ROBOTIC SURGERY AND TELE-SURGERY: BASIC PRINCIPLES AND DESCRIPTION OF A NOVEL CONCEPT

A. Lobontiu, D. Loisance
Department of Cardio-Thoracic Surgery
Henri Mondor Hospital, University Paris 12, France

ROBOTIC SURGERY AND TELE-SURGERY: BASIC PRINCIPLES AND DESCRIPTION OF A NOVEL CONCEPT (Abstract): One of the most important advances in surgical technology in the last two decades of the twentieth century is represented by the introduction of the laparoscopic technique. Using the laparoscopic approach the patient is operated through keyhole incisions as opposed to long, traumatic incisions over the thoracic or abdominal cavity. Many open procedures, such as those for gallbladder disorders, groin hernia repair and anti-reflux surgery of the stomach have been replaced by minimally-invasive procedures, whose advantages include shorter postoperative hospitalization, less pain, and a faster return to normal activity. Although improvements continue to be made in laparoscopic surgery, surgeons are generally still faced with particular drawbacks of this technique. Robotic surgery and computer-enhanced surgery may revolutionize these techniques by restoring most of the advantages of open surgery but in the context of minimally-invasive procedures. For example, cardiac surgery has entered a new era since robotic surgery appeared a part of certain by-pass and valve surgery. This work describes the da Vinci Surgical Robot™ which represents the current state-of-the art of this technology. New developments in system accuracy, planning and simulation of the surgical act are highlighted.

KEY WORDS: LAPAROSCOPY, ROBOTIC SURGERY, MINIMALLY-INVASIVE SURGERY

Correspondence to: Adrian Lobontiu, MD; Henri Mondor Hospital, Université Paris 12, 94010 Créteil, France; e-mail: adrian@lobontiu.com*

INTRODUCTION

Robots are being used in increasingly complex surgical procedures. However these robots are not autonomous machines that carry out simple, pre-programmed instructions. Operating theatre robots are designed to supplement a surgeon's abilities, translating human movements into incredibly steady and accurate robotic movements, which, in turn, manipulate instruments to aid delicate operations.

Keyhole surgery has been in use since the late 1970s for surgical procedures in a number of areas - for example gastrointestinal, gynaecological and even cardiac. The benefits include the reduction of patient pain and trauma, as well as a decline in the chance of infection and a quicker recovery time.

But minimally invasive procedures, using instruments controlled by humans, have their limitations. For one, instruments are not in the surgeon's direct control, being manipulated by assistants. And the instruments' positioning within the body is subject to human tremors and fatigue, which makes working on minute structures difficult and dangerous [1].

Keyhole surgery has hitherto been best used where there is a maximum of space - for instance, in the abdominal cavity, into which CO2 can be blown. While it is possible to carry out minimally invasive heart surgery, it can entail the surgeon having to adopt awkward physical positions for prolonged periods of time.

By handing control of the surgical instruments over to a robot - and positioning the surgeon at a comfortable console with a 3D or and high- resolution display at 10 to 20 times magnification - surgery is easier and more accurate [2].

---

* received date: 01.03.2007
accepted date: 25.05.2007

That means complex procedures such as heart bypasses - in a minimum of space and with arteries between 1.5 and 2.5mm diam wide and using sutures thinner than a human hair - can be performed with the minimally invasive surgery and without stopping the heart.

Rather than stopping the heart and performing a sternotomy or a thoracotomy, just three 8 to 10 mm-long incisions are required for two robotic arms with tiny instruments and a third for a camera.

Patients of conventional open heart surgery need, on average, two weeks recovery in hospital, followed by two to three months rest before they can resume normal physical exercise - this is how long the sternum takes to heal - and even then the patient is left with massive scarring [3].

Heart surgery carried out by robot-controlled endoscopy, on the other hand, means for a drastically reduced recovery time of three to four days in hospital and then a further two weeks before normal activities can be resumed.

ABOUT DA VINCI™ SURGICAL SYSTEM

The basis of the dexterity experienced in open surgery relies on the almost unlimited wrist, elbow and shoulder's degree of freedom.

The degree of freedom in laparoscopic surgery is limited because instruments need to be long and are manipulated through fixed ports. The surgeon has to move around these fixed ports.

In order to solve these limitations tools have been developed that have an articulation at the tip, which increases the degrees of freedom. Addition of the wrist at the tip of the instrument gives tool manipulation much more complex. Computer assistance is warranted, as the human brain cannot efficiently manipulate articulated instruments by mechanical means. A robotic wrist provides articulated motions with a full 7 degrees of freedom inside the abdominal or thoracic cavities (EndoWrist™ technology (Fig. 1, 2)).

