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Human-Machine Interface Evaluation in a Computer Assisted Surgical System*

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Abstract- **This paper presents an approach to the evaluation of two interfaces for the control of a robotic surgical assistant. Each interface is associated to a different mode of controlling the system: by the surgeon (voice commands) or by the assistant (tactile interface). This two modes are allowed by the design of the manipulator, developed to occupy a small volume in the operating room. To evaluate the interfaces, a rating scale for teleoperated systems is proposed.**

Keywords - Surgical robot, Computer Assisted Surgery, manipulators, teleoperation.

I. INTRODUCTION

During the last years, a new field has attracted the interest of robotic researchers. Minimally invasive techniques, such as laparoscopy, have grown as a very suitable domain for robotic systems. In this field, one of the easiest application for robotics is the movement of the endoscopic camera. Those robots [11] aim to move the camera from outside the patient's abdomen to get the image the surgeon wants to get from the patient's inside. This function has been traditionally performed by a human assistant, who follows the surgeon orders, for the latter to use his two hands for manipulation tasks. Since these procedures can last up to two (or even more) hours, the camera image can suffer a significant loss of stability, what can be prevented by the use of a robot arm [3]. Besides, it provides accurate movements to locate the optic within the abdominal cavity, and handles the endoscope with a steady hand during the surgical operation.

A review of the literature shows different ways of facing the development of a laparoscopic assistant. In [12], a complete system has been proposed, including a manipulator, a special end-effector to carry the laparoscopic camera and a new control strategy with an interface based on an instrument-mounted joystick. The HISAR system [6] presented a new configuration of the manipulator. Hurteau [10] proposed a system based on an industrial manipulator, modified by means of an universal joint between the end-effector and the camera holder. The system of Universitat Politècnica de Catalunya [2] presented a motion control system able to move the camera following the movements of marked instruments.

The Computer Motion's Aesop [14] is a commercial system intended to move the camera according to the surgeon's commands, first through a pedal and later through a speech recognition system. It is a 4 DOF robot arm attached to the stretcher, and presents an end-effector with three axes (two passive and one active). Many surgical procedures have been completed using this system, and it has received the FDA-approval. Another commercial device is the Laparobot [4] developed by EndoSista, in which the orientation is obtained by a remote centre of rotation scheme. The robot has to be placed over the patient in such a way that its centre of rotation is placed over the endoscope's insertion point.

A secondary use of these systems, and of many other Computer-Integrated Surgery (CIS) applications, is to extend the robot capabilities to the telesurgery paradigm. In general, robotized instruments can help us to achieve telesurgery, allowing an expert surgeon in a remote place (remote surgeon) to take part in the operation with some telepresence devices. In this sense, Green [8] developed a different concept exploring the possibility of a telesurgery scheme, suitable not only for minimally invasive surgery but also for open surgery. This telesurgery concept was later enhanced and taken to a commercial stage by Intuitive Surgical's Da Vinci system [9]. Remote control of such inspection systems are, however, especially useful for collaboration between specialist surgeons, for telementoring and for teleproctoring.

This paper presents a robotic system to assist in laparoscopic surgery by moving the camera according to the commands of a surgeon or an assistant. An evaluation is performed to compare two interfaces, associated with two different modes of control. To achieve this evaluation, a performance rating scale is proposed.

II. SYSTEM OVERVIEW

The system is based on the concept of functional modularity, obtained via some hardware modules. Fig. 1 below shows a general scheme of the system. There are three main modules: the Endoscopic Robotic Manipulator, the Teleoperation

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Module and the Extended Capabilities Module. Each one of those units provides one or more functionalities and they can, in principle, be used separately or jointly. The Endoscopic Robotic Manipulator (ERM) moves the camera in response to the surgeon commands; the Teleoperation Module allows a remote surgeon to collaborate in, or to surpervise, the operation; and the Extended Capabilities Module provides connectivity with other manufacturers' equipment and/or external databases.

