Intuitive Graphic Interface for Assisted Teleoperation in Surgical Applications

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***Abstract*—Human-Machine interfaces constitute a key factor to guarantee the effective use of technological equipment. In the field of image guided surgery and surgical robots, the availability of an adequate interaction means determines the suitability or not of a given technological aid. This work focuses on the problems surgeons find in planning and executing a robot assisted intervention. Analyzing the potential of computer graphics, together with the surgeons needs during, first, the planning and later on the development of a surgical intervention, the specifications and the implementation of an interface is described. In the design of this interface, special attention has been put on the gesture and attention capabilities that surgeons can devote to the interface.**

I. Introduction

Robotics starts to become a common practice in some surgical areas. However its introduction in the Operating Room (OP) advances slowly due to some problems that prevent its wide dissemination. The main problems to be faced are those related to task definition and to the capability of referring robot, patient and other elements to a given reference frame. In some specific types of surgery, in which the anatomical part undergoing surgery can be immobilized, as in the case of skull, task programming is quite feasible. However, when dealing with parts which still position cannot be guaranteed, robot programming should rely on positioning systems making the programming and operating process more difficult. In orthopedic surgery this problem appears in parts as hip and knee surgery, which cannot be immobilized. The problem is aggravated when dealing with soft and deformable organs. In this situation a previous task planning and programming is not feasible and thus, robotic systems should rely on teleoperation. This operating mode allows the surgeon, deciding and defining each action according to the evolution of the task going on. The human operator can see the scene and eventually can receive other additional feedback to react intelligently. The robot executes the received commands, improving efficiency when some assistive operative performances are available. As a consequence of the tight human-robot interaction, the interface becomes an essential component of the whole robotics system.

Graphical information can complement the semantic contents of control orders, especially when dealing with robotic systems. Free hand interfaces are of special interest in the surgical field since surgeons have their hands busy with instruments and the gloves they wear constitute an additional inconvenience to deal with classical interfaces. Most interfaces require physical contact and mechanical interaction through a master device. They, together with those interfaces that use gloves for gesture recognition are unacceptable in the surgical environment.

Free hand operation is usually related to interaction systems relying on oral interfaces. However, although voice communication can be very useful in some application areas, it can result inefficient in others due to its limited semantics, when restricted to a short vocabulary or reduced set of commands. These limitations affect even more in robot assisted orthopedic surgery, where stronger interaction requirements appear. This kind of surgery can take advantage of systems operating with virtual fixtures (VF), which constitute computer tools that alleviate surgeons from the pressure they suffer in some interventions and to facilitate their work. VF are useful, either to protect critical areas or to assist surgeons in trajectory guidance. VF have to be defined by the surgeon *a priori*, or even on-line, if the interface offers this facility.

Referring to oral communication, although its use in MIS has proved to have some limitations due to the sensitiveness to the speaker's emotions, some efforts have been done to make oral recognition independent of stress, fatigue or other causes of voice modulation. In [1] some robustness is achieved using a high dimensional acoustic feature space. Nevertheless, referring to surgical robots, only simple operations have been reported, as camera guidance in laparoscopic surgery, using oral orders. In [2] a study is done on pros and cons of current interfaces and their suitability in surgery, considering not only the need, or not, of the surgeon hands to interact, but also the attention the interface requires from the user. Among existing interface techniques, gestures constitute an alternative means to communicate with a machine in a natural and intuitive way. A multimodal system is described in [3] combining oral local communication to guide the camera with simple qualitative orders; a mobile interface that offers a Graphic User Interface (GUI) that can even be controlled remotely; and finally a remote interface conceived for an experienced surgeon that can assist the local physician. The possibility of focusing the attention to speech only when required is tackled in [4], based on eye contact and contextual speech recognition. In [5] the free hand concept is tackled considering the needs to be solved using gestures: gesture detection, action generation and the association between gestures and actions. To cope with the limitations of the above mentioned interfaces, and focusing on the needs encountered in robot assisted surgery, mainly orthopedics, a gesture based interface system has been developed.

Analyzing the potential of computer graphics, together with the surgeons needs during, first, the planning and later on the development of a surgical intervention, the specifications of a dedicated interface determine its efficiency. In the design of this interface, aimed to be quite dependable, main attention has been put on the gesture and attention capabilities that surgeons can devote to the interface. It is aimed to cope with the limitations of common graphic interfaces and focuses on the needs encountered in robot assisted surgery, mainly orthopedics. This interface combines two modalities: one semantic, based on the use of menus, and a second one graphic, which complements the former by improving its capabilities and efficiency by reducing the time required to define the actions and orders to be given.