Fig. 1 Endowrist ™ technology at instrument tips.

Fig. 2 Motion scaling

Computer interfacing allows for remote control surgery (telesurgery), for more precise manipulations by downscaling the surgeon's motions and by allowing surgeon's good ergonomic position [4].

Human robotic surgery was introduced by Cadiere's team (St. Pierre Hospital, Brussels, Belgium) in March 1997 when the first telesurgical laparoscopic cholecystectomy was performed together with Dr. Himpens at Dendermonde, Belgium. The first telesurgical laparoscopic Nissen fundoplication was performed by the same team in May 1998 [5].

In early May of 1998 Carpentier and Loulmet performed the first robotic cardiac surgical operations, which included an atrial septal defect closure and several mitral valve repairs. Later that month Mohr and Falk performed additional mitral operations and the first robotic coronary anastomosis.

Broussais group describes the world’s first totally endoscopic coronary bypass (June 1998). All groups used the same surgical device (da Vinci™; Intuitive Surgical, Inc, Mountain View, California) [6].

THE SURGEON’S CONSOLE

The da Vinci™system consists of a master console that that connects to a surgical „manipulator” with two instrument arms and a central arm to guide the endoscope. Two „master” handles at the surgeon’s console are manipulated by the user. The position and orientation of the hands on the handles trigger highly-sensitive motion sensors and translate to the end of the instrument at a remote location (Fig. 3).

The surgeon sits comfortably at a master console located at a distance from the patient with eyes focused down toward the operative site mirroring an open surgical technique and the slave unit provides „tele-presence” within the abdomen or chest for micro instruments manipulation.

Fig. 3 Hands position corresponds to instrument tip orientation

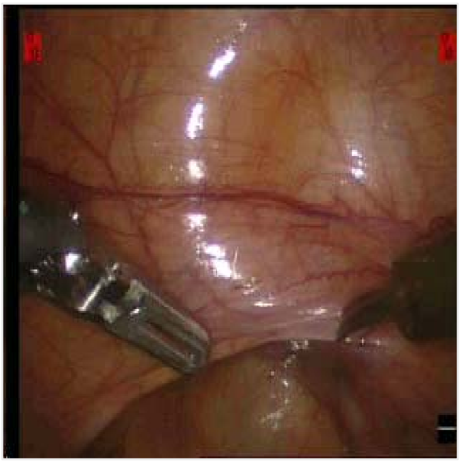

Fig. 4 Intraoperative image

Superior ergonomic design allows surgeon to become immersed in the operative field (Fig. 4). A 10 mm high-resolution 3D 0° or 30° endoscope (with two three-chip charge coupled device – CCD cameras) is used for better perception of depth and optical resolution. The endoscope is held by the central four DOF manipulator of a remote centre design, similar to the slave tool manipulator. The camera manipulator is capable of positioning the tip of the endoscope in 3D by working through the fulcrum made by the port incision at the body wall. This Navigator™ Camera Control system gives the surgeon a 3rd arm to hold and move the camera without the need for an assistant [7].

THE SURGICAL ARM CART

Handles motions are sensed by high-resolution motion sensors, processed and transferred to the two surgical manipulators. These slave manipulators (surgical arms) provide three degrees of freedom (pitch, yaw, insertion). The surgical instrument is attached to the surgical arm. The instrument tip is provided with a mechanical cable-driven wrist (Endo-wrist

Technology), which will add four more degrees of freedom (internal pitch, internal yaw, rotation and grip). The grip is programmed to 1.0 Newton.

In order to enhance precision, the system allows for scaling of the handles-surgical arms motion relationship. A motion scale of 3:1 will move the instrument 1 mm inside the abdomen for every 3 mm motion at the master console.

In addition, unintended movements caused by human tremor are filtered by a 6 Hz motion filter.

The robotic arms together with robotic instruments attached on it can be disconnected from the master-handles by the clutch foot pedal, in order to obtain a more confortable and ergonomic position of the surgeon hands at the console (Fig. 5).

Fig. 5 Operating room set-up

THE 3D IMAGING SYSTEM

The high resolution 3D endoscope consists of two three chip charge-coupled (CCD) device cameras (InSite) with two high-intensity light sources to ensure a bright image of the operative field. Lenses of 0° as well as 30° can be used. The 30° scope can be fixed either down or upside looking. The video image enables up to 10-15 fold magnification according to the working distance compared to the operative field. The endoscope is attached to the robotic camera arm and once inserted it can be moved from the console by the surgeon by pressing the camera food switch. This will lock the instrument arms and gives the operator control of the camera through the master manipulators.

