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An Application of Artificial Intelligence to Medical Robotics

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Abstract. In this paper an application of Artificial Intelligence (AI) to Medical Robotics is described. Namely, a specific AI technique is employed to generate a sequence of operations understandable by the control system of a robot which is to perform a semi-automatic surgical task. According to this technique, a planner is implemented to translate the “natural” language of the surgeon into the robotic sequence that should be executed by the robot. A robotic simulator has been implemented in order to test the planned sequence in a virtual environment. The planned sequence is then to be input to the medical robotic system, which will execute the surgical operation. The work described in this paper features a high level of originality, since no similar applications of AI to medical robotics could be found in the scientific literature.

Key words: ontologies, STRIPS, robotic simulator, medical robotics, neurosurgery, planner, artificial intelligence.

1. Introduction

Applications of Artificial Intelligence to Medicine have been increasing in the most recent years. Artificial Intelligence has been employed in the medical field mainly to perform a rational analysis of the data available from clinical examinations (such as Computerized Tomography, Nuclear Magnetic Resonance, Digital Angiography, etc.) in order to get a reliable diagnosis of the patient’s disease and a suitable decision support.

On the other hand, the set of Artificial Intelligence (AI) techniques used here has never been applied so far, to our knowledge, to the field of medical robotics. Indeed, the idea of employing such techniques in this domain appears quite a promising one since it is very difficult to “translate” the intentions of the surgeon, which are thought and expressed in “natural” language, into a sequence of operations executable by the medical robot, which must be expressed in a way understandable by the robot controller.

The task of AI is thus to provide a bridge between these two different worlds, namely the “natural” world of the surgeon and the world of the robot.

In this paper, we describe a methodology to apply some AI techniques to the task of performing semi-automatic surgical operations by means of a medical robotic device.

The methodology described in this paper is not intended to substitute the existent medical robotic systems, but rather to integrate and assist such systems. Indeed, in this work we propose an intelligent module that can generate the trajectory the medical robot will have to follow in order to perform the surgical task. The trajectory will then be input to a robotic simulator, that will allow the surgeon to monitor the whole operation; finally, the medical robotic device will execute the trajectory and thus perform the surgical task, while meeting all the standard requirements concerning safety and accuracy of the operation.

The paper is organized as follows: in Section 2 we provide an extensive description of the state of the art in the field of medical robotics; so, the most important existing robotic systems aimed at performing surgical operations as well as other medical tasks are mentioned and described, together with the possible and interesting developments in this domain.

Section 3 describes an intelligent system to simulate surgical operations. The proposed AI technique uses ontologies to represent surgical instruments and employs a specific linear planner (STRIPS) to represent the world, as described by the natural language of the surgeon, in a way that can then be analysed by means of well-known AI approaches. A neurosurgical operation is then taken as a test case, and its planning phase is performed by means of the STRIPS algorithm, which is based on logical formulae that describe the natural world and, more specifically, the sequence of operations necessary to perform the surgical task under analysis.

Section 4 describes the planning of the operation, which is subdivided into several steps according to AI criteria. The operation can then be simulated in a dedicated virtual environment that has been designed and implemented *ad hoc* in the Java language. In order to show the effectiveness of the proposed intelligent system, a commercial robot with a simple and well known kinematics, rather than a dedicated medical device, has been chosen for application of the planning task. The robot chosen to carry out the surgical task is a commercial Puma 560 robot, and the whole planning task has been applied to such a manipulator.

2. Medical Robotics: State of the Art

Until very recent times, research in robotics was aimed at developing applications in the industrial domain. Only in the last years the utility of the robots in medical and surgical applications was understood and many applications were set up.

The first applications of automatic systems in medicine were bound to diagnostics: in the 70’s automatic clinical tests, such as CT (Computerized Tomography) and NMR (Nuclear Magnetic Resonance) were introduced with the support of a computer able to elaborate and to transform the clinical signals into images.

In the 80's the computers capacity improved, so that they could elaborate high resolution three-dimensional images. However, virtual reality simulations were set up, that allowed to study clinical cases and perform simulated interactions.