Considering that for some surgical procedures, robotic aids may represent the difference between success and failure, the need of having available useful tools to interact with these devices is evident. Thus, the developed system is oriented to the control of tools such as: grippers, scissors, holders, catheters… which are controlled by electromechanical or robotic systems, providing a means to operate with more ergonomic control capabilities. The proposed interface relies on a methodology for the definition of virtual protections with complex surfaces (for instance, those extracted from medical images) in a simple way and to modify the model of the protection in real time.

Thus, the main goal of the interface is reducing tiredness and stress to surgeons during an intervention and at the same time increase patient's safety thanks to the added performances, virtual boundaries and robot guidance and surveillance.

The paper starts with some considerations on the typology of typical graphic commands. Section III introduces the concept of using constraints that according to the task restrict operation movements. Such constraints limit operation but do not threat the execution of ongoing tasks. Based on the typology of movements' constraints, a reduced set of commands has been selected and from them the interface operability is described. The paper finishes with an indication of its application and with some comments on the evaluation process.

II. Typology of Commands with Graphic Support

Some simple orders can be given operating "free-hand", by means of oral communication (voice recognition), but they can become useless to perform guidance tasks in which the orders necessary for the control of the system have a much wider pass band than that achievable using oral commands. Furthermore, oral communication would become very noisy under these conditions. Other devices can complement oral information, but for complex orders no good enough solutions are commonly found.

Alternatively, gesture based orders are very efficient and intuitive to the user. Gesture, as voice, also constitutes a natural language. Gesture commands can either rely on a mechanical support such as joysticks, 6D devices or so, or operate "hands free". In this case, either inertial sensors or those relying on magnetic or optical technology are considered [6, 7]. However, in spite of their good performances they have some drawbacks as they demand sometimes uncomfortable postures from the user, mainly if the task to be carried out takes place around complex geometries.

In order to deal with such limitations, a graphical complement allows the user to rotate, move, approach or move away the visualized working space, or generate and edit surfaces within this workspace.

The former actions are oriented to have the best point of view available at any moment, while the latter is aimed to generate virtual fixtures that behave as protection surfaces or as guiding surfaces to help in instrument guidance.

The most common 3D graphical interfaces which allow the user to move the controlled element in X,Y and Z directions and to rotate them over these three axes, fig. 1, are used without much difficulties by users of CAD systems. However, they become extremely tough to users less accustomed to such computer systems. Moreover, the enormous versatility of these interfaces usually brings such users to desperation, when he or she sees something rotating undesirably, or when due to bad luck an object rotates erroneously, or if by mistake a rotation is produced in two consecutive axes. In these situations, in most interfaces, there is no way to return to the "stable" initial position without an enormous effort that takes time and requires high attention. All these factors produce unacceptable situations that surgeons cannot admit during an intervention.

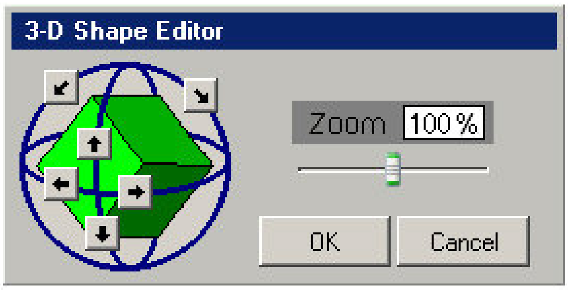

Fig. 1 Usual 3D commands in CAD environments

III. 3D Graphic Commandment System with Imposed Constraints to Facilitate their Operability

After a common work together, engineers and surgeons, a graphical interface has been established which is highly simplified compared to those used by CAD designers. In contrast with common computer interfaces that provide many options, as the one shown in fig. 2, causing too much burden to surgeons, more concerned in the intervention than on the computer tools, the designed interface provides an easy interaction with a much reduced menu than those commonly used. This menu, based on flip flop operating icons, type activated/deactivated, consists of two independent blocks, which are independently activated.

They are:

- Visualization block (change of the observation point)
- Commands block, for the generation and edition of constraints

These constraints are oriented to define or modify the limitations of the working space during the robotized actuation of the surgical instruments, with two main goals; to guarantee patient safety and at the same time reduce the stress that surgeons suffer when operating close to critical zones. Fig. 3 shows the interface designed in common agreement with the medical team. It has been conceived to be operated by means of gestures.

