HUMAN
Robot Cooperation Techniques in Surgery

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Keywords: Medical Robotics, Human Robot Interaction, Human Machine Interfaces, Surgical Robots.

Abstract: The growth of robotics in the surgical field is consequence of the progress in all its related areas, as: perception, instrumentation, actuators, materials, computers, and so. However, the lack of intelligence of current robots makes teleoperation an essential means for robotizing the Operating Room (OR), helping in the improvement of surgical procedures and making the best of the human-robot couple, as it already happens in other robotic application fields. The assistance a teleoperated system can provide is the result of the control strategies that can combine the high performance of computers with the surgeon knowledge, expertise and will. In this lecture, an overview of teleoperation techniques and operating modes suitable in the OR is presented, considering different cooperation levels. A special emphasis will be put on the selection of the most adequate interfaces currently available, able to operate in such quite special environments.

1 INTRODUCTION

Technological evolution has continuously been introducing new equipments and changes in the Operating Room. Technology does not only affect real surgical interventions, but it also has a bear on all diagnosis and planning strategies, according to the diagnosed pathology. The history of surgery has suffered a continuous evolution through which three significant phases can be identified. They can be summarized in fig.1. From the practice of open surgery, fig. 1 a), in which surgeons get in touch directly with the patient organs or corresponding body parts, as purely manual actuation, the advent of new instruments and visualization techniques opened the era of minimally invasive surgery. Instruments with long handles allow entering the body through natural holes and small incisions over the patient fig. 1.b). This image shows the common scenario in laparoscopic surgery. At this stage, surgeons rely on instruments and specific equipment to perform surgery. The era of surgical robotics emerges as these instruments acquire new performances, or others appear in the scene, fig. 1.c).

New surgical procedures, not conceivable several decades ago, are more complex and require much higher performances. To face the challenges this kind of surgery relies on robots cooperating with humans, so as to extract the best of both of them. Humans provide intelligence and decision making while robots contribute with their precision, computing capabilities and no tiredness. In this context, with human and machines sharing the working scene, and the task itself, more powerful interfaces and interaction means become necessary.

Both, cooperation and interface requirements will depend on the typology of surgery. Speaking in terms of robotics technology and considering that technological needs vary enormously with the kind of surgery, surgery can be classified in: microsurgery, neurosurgery, intracavity and orthopedic, and percutaneous and transcutaneous interventions. As significant distinction among them, some characteristics, as the kind of tissue (hard or soft) or the body parts undergoing surgery, are to be considered.

Since hard tissues are able to maintain its shape, when they can be immobilized some techniques applied in industry can be exported to surgery, otherwise, a tracking system to dynamically determine the changing reference frames is required. Soft tissues present the problem of deformability, making robot operation more complex. In this case, teleoperation is an alternative solution.

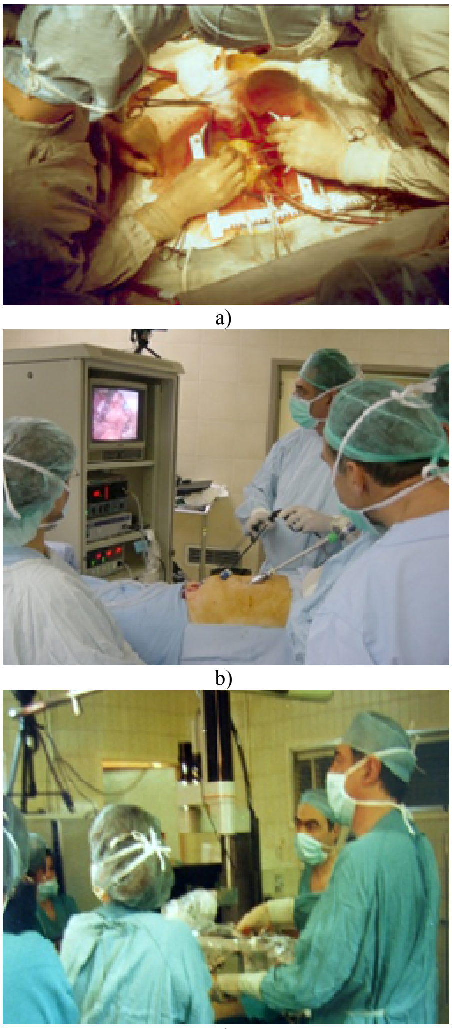
a)
b)
c)

Figure 1: Evolution of surgical procedures. a) open surgery, b) minimally invasive surgery, c) robot assisted surgery.

2 HUMAN ROBOT COOPERATION MODES

Human robot cooperation is implemented by means of teleoperation, therefore, a master device in the surgeon side controls a slave arm, a teleoperated robot, patient side. In between, a computer implements the required assistive functions that enhance human capabilities, resulting in a "super surgeon". Such assistive functions can be a change of scale, defining constrains within the working space, tremor reduction and movement compensation (breathing or heart beating) and so. The surgeon can be located in a close position, or in any other location, a few meters or some kilometers away. Fig. 2 shows a schema of such system.