The first medical robots were introduced in the 90's. In 1994 Computer Motion Inc. built the robot AESOP1000 (Automated Endoscopic System for Optimal Positioning) that could be used in the endoscopic surgery to automatically hold the television camera in the position wanted by the surgeon. In 1996, a newer version was released, namely the AESOP2000, that could be driven by vocal orders (Koneckny, 1996; Kukleta, 1998).

In 1996, the first surgery robot for orthopaedic applications was released: ROBODOC, designed by Robert Paul and made by Integrated Surgical Systems Inc. This robot could sculpt the acetabulum cavity, by means of a milling cutter, for the placement of a hip prosthesis with more accuracy than a surgeon (Cohn et al., 1995). The robot was also integrated with an expert system for the choice of the optimal prosthesis profile. A further integration of the robot with a vision and a remote control system led to the ORTHODOC robot, that could perform remote operations with better accuracy than the surgeon's hand (Taylor et al., 1999).

Endoscopic surgery is another important application of robotics in medicine. The most popular robots for endoscopy are: DAVINCI and the ZEUS Robotic Surgical System, which is an evolution of the AESOP robot (D'Attellis et al., 2002; Reuthebuch et al., 2002; Austad et al., 2001).

Medical robotics is developing very fast in the latest years, and has a large range of potential applications that will allow dramatic improvements in the therapeutic approach to a number of surgical pathologies.

The latest systems (such as DA VINCI and ZEUS) can operate through the remote transmission of clinical data for diagnoses and therapies, they implement the so-called "tele-surgery". It must be recalled, though, that robotic tele-surgery is subject to distance limitation, say 50 km for wireless transmission and 300 km for cable transmission, due to the delay between transmission and reception.

Some robotic systems have been proposed in the orthopaedic field, where it is required to insert screws and nails in order to reduce fractures. Several hospitals are active in this field, e.g., the Neuro-surgical Clinics of Lausanne (Switzerland) and the London Imperial College, where the ACROBOT and PROBOT robots have been built. ACROBOT is a semi-active robot for knee surgery, while PROBOT is an active robot for prostate resection (Harris et al., 1997).

Radio-surgery is also subject to automation: in the last years several systems have been developed, to ensure an accurate performing of radio-surgical tasks, mainly consisting in the irradiation of tumour areas of the brain or of other parts of the patient's body (Dinsmore et al., 1996; Beatty et al., 1996).

It is well known that the use of robots is convenient when it is needed to abbreviate the time for executing some elementary tasks requiring precision and accuracy.

Thus, the convenience of employing robots in the surgical field is mainly due to the high repeatability and precision of the executed operations (Kavoussi et al., 1995). Such operations can also be recorded (on magnetic tapes or floppy disks) and then reproduced. Moreover, robots in medicine can be integrated into complex automatic systems for diagnosis and therapy. Hence, the robotised tele-surgery appears to offer revolutionary and important perspectives.

However, some important aspects have to be carefully considered. First of all, the reliability of the robotised surgical operation has to be estimated, because safety is the biggest priority in the use of robotic surgery (Troccaz et al., 1993).

The criteria used today to estimate the risks are more valid of the one used in the past. The most popular quantitative parameter is the MTBF (Mean Time Between Failure), that is, the average time between two failures. If this value is much higher than the machine life, then the system can be considered safe.

The possible applications of robotics to surgery are numerous. Some of these are included in Table I, following the famous classification by Takeyoshi Dohi.

With respect to surgical robots, they can be divided into two main classes: localizers and tele-manipulators. The localizers are robots that should reach a certain physical point of the patient (e.g., a tumour area) on the basis of a set of coordinates supplied by the surgeon. Up to date, they have been used in neuro-surgery and orthopaedics.