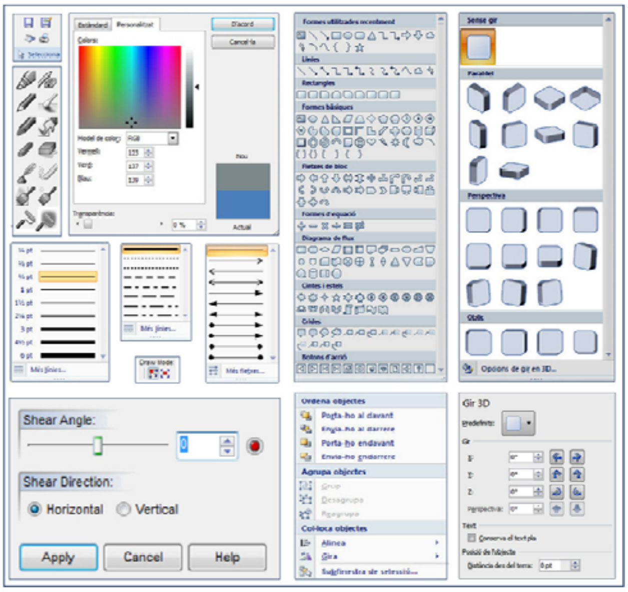

Fig. 2 Menu used in the graphic interface

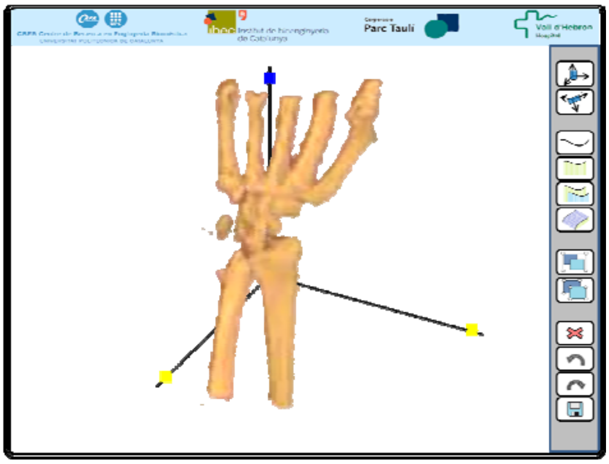

Fig. 3 Menu used in the graphic interface

This gesture based interaction relies on a stereoscopic vision system developed within the research team, [6] that locates the operator hand in front of the screen, emulating a mouse. Besides its location, the system models the hand in such a way that it can determine two different states: open-hand or closed-hand. These two states emulate the mouse click, as well as the double click, with the close-open-close hand, at speeds that can be adjusted to each user.

The developed system allows the user moving any element in space and visualizes the sticking point (when closing the hand). This action is indicated with a yellow point (picking point). If the picked element has available a constraint in one degree of freedom (for instance a rotation over a point) these constraints are visualized with a blue point. Therefore, with the yellow points-blue points code, the selected object can be moved, either in the free space or leaning on a point or an edge.

To improve the efficiency of the vision system (gesture based mouse) and be able to lock the cursor movement at user's will, a pedal is used that activates the vision when pressed and deactivates it when released.

In what refers to computer facilities, the interface offers the user the possibility of generating any kind of constraints. Thus, the software tools allow the user to generate lines (straight or curves) that can be used as trajectories, the user can convert or generate surfaces (flat or curved) and by aggregation of surfaces the user can configure three-dimensional limits, which bound the working space that contains the robot end-effector.

IV. Reduced Set of Commands for Interactive Surface Generation

The accessible working spaces that a surgeon generates are composed of elemental surfaces that can be further composed together so as to generate the desired volume. Later on, they can be modified at the surgeon's will. This task, operating in normal conditions in 3D CAD environments, takes some learning time; a too long and tough process for non specialized users. The large range of possibilities these systems offer carry with them the need of spending great learning and training efforts that most of health professionals are not prone to undertake.

For these reasons, the interface designed has been conceived to be very simple and intuitive, allowing the user to generate all the characteristic restrictions usually needed in orthopedic surgery. The criterion that has been followed to generate such constrained spaces is to provide tools to configure them from surfaces, being these surfaces generated from generatrix lines.