The different modules communicate with each other via a wireless communication network, and other manufacturers' equipments can be incorporated to it.

The three main modules of the system are described below.

A. Endoscopic Robotic Manipulator

This is the main element of the system. It is a light manipulator, with three active DOF and two passive DOF, that moves the laparoscopic camera (see Fig.2). The controller is integrated in the robot base, which includes two batteries providing the power supply to the set. The surgeon has a wireless microphone through which he sends his commands to a local interface, a speech recognition system integrated as well in the robot base. Additional means can be incorporated as explained below.

The robot has been designed to occupy a small volume and not to need anchorage to the operating table. Those facts, together with the battery supply and the wireless microphone, make the system to be a wireless set, facilitating the integration into the operating room.

The robot local control is very simple: from the moment the power switch is pushed, the robot initializes and sends an oral message indicating that it is ready. There are two operation modes, depending on the optic being or not gripped to the end-effector. If the optic is not gripped, the commands are interpreted in cartesian coordinates to move the robot end to the desired point, and if the optic is gripped, they are interpreted as spherical movement commands with fulcrum compliance.

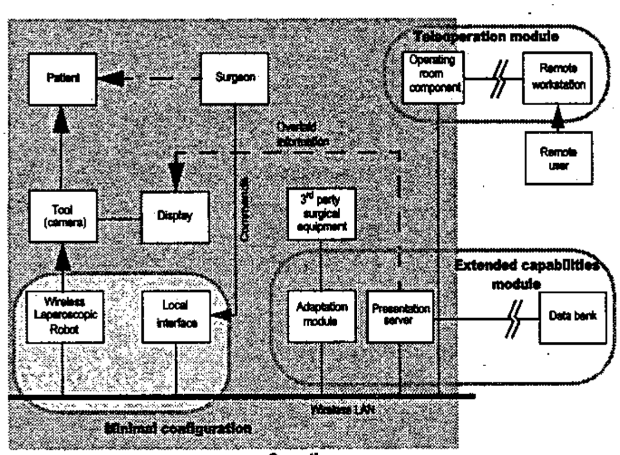

Fig. 1. An overview of the modular concept of the system.

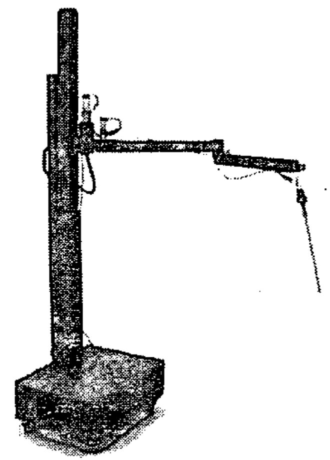

Fig. 2. The Endoscopic Robotic Manipulator.

Locating the fulcrum point is a key problem in robots with passive wrists. The usual approach is based on geometry, calculating the distance between two consecutive optic axis orientation vectors and assuming that the insertion point is located at the middle point of this segment. However, this approach does not compensate the fulcrum location imprecisions during the current motion. To solve this problem, an adaptive motion control scheme has been developed.

B. Teleoperation Module

This module allows telecollaboration between two surgeons, so that an expert may guide or supervise the operation performed by the surgeon present at the operating room. The target is to offer a tool making possible the joint work of two distant surgeons, by using standard TCP/IP networks. This limitation is intended to provide a wider range of applications, since a larger number of possible remote sites are available. Thus, concepts like telementoring (an expert teaches a novice), teleproctoring (a person supervises another one), or telediagnosis (a remote physician identifies a disease), can occur with the help of the same system.

To facilitate this work schemes, the remote surgeon gets the laparoscopic image, where he can make marks and comments. This information is sent to the operating room, where it is showed overlaid on the laparoscopic image on the video monitor. The remote surgeon can also take control of the robot to help the local operator to find the area of interest. Then, a procedure can be suggested. Besides, a videoconference channel allows communication between both surgeons.