The AESOP (Automated Endoscope System for Optimal Positioning) robot, mentioned in the foregoing, is an example of a robot that can be employed to help during mini-invasive surgical operations. It carries out the role of supporting arm for the laparoscope and can modify its own position according to the surgeon's requirements. The AESOP robot is composed by several elements: a control com-

Table I. Applications of robotics to the surgical and medical field

SURGICAL OPERATIONS	Robots for microsurgery Robots for endoscopic surgery Robots for orthopaedic surgery Robots for mini-invasive surgery
INSPECTION, CONTROL	Robots for samples collection Robots for transportation of tissue samples
BASIC RESEARCH	Robots for cellular surgery operations Robots for simulation (virtual reality)
TRAINING	Robots for training in anaesthesia Robots for training in emergency medicine Robot for training or simulation in surgery
PATIENT ASSISTANCE	Robots for patient assistance (nurse robot) Robots for assistance to the disabled

puter, a set of luminous pointers and a switch. The control computer is connected to all the sensors and actuators of the system and it acts as an interpreter of the surgeon's commands.

The tele-manipulators are not pre-programmed to follow a trajectory, but are controlled directly by the surgeon. The endoscopic tele-manipulators have a modular structure (Wendlandt and Sastry, 1994) composed of the following subsystems:

- manipulator,
- end-effectors and instruments,
- three-dimensional video-endoscopic system,
- sensors,
- intelligent control systems,
- graphical system for the creation of models,
- man–machine interface system.

These elements are connected so as to form a master-slave system. The master consists of the intelligent control system, the graphical system and the man–machine interface. The slave is constituted by the manipulator, the end-effectors and instruments, the three-dimensional video-endoscopic system and the sensors.

The manipulator can be mounted on a transport system (like a vehicle or a crane) that is controlled remotely by the surgeon. After reaching the operation position, the transport system is blocked. The exact position of the manipulator can be determined in every moment by the computer.

The sensors enable the operator to receive information such as mechanical pressure, force, speed, acceleration and stress. Basing on their functions, they can be divided into:

- sensors that replace the manual palpation of the surgeon,
- sensors for the *in situ* diagnosis,
- sensors for the control of the movement of the tele-manipulator and the effectors,
- sensors for the monitoring of the various functions of the tele-manipulator.

The video-endoscope supplies the surgeon with the image of the operation field (Rodin and Ayache, 1993).

The control and monitoring system (CMS) constitutes the connection and the coordination unit between the slave and the master of the tele-manipulator.

The man–machine interface has a remarkable importance for the efficiency and the safety of the surgical manipulation. The interface can be constituted by a master arm (with a special grip in order to control the action and the intensity of the grip) or a control lever, that can be assisted by a vocal system (Costi et al., 1995). Recently, haptic interfaces are used (Prisco et al., 1998) that actively reproduce the force sensation from the signal output by adequate force sensors placed on the end effector of the slave robot, so as to give the surgeon an effective force feedback.

A field that has undergone great increase and development in the latest years is the mini-invasive surgery. This kind of surgery acts through small cuts, achieving the same results of the traditional surgery, but avoiding large external or internal cuts. Surgery has been revolutionised by the techniques of mini-invasive surgery that present lots of improvements with respect to the traditional operation techniques. The main advantage is the minimisation of the traumas of the healthy tissues, so that both the hospitalisation times and the risks of post-operation complications are decreased (Tendick and Cavusoglu, 1997).

In the laparoscopic and the thoracoscopic surgeries, the operations are carried out by inserting surgical instruments in the body of the patient through two or more holes and observing the operation field by means of a micro television camera that is inserted through an ulterior hole. The task of the robots used for laparoscopy is to hold and move the camera. They are controlled by the surgeon through a special pedal.

Research in this field is mainly focused on two topics:

– design and implementation of better instruments, that can supply the surgeon with high standard sensorial feedback;
– implementation of more advanced man–machine interfaces.

There are several research programmes being carried out in this field. At the University of California at Berkeley, a project for building of a laparoscopic surgical station is under development. The Centre of Nuclear Researches of Karlsruhe and the University of Tübingen (Germany) are studying several kinds of surgical manipulators and arms to move television cameras and surgical instruments.