Under these premises, if it is necessary to define a simple trajectory corresponding to a cut, the surgeon has to trace a trajectory over a 3D model (MR, …) fig. 4a. This trajectory, using n reference points will generate n-1 segments, calculated trigonometrically from a space dimension R^2, the composition of which will generate a spline line.

$$[X]=[A]+t\cdot[B]$$

Once the trajectory is described, the surgeon can convert that line to a plan π, when dealing with straight lines or a surface otherwise, Fig. 4b. That conversion is provided by equally increasing the same coordinate value of the n points of an existing line (duplicating it), and composing the m segments between them.

$$\pi \Rightarrow ax+by+cz=d$$

The generation of a surface that contains a line constitutes an undetermined problem, and consequently, it is necessary to define additional conditions, such as determining a passing point in space or defining an orientation from which a growing process starts. In order to simplify this operation, the developed system presupposes that this surface has to be formed perpendicular to the visualization plan. This simplification is possible since it has been observed that surgeons place the vision plan in a position frontal to the cut to be done. This assumption is also extended to the election of the semi plan defined by the generatrix line, since usually the direction of the cut to be performed is from outside to inside the screen and any observation has indicated that it happens in the opposite direction. Anyway, this automatic assignation of an orientation in the 3D space is equivalent to an assignation by default, since the user can correct this initial orientation by "picking" the generated plan from any point external to the generatrix line (then appearing a yellow point as indicator). This point can also be moved in space.

These corrections are equivalent to a reconfiguration of this plan in the 3D space according to its new orientation, using a single-axis rotational matrix and its movement configuration and composition.

$$(X' \quad Y') = [X \quad Y]\begin{bmatrix} \cos a & \sin a \\ -\sin a & \cos a \end{bmatrix}$$

Therefore, this semi surface generation is assisted by the designed interactive interface, since it minimizes the number of actions to perform, which are tedious and even unacceptable by qualified personal staff, which do not belong to the world of geometry and informatics. Once the semi surface has been traced, the surgeon can convert this constraint to a bilateral constrain, by clicking the duplication function and positioning it, a new surface, which is parallel to the previous one, fig. 4c.

Usually, this visual protector of the cut to be done is also complemented with a new surface, the depth limit. A final click action over the "grouping" function forms an "allowed" work space.

In this way, and through a successive aggregation of limiting surfaces, it is possible to configure a restricted work space that impedes the access of the surgical instrument to the protected parts, when a robot is controlled in comanipulation mode.

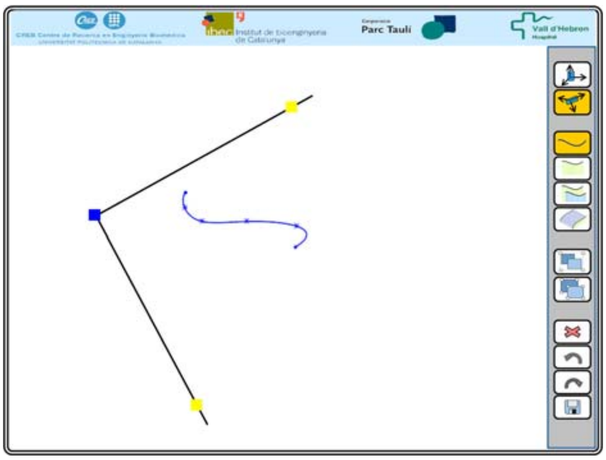

Fig.4 a) Frontal view of a line with some passing points

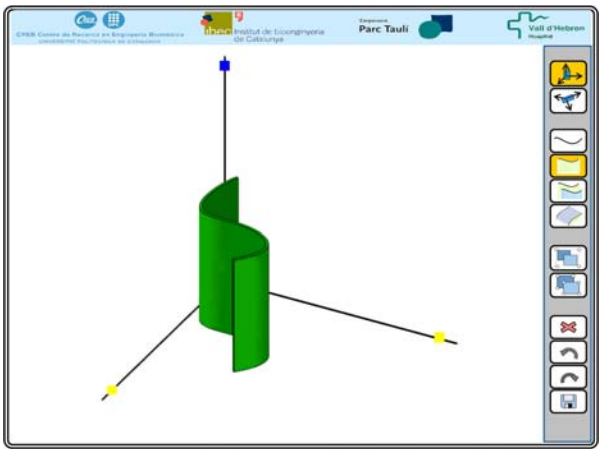

Fig. 4 b) View of the image with a line that has grown down to the X,Y axis to become a surface.

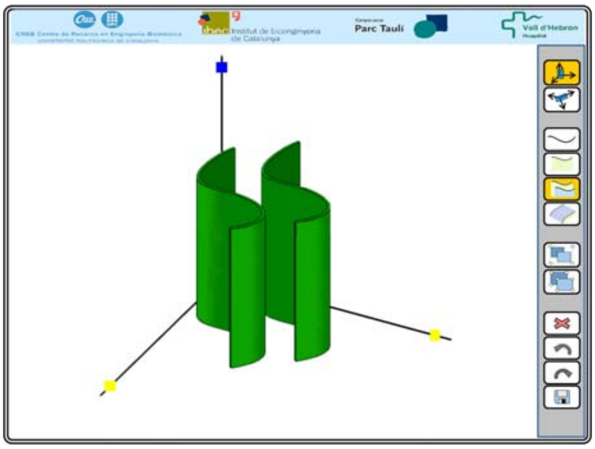

Fig. 4 c) Bilateral constrain generated by plane duplication

V. Application to the Generation of Virtual Fixtures in Orthopedic Surgery

This interface has been evaluated in the implementation of different operations in the laboratory, using animal skulls, Fig. 5, having achieved very precise cuts, Fig. 6.