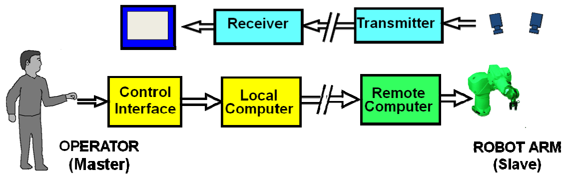

Figure 2: Schema of a teleoperation system.

However, the surgeon could also be in close contact with the robot, which guides and supervises his or her actions. In this cooperative mode, comanipulation, the surgeon hand and the robot end effector move simultaneously holding the surgical instrument. Working in these conditions, a change of scale or movement compensation is not an issue, but assisted teleoperation allows establishing constraints, virtual fixtures, operating over reference frames either fixed or floating over the patient anatomy. Comanipulation also allows directly perceiving both, images and the operating environment, what is especially useful in orthopedic surgery. The definition of virtual fixtures during the surgical planning facilitates a safer operation reducing the surgeon stress in critical interventions. Working with this configuration the robot itself behaves as a *haptic* device, Fig. 3.

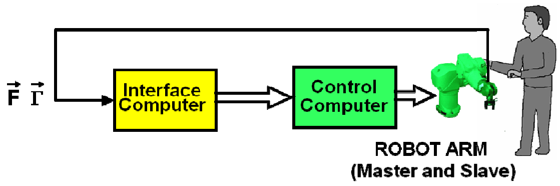

Figure 3: Schema of a comanipulation system.

The level of cooperation can also vary with the typology of the surgical interventions since the level of preplanning and programming varies depending on the predictability of the intervention. Three levels can be considered: manual guidance, supervised guidance and autonomous control.

The role of the interface in such cooperation systems is crucial as the surgeon cannot pay much attention to the robotic system, but to the patient and the own surgical procedure. A schema of the characteristics an interface should provide is shown in fig. 4.

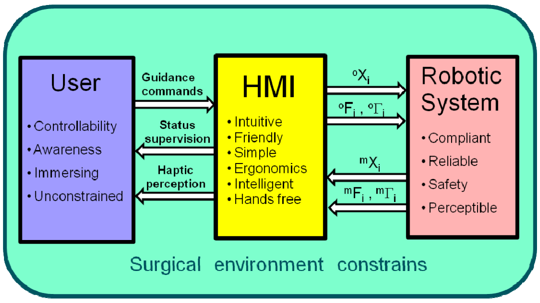

Figure 4: Schema of the characteristics of a teleoperation interface.

3 ROBOT ARCHITECTURES

Different surgical specialties work along different scale ranges and with different working requirements. Considering the variety of working conditions and from the robotics point of view, surgical procedures can be classified as follows: microsurgery, neurosurgery, transcutaneous, percutaneous, intracavities interventions and orthopedics. In what follows the main characteristics of each of them are described.

3.1 Microsurgery

Most interventions requiring microsurgery performances are related to sewing nerves in transplants or to ophthalmology. In this specialty, one or more high precision and high accessibility 6 Degrees of Freedom (DoF) arms are necessary. Additional DoF might be required to increase accessibility. As teleoperation assistance functions, a change of scale between the master and the slave increases the achievable precision as the application requires. Compared to former manipulators or holding devices used in classical manual practice, robots substitute them with advantage

3.2 Neurosurgery

Interventions in the skull also require high precision. However, its accessibility requirements are no so demanding since insertions are applied through incisions done just over the target area. In this case, movement compensation or floating reference frames are not needed as the skull can be fixed, with stereotaxis devices.

3.3 Transcutaneous

Some interventions can be performed through the skin and soft tissues using radiation focused over the target area. This radiation can be of different types: RX, Gama, or High Intensity focused US (HIFU). In such minimally invasive technique, 5DoF are enough to focus the therapeutic beam over a point in a 3D space, with any orientation.

3.4 Percutaneous

Relatively simple interventions as biopsy, aspiration, ablations or releasing therapeutic payload, are more and more used due to the few invasiveness of the technique. This technique implies inserting needles with high precision, to produce the advance and drilling movements when the needle is manually oriented into the insertion point. 5 DoF are necessary to place and orient the needle with a robot.

Taking advantage of this minimally invasive surgery or intervention, deflection and guided probes can be used to reach areas not easily reachable. Operating through natural ways, as the arteries, this technique is being used successfully to treat brain aneurisms.

3.5 Intracavity Interventions

When the intervention cannot be carried out by means of needles and more versatile instruments are needed with two, three or four DoF, endoscopic techniques are required. There are two endoscopic techniques, one based on the use of natural orifices (NOTES) and the second based on small incisions to access the abdominal and thoracic cavity (laparoscopy) or the joints between bones (arthroscopy).

These techniques were introduced in the seventies operating the instruments manually. At present, these instruments can be guided by teleoperated robots, so as they can take advantage of assisted teleoperation techniques. These robots should be multiarm (2, 3 or 4), each with several DoF, not only for tool positioning but also to increase accessibility and to make the pose of each arm compatible with the patient in the operating table.