Another important field is given by the stereotactic surgery, which makes use of systems for the three-dimensional reconstruction of the images, so as to provide the surgeon with spatial information of the point where he is operating using a determined reference system. These systems are usually integrated with robotic devices for the accurate positioning of medical instruments and execution of the operation.

Some researchers (Masamune et al., 1996) have studied a small robotics arm to be used in neuro-surgery with the aid of three-dimensional information for its positioning.

With respect to tele-surgery and virtual surgery, which have been defined in the foregoing, the research in this field is focused on the implementation of a tele-surgery system that allows the surgeon to carry out operations and diagnosis on patients settled in a different place. This kind of system needs a data transmission network for the transfer of multimedia information in real time.

The mini-invasive surgery is one of the most propitious fields for the research in the domain of the tele-surgery. The mini-invasive surgery is based on three fundamental characteristics:

(1) the availability of high resolution video-endoscopic images,
(2) the use of accurate precision surgical instruments,
(3) the ability of surgeons trained on purpose.

The current endoscopic surgery technologies need further developments in order to facilitate the remote surgical manipulations carried out through endoscopic vision and to increase the safety. A modern approach is based on robotics systems that are guided and controlled by a human operator in order to execute video-aided operations (Giorgi et al., 1989).

Thanks to virtual reality, imaging systems, computers and manipulators, the surgeon can use three-dimensional images, and also the transmission of the tactile sensations is possible (Fearing et al., 1997; Gray and Fearing, 1996).

Some of these applications have already been realised.

In 1991, Jaron Lanier created a computerised three-dimensional model of the optical nerve. In 1994 the first 3D neuro-surgery operation was carried out at the Brigham Hospital in Boston, and the Belgian surgeon Jacques Himpens executed the first tele-surgery operation. In September 1995, the surgeon Enrico Pisani from the Laboratory of Tele-Robotics of the Polytechnic of Milan, operated a patient who was located approximately 10 kilometers far, by means of a robot connected through optical fibres. The operation was a tele-robotised prostatic biopsy, carried out under total anaesthesia. The operation on the human patient was executed by the robot assistant after more than 1200 simulations on models with the identical procedure and after three years of test on dummies, in order to get the system reliable and to exclude every possible technical deficiency of the machines and the software. This operation was performed during the “IX World Congress on the Theory of Machines and Mechanisms”.

The laporoscopic and the mini-invasive surgery are the field where the developments of the modern surgery are more evident. However, besides its great advantages, the mini-invasive surgery has also created new problems: the loss of the three-dimensional vision, of the tactile sensibility and of the eye-hand coordination.

The virtual reality is focused on the resolution of this kind of problems. Several systems have been designed for this purpose by different researches from Europe and U.S. Each of these systems has its own manner to improve laparoscopic surgery. Thus some of those systems operate with the aid of sophisticated computerised systems, that process digital signals in order to eliminate the tremor of the surgeon’s hand.

Another field of future development of robotic surgery is the computer-guided and computer-performed surgery. It is based on a principle similar to that of the automatic pilot on aircrafts. After studying, standardising and recording the possible situation of the surgical operation, a decisional procedure (algorithm) is employed to face the situation and to choose the optimal action. The final aim of this technique is to program and execute the whole surgical operation automatically, so that the surgeon only acts as an external controller, who is ready to intervene if anything unexpected occurs (Autret, 1996).

3. An Intelligent System for Simulating Surgical Operations

The main goal of the work presented here was to simulate a surgical operation in a ‘virtual reality’ environment. The trajectory the robot has to follow in order to perform the surgical task is generated by an intelligent planner, based on Artificial Intelligence techniques, starting from the commands given by the surgeon in the natural language. The trajectory is then input to a robotic simulator, so as to allow the user (say, the surgeon) to watch the simulation of the actions commanded to the system, for a better monitoring of the whole operation. Once the trajectory is thoroughly checked, it can be input to the medical robot for execution of the operation.

The neurosurgical operation chosen as a test case consists of a sequence of steps. First, the skin is cut in order to allow the access for perforation of the skull. Then, the neoplastic area of the brain is detached at the borders and extracted. Finally, the initial cut is closed.