COMMUNICATION BETWEEN OPERATING AND ASSISTANT SURGEON

Adequate coordination between the surgeon at the console and his assistant at the operating table is guarateed by a permanent communication. In some operating rooms the surgeon’s console is installed in a separate room connected with a microphone to the operating room. In other hospitals the console may be in the same room [8].

SYSTEM ACCURACY

Because the da Vinci™ System naturally becomes a part of the surgeon’s eye-hand coordination loop, the most telling measure of the system’s accuracy is through touch tests where the surgeon is an active participant. At Intuitive Surgical, we have performed tests to measure the total performance of the man-machine system [9]. The test was conducted as follows. Sonomicrometry measurements were obtained for a crystal sutured to a stabilized porcine LAD with respect to a fixed coordinate frame. The data were processed to produce a driving signal for a cardiac anastomosis trainer, which we modified to drive with a servocontroller (Fig. 6). The sampling frequency exceeded 1 kHz. The data contained up to 14 beat cycles before repeating and included breathing modes, therefore closely replicating the quasiperiodic motion of the target vessel.

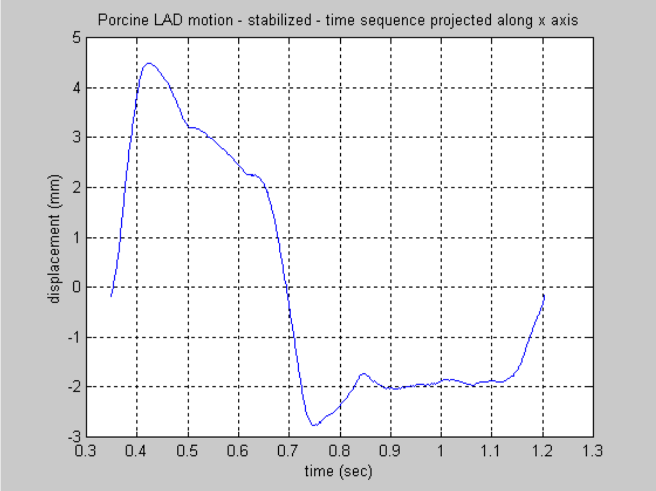

Fig. 6 Typical heartbeat motion (reduced to one-dimensional approximation) programmed into trainer.

A target was mounted to the trainer, consisting of lined graph paper with a gel backing. Surgeons were tasked with touching the graph paper at prescribed locations as accurately as possible while the target beat. A 6-0 needle was used. Afterwards, the target was analyzed by standard inspection techniques to determine the accuracy of each touch. Figure 7 below shows a typical result; for this extremely demanding dynamic test the mean error for three subjects with eight touches each was 220 μm, and the standard deviation was 150 μm.

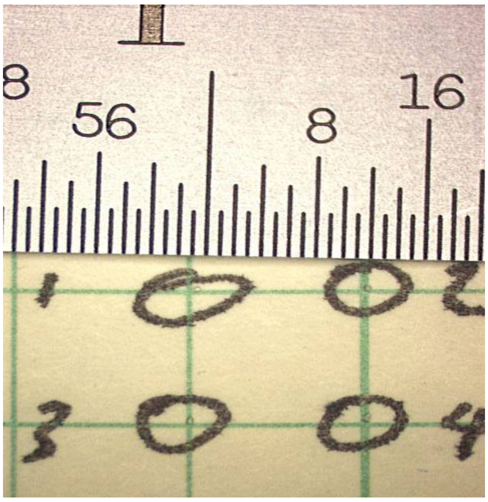

Fig. 7 Typical results for tester attempting to touch gridline intersections while grid is mounted on dynamic beating heart trainer.