A good intervention type that can benefit from this interactive assistance is maxillofacial surgery, in operations of bone reconstruction in oncology. The procedure consists in extracting a piece of the tibia bone to graft it in the affected jaw. In this case, the formation of a cut line can be done in a much precise way. Using the same defined pattern, both in the tibia where the bone tissues are extracted and in the jaw where they are grafted, the extracted tissue can be adjusted to the shape and size of the volume of the affected jaw, and thus, the graft fits better.

These VF can be, as well, of utility as a safety protection over critical elements as can be the facial nerve. For such applications the benefit of VF is mainly the reduction of stress that the surgeon suffers when approaching such elements, and indirectly, gaining in patient's safety and efficiency.

Fig. 5 Test bed for experimentation

Fig. 6 Detail of a cut operation

VI. Evaluation of Acceptability

The evaluation of the interface by different professional staff has provided some inputs to estimate its operability and acceptability. A significant parameter evaluated has been the time spent in the definition of a cutting restriction defined over a plan, as shown in fig. 7, programmed in a previous planning phase. Two issues are evaluated; first, the difficulties each operator founds in converting the described plan or surface into a bilateral space, that is, a corridor comprised between two surfaces, and second, in defining a bounding surface that limits the depth of the cut to be performed.

With the commands available in the interface, shown in fig. 3, the operation times obtained from different users are shown in fig. 8. It can be clearly observed that the learning factor, for task implementation (not the commands), does not represent a dramatic time reduction. Thus, it can be seen as an index of the simplicity in its use.

Due to the characteristics of this graphical interface, these interaction orders can be given by means of gestures. Thus, the three dimensional information of the surgeon hands movements is used to interpret intuitive gestures for the definition of, for instance, planes, pushing or steering points, and pointing. Thus, through the natural language of gestures the interface gains new performances.

Gesture based control is additionally of high interest in surgery since surgeons have their hands busy with instruments, and sterilization requirements produce conflict situations if they have to physically touch screens or other equipment.

VII. Conclusion

From the conviction that the interface is a critical part of robot and computer assisted systems, this work has focused on the needs of a particular kind of robotic or teleoperated (or comanipulated) systems. The interface has considered a limited number of actions to be performed with the hand and has designed an interface that facilitates an ergonomic operation.

Placing and orienting adequately the elements to be visualized and the movements to be carried out by the surgeon it is possible to avoid too large turns or rotations, thus improving ergonomics. In what refers to the required user's attention, and thanks to the reduced number of remaining actions, the identification of the minimum number of icons and their type, oriented to this application field, the interaction becomes friendly, intuitive and easy to learn.

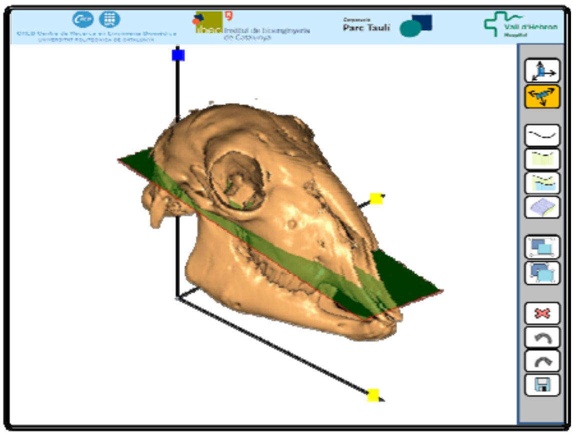

Fig. 7 Anatomic image with a restriction plan inserted

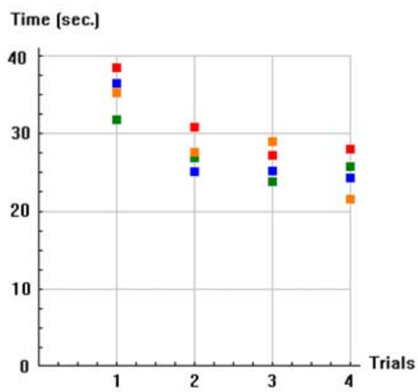

Fig. 8. Time spent in successive test trials by four different users

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