Figure 1 represents the phases of the intelligent system, which starts from the surgeon commands expressed in the natural language and, through the STRIPS algorithm, carries out a simulation in a Java environment to get the robot motion.

3.1. USING ONTOLOGIES TO REPRESENT SURGICAL INSTRUMENTS

An ontology is viewed in this work as a specification of a domain knowledge conceptualisation (Van Heijst et al., 1997). In addition, ontologies will be represented here by means of *multiple hierarchical restricted domains* (MHRD) in a similar manner to those employed by other authors (see, for instance, Eschenbach and

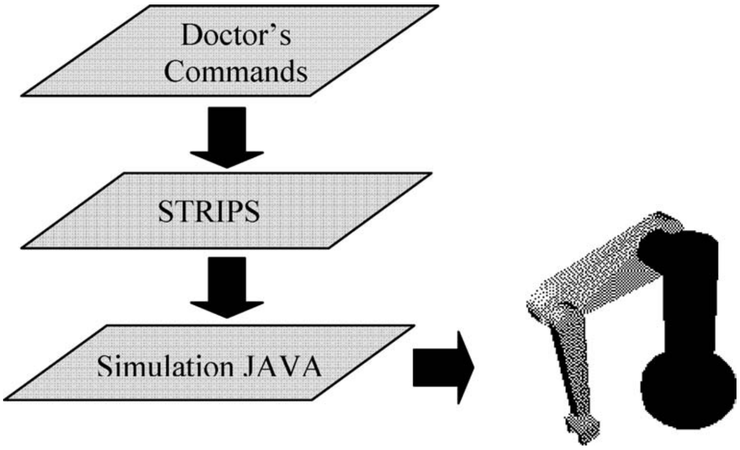


Figure 1. Phases in the intelligent system.

Heydrich, 1995). In particular, we term MHRD to a set of concepts holding the following:

- They are defined through a set of attributes, so that the presence of axioms between these attributes will not be considered.
- There can be taxonomic relations among the concepts, so that attribute (multiple) inheritance is permitted.
- There can be temporal relationships among the concepts.
- There can be mereological relationships among the concepts. Different types of mereological relations are distinguished in this model, namely, stuff-object, component-object, member-collection, portion-mass, feature-activity, place-area, and phase-process (Winston et al., 1987).
- Other type of relations among concepts, which are considered the most common relations in problems (Fernandez-Lopez et al., 2000) are also included in our model, such as equivalency, dependency, topology, causality, functionality, similarity, conditionality, purpose, synonymy.

The ontology used to represent the surgical instruments can be viewed in Figure 2.

3.2. THE STRIPS PLANNER

STRIPS (Fikes and Nilsson, 1971) is a linear planner that attempts to find a sequence of operators in a space of world models to transform a given initial world model into a model in which a given goal formula can be proven true. It represents a world model as an arbitrary collection of first-order predicate calculus formulae and works with models consisting of a large number of formulae. It uses a resolution theorem demonstrator to answer questions of particular models and mean-ends analysis as a guide towards the desired goal-satisfying model.

For any world model, we are going to have a set of applicable operators which transform the world model into some other world model. The problem solver finds

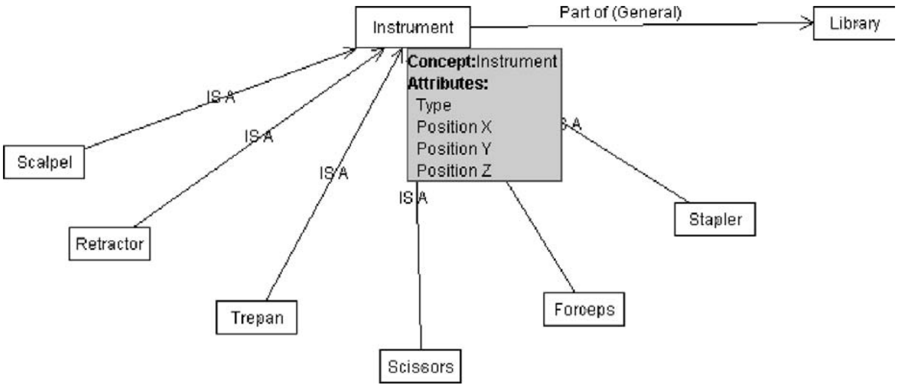


Figure 2. Instruments represented by means of ontologies.

some composition of operators that transforms a given initial world model to one that satisfies a stated goal condition.