To obtain the capability of moving the camera from a remote workstation, a telerobotic architecture has ben designed. This architecture is based on the one proposed in [7], and detailed in [5]. It allows local autonomy in the controlled robot, and since the trajectory generation and feedback control loop are local, the remote system teleoperation is stable under remote supervisory commands.

The implementation of this module consists of two parts: a component within the operating room and a remote workstation. The first element communicates with the rest of the operating room equipment via a wireless communication network, and with the remote workstation via another communication network, which may be a conventional one. That is, one of its purposes is to act as a bridge between the operating room network and other ones. Another purpose of this component is to overlay the marks in the laparoscopic image.

C. Extended Capabilities Module

The main component of this module is the presentation server. This element communicates with the local interface, via which the local surgeon can request information, such as previous patient explorations or documentation on the procedure in progress. Additionally, if the operating room has surgical equipment prepared for centralized operation, such as those of Storz™ or Stryker™, the surgeon can also control them using the local interface. In this case, and as long as a standard on communication of that kind of equipments is not adopted, it is necessary to incorporate an adaptation module.

III. Human-System Interfaces

Three control modes have been implemented in the system: local (the surgeon commands the movements of the camera via a voice recognition system), mobile (an assistant is in charge of moving the camera, as usual, but employing the robot instead of directly handling the endoscope), and remote (a supervisor or experienced surgeon guides a novice from a distant workstation, and can control the robot to position the camera properly). There is a different human-system interface for each control mode, and each one has been implemented based on a different technology. A short description is given below.

A. Local Interface

The purpose of this interface is to allow the surgeon control the robot while carrying out the surgical procedure. Several aspects have been taken into account -specially speed and ease of use- to design the user interface, in order to avoid new workloads for the physician, or new task that can delay the procedure. Finally, like in most of the robotic surgical assistants, speech recognition has been chosen to provide command input, since it constitutes a simple and intuitive way of controlling the robot. As the feedback loop is closed through a human operator and is still visual, the implemented commands are high level instructions of incremental displacements of the camera related to its own reference frame.

The implementation is based on a speech recognition module from Sensory Inc., integrated in the robot controller. It is trained to recognize a small set of commands like 'Move Up', 'Move Left', 'Move Out',... These commands must be trained previously with the surgeon's voice. This module is able of playing oral messages to confirm what instruction has been recognized and is about to be executed. The module is programmable in C-like language, so it can be also in charge of the local interface control, carried out in a very compact and simple way without the need of PC computers.

To provide the link between the surgeon's microphone and the speech recognition module, several methods -from cabled to wireless solutions- have been tested. DECT technology has the advantage of not being affected by other devices' electromagnetic noise, but it has, however, a poor frequency response for the application of speech recognition. The best results were achieved using an analog FM transmitter.

B. Mobile Interface

Most of the robotic endoscope systems proposed in the literature release the assistant surgeon of the task of moving the camera. The target is to achieve the *solo-surgery*, allowing a single surgeon to complete the surgical procedure, thus reducing expenses of health care. But some operations require the use of more than two tools -apart from the endoscope- at the same time, so the help of an assistant is mandatory. In these cases, the assistant could be kept in charge of the camera even in the presence of the robot. A user interface should then be provided for the use of a second person.

The implementation of such an interface could be based, as the Local Interface mentioned above, in speech recognition. The problem is the lack of capacity of most (if not all) available modules to cope with two different users at the same time. Then, to allow the operation of the robot by the surgeon and the assistant, a new interface has been designed.

The Mobile Interface is intended to offer a versatile graphic user interface (GUI) to the system. It is based on a Palm™ Tungsten T™ PDA connected to the robot controller via a BlueTooth link, running a set of specially designed applications. Its characteristics include sending commands but also receiving and presenting data, although this capability has not been used in the work presented in this paper. Another feature is the use of a long distance GSM/PCS link to allow distant users the retrieval of data from the robot, for instance for supervisory purposes.

