only position controlled mode, which has an important drawback: High forces exerted either on tissue or between two robots are a potential source of damage and injury. Furthermore, a high level of immersion of the surgeon into the remotely performed operation has to be achieved. These goals can be met with advanced control algorithms such as impedance control in combination with kinesthetic feedback [6].

The objective of an impedance controller is to establish a mass-damper-spring relationship between the position/orientation and the force/torque at the endeffector. The advantage of impedance control in contrast to position control consists in that the reaction behaviour of the robot can be specified by the user according to the considered task. This allows to run the robot in a compliant, stiff, or even viscous mode. The impedance control structure is given in the left part of figure 3. It consists of a fast (3 kHz) joint level task and a slower Cartesian level task (1 kHz). The joint impedance controller is realized as a fourth order state feedback control law [15]. Dependent on the desired stiffness k, even a joint position control law ($k \rightarrow \max$) or a joint torque control law ($k \rightarrow 0$) can be achieved. Based on the joint level controller a Cartesian level impedance controller can be implemented: The reaction behaviour covers a wide range, including position and force control.

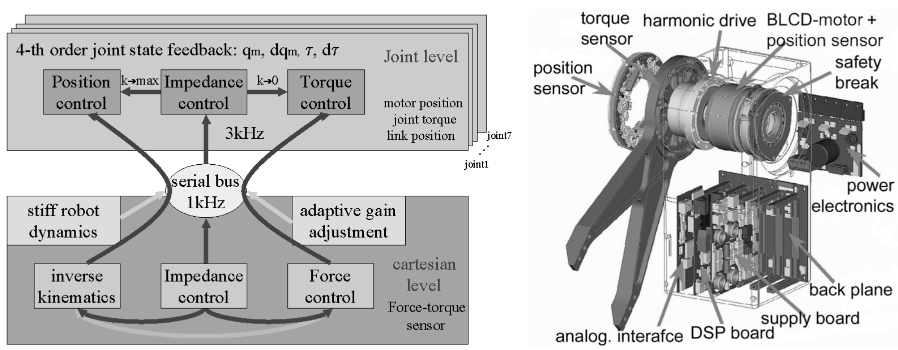

Fig. 3. Impedance controller structure and integrated joint unit

Impedance control can be realized with the highly integrated and sensorized joints (see figure 3 right) as developed for DLR's light-weight robots. These joint units consist of the following components: electronic interface to serial bus, customized motors with good torque to weight ratio, light-weight breaks and gears, joint position sensors, and joint torque sensors. Each of these joint units possesses two position sensors: one motor-side and the other one link-side. Additionally, the joint units are equipped with a torque sensor allowing the straight-forward realization of the joint state feedback controller depicted in the left part of figure 3.

3 Instruments and Sensors

Presently, instruments for MIRS differ from those for conventional MIS mainly in the substitution of the handles by electrically driven joints. Additional capabilities making the instruments more similar to the surgeon's hands and reducing the restriction due to the entry point are implemented only rarely. The da VINCI system provides with its Endowrist technology full dexterity (i.e. 6 DoFs) inside the patient, whereas the ZEUS system offers restricted motion (5 DoFs) only.

Today's minimally invasive instruments as utilized by ZEUS, da VINCI, and RTW do not allow the measurement of forces. However, by experience, the surgeon is able to interpret tissue deformations as a measure of the exerted forces and to compensate for the lack of haptic information. Unfortunately, this interpretation leads to a reduction of the surgeon's dexterity to perform manual work. A sensorized scalpel for MIS with a diameter of only 10 mm (see figure 4 left and middle) was developed to circumvent this drawback and to provide the surgeon with direct kinesthetic information. Forces can be measured in all three dimensions and so can torques. The force information can be also augmented to the video stream, if no appropriate kinesthetic feedback device is available (see figure 4, left). In our setup the relative pose between instrument tip and laparoscope is unknown. Therefore, a colormark near the instrument tip is tracked with a stereo laparoscope, the 3D position is reconstructed and then used to display the force information.

Fig. 4. Sensorized instruments developed by DLR

The sensor which is contained in the scalpel consists of a hexapod structure equipped with 6 strain gauge sensors. The chosen mechanical structure provides good stiffness and measurement sensitivity in all directions. A large central hollow allows to place steering and electrical wires through the sensor which may be necessary for the functional end. The sensor can handle mechanical forces up to 30 N and torques up to 300 Nmm without being damaged. The measurement range is ± 20 N and ± 200 Nmm respectively. The measurement electronics is placed inside the instrument shaft. This reduces the influence of noise but imposes questions on sterilizability and electromagnetic compatibility. The digital resolution achieved so far is approximately 9 bits, the sample rate is 800 Hz. Further details on the sensor design can be found in [4].

A rigid instrument limits the work space behind the trocar. Full manipulability cannot be achieved because additional DoFs similar to the human hand are missing. A pair of forceps with two additional actuated degrees of freedom near the tool tip is currently being assembled. This enables the surgeon to move the tool tip of the instrument in six DoFs inside the human body. Thus, the surgeon regains the full dexterity of open surgery and can therefore work intuitively in a manner similar to open surgery. The drives for the joints and the forceps themselves are realized as electro-mechanical actuators and are located outside the body. The instrument has a diameter of 10 mm only (see figure 4 right).

As the instrument is equipped with sensors close to the tip real contact forces can be measured. Additionally, this instrument will be able to measure grasping forces, too. This allows for a variety of additional functions: Force information can be displayed in the laparoscope's picture giving the surgeon visual feedback of actual forces being applied. Furthermore, kinesthetic feedback of contact and grasping forces is also possible, producing force feedback at the surgeon's fingertips (see figure 1). In combination with appropriate control laws limitation to a maximum force (e.g. during suture) or a constant force (e.g. holding tissue while the organ is moving) is possible, too.

The sterilizability of electrical components still involves unanswered questions, so alternative methods may have to be used to measure and transmit information (e.g. optical methods). Due to their high complexity those instruments cannot be built entirely disposable. One has to develop sterilizable instruments or a combination of complex, reusable components with simple and easy to change disposable components.

4 Summary and Outlook

Tele-surgical MIRS systems are set out to broaden the application fields of MIS and to improve the quality of surgical interventions. They should provide a high level of immersion of the surgeon into the remotely performed operation: The surgeon regains direct virtual access to the operating field.

The new DLR robot for MIS tries to meet this challenging and demanding goal by exploiting the possibilities of current robotics and mechatronics. Consequently, this approach leads to a compact, light-weight, kinematically redundant, and impedance controlled robotic arm, which occupies few space in the crowded OR. Actuated instruments are necessary to provide full dexterity inside the patient. This makes MIS more similar to open surgery and it is to be expected that more operations will be carried out in a less invasive way. Small force/torque sensors placed near the instrument tip in combination with appropriate input devices provide realistic kinesthetic feedback of the remote forces. This gives the surgeon direct access to manipulation forces inside the patient and allows for a more delicate manipulation of tissue, avoiding unintentional damage.

Advanced MIRS systems in combination with highspeed computer networks will allow to overcome distances if surgeon and patient are located in different rooms or even hospitals (so-called virtual hospital). Whereas routine long distance tele-operations seem to be far away, third opinion getting or getting support by a remote expert might be realized in the near future. The remote expert is equipped with a console which is connected via broad-band communication lines to the hospital where the operation takes place. In this way he is able to take temporarily control over the teleoperated robots and to participate in the operation. This setup is also very suited for new surgeon training methods where the remote expert trains the unexperienced local surgeon [16].

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