In STRIPS a world model is represented by a set of well formed first-order predicate calculus formulae. Each operator in a solution corresponds to an action routine whose execution causes a robot to take certain actions.

Each operator in STRIPS is composed by:

- A set of preconditions. To execute the action related to the operator it is necessary that preconditions are true before the operator can be applied.
- Delete list, which is a set of formulae that will not be true after the operator has been applied, so the planner has to delete them from the current world model.
- Add list, which is a set of formulae that will be true after the operator has been applied, so the planner has to add them to the current world model.

For example, an operator for the Blocks World problem is shown in Table II.

In Table II, *clear*(*block*), *on-table*(*block*), *arm-empty* and *holding*(*block*) are well formed formulae. Clear(*block*) means that there is nothing on the *block*, on-table(*block*) means that the *block* is on the table, *arm-empty* means that the robot does not hold anything, and holding(*block*) means that the robot holds the *block*.

STRIPS, like most of other planners, has been applied to the blocks world problem as an effective benchmark (Slaney and Thiébaux, 2001). The blocks word problem consists of a finite number of blocks stacked into towers on a table large enough to hold them all. The positioning of the towers on the table is irrelevant. The Blocks World planning problem is to turn an initial state of the blocks into a goal state, by moving one block at a time from the top of a tower onto another tower or to the table. The optimal Block World planning problem is to do so in a minimal number of moves.

Table II. An operator for the Blocks World problem

pick-up(Block)	
Preconditions:	clear(block) on-table(block) arm-empty
Add list:	holding(block)
Delete list:	on-table(block) clear(block) arm-empty

Most of the planners adopt the STRIPS representation and search forward the state space. The GRT planner (Refanidis and Vlahavas, 2001) is a domain-independent heuristic planner which solves planning problems calculating in a first phase the distances between the facts and the goals of the problem. The second phase consists of a simple best first search strategy using the distances calculated in the previous phase. This planner has been validated in several domains like blocks-world domain in which GRT can easily solve problems with more than 20 blocks.

Another planner which adopts the STRIPS representation is the Fast-Forward Planning System (Hoffmann, 2001) which attacks the planning problems by forward searching in state space, guided by a heuristic function. This function is extracted from the domain description relaxing the planning problem by ignoring parts of its specification, concretely the delete lists of operators.

3.3. STRIPS FOR PLANNING NEUROSURGICAL OPERATIONS

Due to the simple surgical operations domain is a well known and structural domain, we have used STRIPS for planning simple surgical operations. Our problem is very similar to the blocks world problem, where the word model is represented by a set of well formed formulae of first-order predicate calculus showed in Table III.

The initial world model is formed by the formulae which represent that all the instruments are allocated in the library, the position of the robot is X_0, the robot does not carry any instrument, and the tumour is present. The formulae of the final world model represent that the instruments are at the correct position into the library, the tumour is absent, and the patient skin is closed (Table IV).

The surgical operators which have been designed can be viewed in Table V.

A robotic simulator has been built using the Java language, so that the operator can check the robot motion in a virtual environment prior to the execution of the operation in the real world. Figure 3 depicts the graphical interface of the simulator.