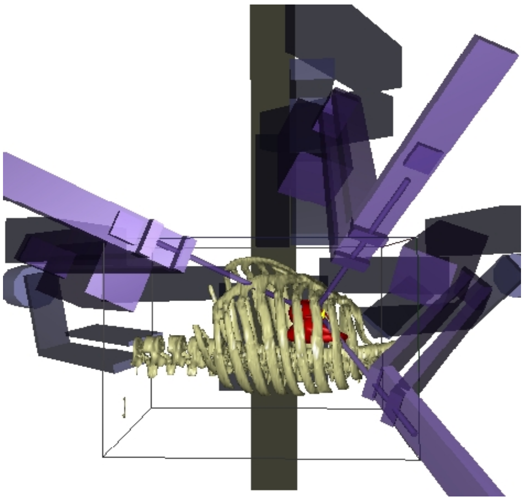

Fig. 8 A validation sequence for MIDCAB intervention

The da Vinci™ Surgical System uses high-resolution optical encoders to measure the position of each powered joint. The system checks the position of these joints by reading the sensors over 1300 times each second. The sensors give extreme positional precision: more than 2000 sensing points per degree of arc for the major revolute axes and over 750 sensing points per millimeter for the prismatic axis. This corresponds to well over 500 sensing points per millimeter in any direction at the worst case working depth. With this resolution ability, the da Vinci™ System takes full advantage of fine surgical skills.

To periodically check that the accuracy of the system is maintained, it is a simple matter to recreate a static version of the above test. A baseline performance for the surgeon(s) should be established when the system is new, and repeated as often as desired. Commercial optical inspection machines are well suited to quick measurement of errors. Standard graph paper taped onto a gel material works well as a target.

PLANNING AND SIMULATION OF ROBOTICALLY ASSISTED MINIMALLY INVASIVE SURGERY

A common telemedecine project research in robotics and medical images is currently carried out between INRIA (Sophia Antipolis, France) Georges Pompidou Hospital (Paris, France) and Intuitive Surgical Inc. Mountain View, CA) [9].

The project defines a framework for pre-opeartive planning and simulation of robotically assisted minimally invasive surgery (MIS).

The approach consists of a planning, validation and simulation phase in order to propose optimal incisions sites for the robot, to validate the sites and to enable realistic simulation of the intervention. With the patient’s pre-operative data, we formulate the needs of the surgeon and the characteristics of the robot as mathematical criteria in order to optimize the settings of the operation. Then, we automatically reproduce expected surgeons’ movements and guaranty their feasibility. Finally we simulate the intervention in real-time, paying particular attention to potential collisions between the robotic arms (Fig. 8).

CONCLUSION

Robotic surgery is now routinely performed in specialized centers throughout the world. Da Vinci™ surgery offers a number of advantages over standard laparoscopy: 3D magnified imaging, tremor filtering, motion scaling and restoration of all degrees of freedom which should allow surgeons to surpass the current limitations of human performance.

In the future the development of new instruments, reduction in the size of the system and improvements in ergonomics will likely result in wide spread dissemination of this technology.

ACKNOWLEDGEMENTS

This work was performed in the cardiac surgery unit directed by Professor Daniel Loisance. The program of robotic surgery was made possible thanks to the outstanding generosity of François Pinault.

REFERENCES

1. Satava RM. The Virtual Surgeon. *The Sciences*. 1998; 38 (6): 34-39.
2. Rassweiler J, Binder J, Frede T. Robotic and telesurgery: will they change our future? *Curr Opin Urol.* 2001; 11(3): 309-320.
3. RoboDoc. *Electronics Times.* April 30, 2001. available online at [http://findarticles.com/p/articles/mi_m0WVI/is_2001_April_30/ai_74093628/print].
4. Abbou CC, Hoznek A, Salomon L, Olsson LE, Lobontiu A, Saint F, Cicco A, Antiphon P, Chopin D. Laparoscopic Radical Prostatectomy with a remote controlled robot. *J Urol*. 2001; 165(6 Pt 1): 1964-1966.
5. Cadiere GB, Himpens J, Vertruyen M. The world’s first obesity surgery performed by asurgeon at a distance. *Obes Surg.* 1999; 9(2): 206-209.

6. Loulmet D, Carpentier A, d'Attellis N, Berrebi A, Cardon C, Ponzio O, Aupecle B, Relland JY. Endoscopic coronary artery bypass grafting with the aid of robotic assisted instruments. *J Thorac Cardiovasc Surg.* 1999; 118(1): 4-10.
7. Falk V, Diegeler A, Walther T, Bannusch J, Autschbach R, Mohr FW. Total endoscopic coronary artery bypass grafting. *Eur J Cardiothoracic Surg* 2000; 17 (1): 38-45.
8. Cichon R, Kappert U, Schneider J, Schramm I, Gulielmos V, Tugtekin SM, Schuler S. Robotic-enhanced arterial revascularization for multivessel coronary disease. *Ann Thorac Surg.* 2000; 70(3): 1060-1062.
9. Adhami L, Coste-Manière E, Boissonnat J. Planning and Simulation of Robotically Assisted Minimally Invasive Surgery. *ISER* 2001 [in press].