The Mobile Interface (i.e., the PDA) has been attached to the robotic arm beside the passive wrist, so that the assistant surgeon can easily access to the tactile display. This one presents a set of buttons, every one of them associated to a high level instruction ("Move Right", etc.). To prevent mistakes, the arrangement of the buttons and of the PDA itself must be coherent with that of the monitor showing the image of the endoscope.

C. Remote Interface

The possibility of being supervised, or simply getting advice from an experienced surgeon, is a very desirable feature from the point of view of the physicians. Thus, telecollaboration capabilities have been incorporated to the system via a Remote Interface. Besides the usual functions to enter commands, a way of interaction between both surgeons (local and remote), must be provided. The chosen way has been the endoscopic video image: the remote operator receives the laparoscopic image in the workstation, where the user interface allows an overlaid graphical annotation system. These marks are sent back to the operating room, where the local surgeon can see them on the standard laparoscopic video monitor. Also, a video-conference channel is available for a more natural communication.

While the local user (surgeon) interface allows verbal commands, the remote user (experienced/mentor surgeon) can control the arm in two ways: sending the same commands than the local surgeon ('Move Left', 'Right', 'Up'...); or clicking on the endoscopic image. In this case, the robot moves the camera in order to centre the image on the selected point.

To offer to the experienced surgeon the possibility of working from the widest possible range of locations, the Remote Interface has been implemented on a standard PC computer, with only a few variations. The main modification is a dual monitor, which gives a larger field of view, and showed to be more convenient in a preliminary series of experiments (see Fig. 3). However, a single monitor is also suitable.

A standard mouse has been selected as input device due to its ease of use and integration with the operating systems's GUI. It is used for graphic annotation and for sending robot motion commands. These commands can be issued by means of a single mouse click on the new target point. Insertion/extraction commands are issued using the now standard mouse wheel. It is also possible to select special robot commands from a context-sensitive menu, or using the keyboard.

A PC-based module located in the operating room provides the connectivity between this place and the rest of the world, managing the communications through a standard TCP/IP connection, as well as overlaying the graphical information from the remote user.

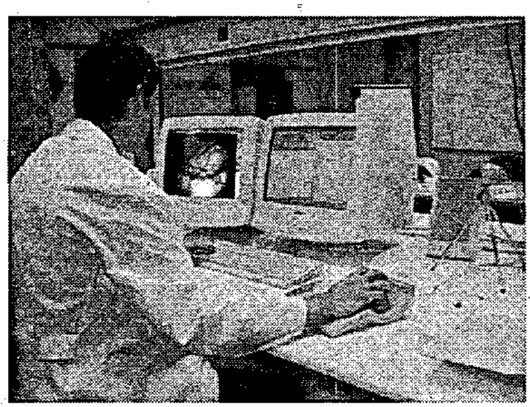

Fig. 3. The dual remote workstation display

IV. Experiments and Evaluation

Performance evaluation in teleoperated systems -as surgical robots might be considered- is limited by the presence of a human in the control loop. Getting an objective measure of the capabilities of a system without considering those of the human has attracted a lot a attention in many works devoted to telerobotics, and now to surgical robotics. In this discipline, one of the first key issues has been to compare the performances of a surgical team including a robot to those of an all-human team [13]. However, a problem arises when the robotic team can achieve some goal that has no meaning for the all-human one, for instance when remote telecollaboration schemes has to be evaluated. In these cases, subjective opinions from the participants in the experiments or completion times are the only measures available, limiting the capability to separate the tested system characteristics from the human ones.