NOTES are used in intra vaginal interventions, ear, laparoscopy for abdominal, prostate, heart, gynecology or arthroscopy, knee specially.

3.6 Orthopedics

Orthopedic surgery uses as end effectors drilling, cutting or milling tools to operate over bone tissues. These techniques are oriented to bone repair either with prosthesis implants, subjecting or immobilizing boards or to reconstruct bones with grafts after oncologic surgery, for example.

For these procedures CAD/CAM techniques can be used, with similar methods than those used in industry. Reference frames registration between anatomical elements in the operating table and the CAD model previously obtained from CT images are used to make task planning possible.

4 SENSOR REQUIREMENTS

Based on these different scenarios, robotics requires different kind of sensors to be able to implement the required control strategies. Two kinds of sensors are needed: 3D geometrical positioning sensors (navigators) and physical interaction characteristics (force and torque sensors).

Positioning anatomical parts in the 3D space is not simple, especially when dealing with not immobilized rigid elements, soft, deformable or rhythmically moving tissues. The success of surgical robots rely on their capability for adequately sensing positions either using physical contact sensors (optical or magnetic techniques) or remote sensing, specially vision. Current limitations of computer vision strongly condition its advances.

Apart from being able to control the robot, not only geometrical strategies are necessary to generate trajectories, but additional force control techniques are required to avoid injures, as for instance, necrosis. On the other hand, force sensors provide the information required to generate *haptic* information to be feedback to the surgeon. .

5 INTERFACES REQUIREMENTS

The requirements of an interface for surgical applications does not imply uniquely the interpretation of human will to control the teleoperated robot, but also to provide some feedback of the task going on to the surgeon. Thus, an interface constitutes a complete system, fig. 5, consisting of master devices adequate for every specific kind of surgery, actuators to feedback information to the surgeon, monitoring devices, and the computing power to process the information coming both, from the teleoperated system to provide the adequate information and from the human operator to provide the adequate control orders.

The schema of fig.5 shows that an interface can be a complete system that in some environments should provide certain intelligence level and, as indicated in the schema, even generate synthetic information to improve human operator's perception.

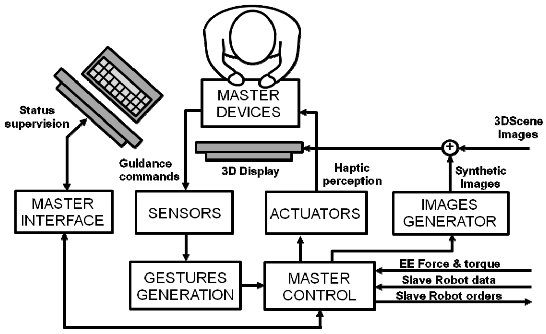

Figure 5: Schema of the master station in a teleoperated system.

Besides considering the best kind of master devices, either classical manual devices or hand free systems, the information coming from the robot side are key to achieve an efficient and smooth interaction. Feedback information can be either visual: direct images, augmented images or virtual, besides other kind of numerical and graphic data; or haptic, based on the force data measured in the robot working environment.

6 CONCLUSIONS

Interfaces are key components in teleoperated systems, or in robotic systems that work in close cooperation with humans. In the field of surgery, the surgeon faces the problem of dealing with complex systems while they are performing their own job, surgery. On the other side, their specialty is far from informatics and mechatronic systems. Thus, the design of a human robot interface in such fields should consider the three parts that compose the working environment, as shown in fig. 4, the user, the interface and the robotic system. While the surgeon has to pay complete attention to the intervention itself, the interface should provide the means of reacting to the humans' will, to interpret their needs, and to supply any kind of information that can help them to take decisions.

Teleoperation and its interface with the human operator can take different configurations according to the application needs, considering both, the distance from the master to the slave and the typology of the application. In each case, the availability of the required teleoperation assistance functions to improve human and system performances is essential. Together with such assistance, the information fed back to the user, visual, haptic or even sound, can be intelligently processed to constitute a significant help for the whole process.

BRIEF BIOGRAPHY

Alicia Casals is professor at the Technical University of Catalonia (UPC), in the Automatic Control and Computer Engineering Department. She is currently leading the research group on Robotics and Medical imaging Program of the Institute for Biomedical Engineering of Catalonia, and is member of the research group GRINS: Intelligent Robotics and Systems at UPC. The research is oriented to improve human robot interaction through multimodal perception, focused mainly in the area of medical robotics. In this field she is working both in rehabilitation, assistance and surgical applications. Her background is in Electrical and Electronic Engineering and PhD in Computer Vision. From 2001 to 2008 she was the coordinator of the Education and Training key area within Euron, the Network of Excellence: European Robotics Network, and RAS Vice President for Membership in the period 2008-2009. From the developed research projects she won different awards, Award to a social invention (Mundo Electrónico), International Award *Barcelona'92* (Barcelona City_Hall), *Ciutat de Barcelona* Award 1998 (Barcelona City_Hall), and *Narcis Monturiol* Medal from the Catalan Government as recognition of the research trajectory 1999. From 2007 Prof. Casals is member of the *Institut d'Estudis Catalans*, the Academy of Catalonia.