Nevertheless, this kind of evaluation (i.e. on a system incorporating a human in the control loop) are quite usual in fields like aeronautics. Pilot ratings have been employed from the 1960s to assess whether a device is helpful for a pilot or not, and they are almost a standard in defence activities [1]. One of the more common ratings is the Cooper-Harper Handling Qualities Rating Scale for measuring the handling qualities of an aircraft as a function of the pilot workload. A very similar approach is followed by the Bedford Scale, used to qualify pilot workload for tasks that do not involve flying qualities. Both scales are very similar in concept, obtaining as a final result a number from 1 (the best result) to 10 (the worst qualification) as a function of the difficulty in achieving the task and the spare capacity/level of effort.

This paper proposes a rating scale for evaluating devices or characteristics in teleoperated systems, in particular in surgical robotics. Since a surgeon has a very clear definition of the primary task (to operate the patient), but some other task must be accomplished during a surgical procedure, the proposed scale (see Fig. 4) has two levels of definition: related to the completion of the primary task and related to secondary tasks. As a function of the user workload and the fulfilment of primary and secondary tasks, a rating between 1 and 6 is obtained.

This rating scale has been used in a set of experiments designed to evaluate the described Local Interface and Mobile Interface in the ERM system. Beside this scale, some other measures have been acquired, like times or number of required instructions. A brief description of the experiments is given below.

A. Experiment 1

The goal in this experiment is to grasp small objects within a surgical simulator and to leave them in specified positions. Manipulating the objects is the primary task, while identifying the desired location of the part is the secondary one. The list with the designed point for every object is fixed to a side of the standard video monitor. A view of the surgical field is obtained

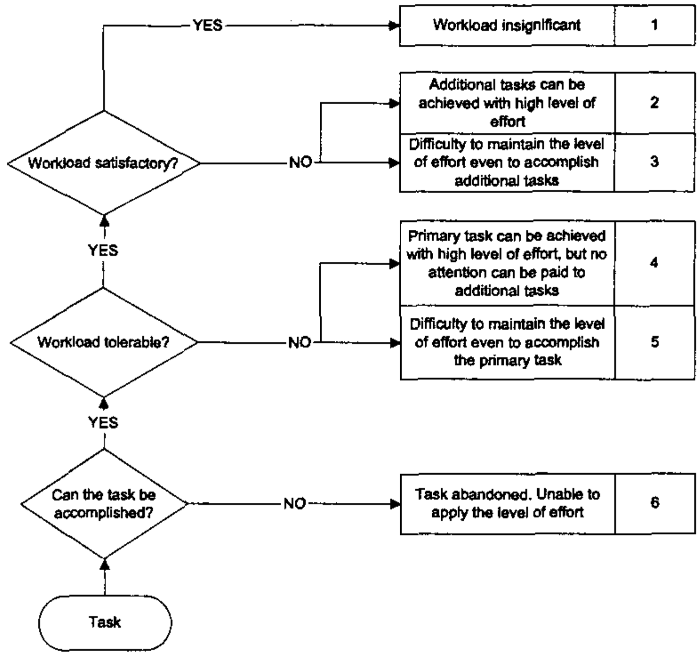

Fig. 4. The proposed rating scale.

through the camera attached to the ERM system, and presented in the mentioned monitor. The robot is controlled in two different ways: a solo surgeon using the Local Interface (voice recognition), and a two persons team, with an assistant entering the commands by means of the Mobile interface (PDA). Five different users with variable grades of experience in surgical tasks and in using the ERM system have performed the test. Experience is described with a number from 1 (novice) to 5 (expert). After completion, they have assigned a scale according to the proposed rating. Additional measures include time to finish, number of instructions and -in the Mobile Interface mode- number of verbal indications from the surgeon to the assistant. The users were told to avoid this instructions while possible. Tables I and II show the results of the experiment.

B. Experiment 2

To add a stronger workload, the target in this experiment is to guide a small peg through a three-dimensional path attached to a platform, which is held by the surgeon and the assistant. The path is located inside the surgical simulator, and both members of the team use a laparoscopic tool to grasp a part of the platform. Guiding the peg is considered the primary task, while holding the path is the secondary one. Then, a very good coordination is needed to achieve both tasks. The surgeon must move the peg, but must also hold the platform and, if the Local Interface is being used, he must control the robot. The assistant commands the movements when the Mobile Interface is used, but another task (holding the path) is always present. Five teams have performed the experiment, again with different levels of experience. After finalization, all users decided what rating to select according to the proposed scale. Additionally, the same measures than in Experiment 1 were acquired. Results are shown in Tables III and IV.

V. Discussion and Conclusions

Results show good ratings for both interfaces, higher for Experiment 1 (less workload implicit in the tasks). A little advantage is noticed for the Local Interface in this experiment, possibly due to the light workload. It must be noticed that this ratings were obtainde despite users had a shorter experience both with the robot and on the task. However, faster times were registered for the Mobile Interface, since it allowed a better sharing of the -already low- workload.

In Experiment 2, experience of users played a major role in obtaining good outcomes. A less experienced team was unable to complete the experiment both with the Mobile and the Local Interface. The Mobile Interface was the preferred option in view of the ratings for all users. It has been a remarkable advantage a good coordination between both members of the team, but sharing of the workload was more balanced since the assistant was responsible for the camera.

Summarizing the results, the Local Interface was successful when low workload was a characteristic of the task. When it was not so (as it would happen in a surgical operation requiring more than two instruments apart from the camera, i.e., when the presence of an assistant is mandatory), the Mobile Interface was the preferred option, particularly when a good coordination exists.

TABLE I

EXPERIMENT 1: LOCAL INTERFACE

Surgeon	Experience (robot)	Experience (task)	Time	Number of instructions	Rating
1	4	3	2m55s	34	1
2	2	2	3m40s	60	1
3	2	3	3m25s	46	1
4	1	1	6m15s	52	1
5	4	2	2m32s	33	1

TABLE II

EXPERIMENT 1: MOBILE INTERFACE

Team	Experience with the robot (surgeon/ assistant)	Experience on the task (surgeon/ assistant)	Time	Number of instructions	Indications from the surgeon	Rating
1	4/2	4/4	2m10s	49	0	1/1
2	3/4	4/4	2m22s	47	0	1/1
3	2/4	3/4	3m	49	3	2/1
4	4/2	4/3	2m15s	52	0	1/1
5	4/2	4/4	2m25s	52	8	1/1

TABLE III

EXPERIMENT 2: LOCAL INTERFACE

Team	Experience with the robot (surgeon/ assistant)	Experience on the task (surgeon/ assistant)	Time	Number of instructions	Rating
1	4/5	3/4	Fail	-	6/6
2	4/5	4/5	2m45s	24	2/1
3	5/5	5/5	2m40s	22	1/2
4	5/4	4/4	2m50s	27	1/1
5	5/4	5/4	2m38s	29	2/1

TABLE IV

EXPERIMENT 2: MOBILE INTERFACE

Team	Experience with the robot (surgeon/ assistant)	Experience on the task (surgeon/ assistant)	Time	Number of instructions	Indications from the surgeon	Rating
1	4/5	3/4	2m20s	23	0	1/1
2	5/4	4/4	1m55s	25	0	1/1
3	4/5	2/2	4m50	67	3	1/2
4	5/4	3/3	Fail	-	-	6/6
5	5/4	3/3	4m23s	79	12	1/2

As a conclusion, a test has been proposed to measure the performance of teleoperated systems, specially in those cases where the tested system is intended to provide new capabilities not previously available. This test is an adaptation of those employed from many years ago in the aerospace industry for estimating the handling qualities of aircraft and related devices and systems. The proposed evaluation has been employed in the comparison of two different interfaces for a surgical robotic system, the ERM, not only to obtain results about the accomodation of those intruments, but also to get information about the feasibility of the test itself. From this point of view, a certain amount of the usual subjective perturbation in the estimation of performances in teleoperated systems has been avoided. However, to improve the measure of performances of the interfaces, new experiments are planned including more variation in the workload of the users.

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