Table III. The set of well formed formulae

Formula	Description
Allocated(instrument, library)	The instrument is allocated in the library
Position(pos)	The tumour is allocated in the position *pos*
Grasped(instrument)	The robot has the instrument
Patient_status(part, status)	The part of the body or the tumour has an status. For example: Patient_status(skin,closed); Patient_status(tumour,present);

Table IV. Initial and final state

Initial state	Final state
Allocated(scalpel,library_scalpel)	Allocated(scalpel,library_scalpel)
Allocated(retractor,library_retractor)	Allocated(retractor,library_retractor)
Allocated(trepan,library_trepan)	Allocated(trepan,library_trepan)
Allocated(scissors,library_scissors)	Allocated(scissors,library_scissors)
Allocated(forceps,library_forceps)	Allocated(forceps,library_forceps)
Allocated(stapler,library_stapler)	Allocated(stapler,library_stapler)
Position(x_0)	Grasped(nothing)
Grasped(nothing)	Patient_status(skin,closed)
Patient_status(skin,closed)	Patient_status(skull,intact)
Patient_status(skull,intact)	Patient_status(tumour,absent)
Patient_status(tumour,present)	

Before performing the simulated neurosurgical operation, the surgeon must input some preliminary data to the computer (Figure 3), such as:

- the starting point of the manipulator;
- the position of the surgical tools;
- the position of the tumour inside the brain, according to the diagnosis based on some previously performed medical tests (such as Computerised Tomography, or Nuclear Magnetic Resonance).

The operation is then performed in a step by step manner as follows:

(1) the surgeon commands the manipulator to **cut** the patient's skin between two points, whose coordinates are provided by the surgeon himself;
(2) the surgeon commands the manipulator to **anchor** a retractor to the patient's cut, so as to hold it adequately open;
(3) the surgeon commands the manipulator to **perforate** the patient's skull within the cut area;
(4) the surgeon commands the manipulator to **detach** the brain along the borders of the neoplastic zone, whose coordinates have been previously input to the computer;
(5) the surgeon commands the manipulator to **extract** the tumour;
(6) the surgeon commands the manipulator to **disanchor** the retractor from the patient's head;
(7) finally, the surgeon commands the manipulator to **close** the cut on the patient's head.

The robotic manipulator chosen to perform the operation undergoing the test phase is a commercial Puma 560 (Unimation), whose kinematic features are well known.

Table V. Surgical operators

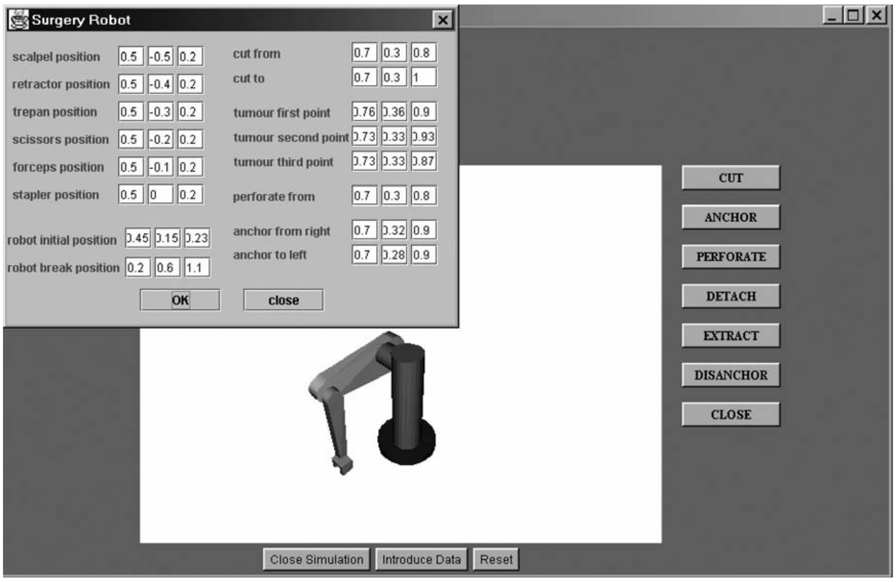
Operator		
Move_to(x,y)	Preconditions:	Position_robot(x)
	Delete list:	Position_robot(x)
	Add list:	Position_robot(y)
Take(instrument, Library_instrument)	Preconditions:	Position(library_instrument)
		Allocated(instrument,library_instrument)
		Grasped(nothing)
	Delete list:	Grasped(nothing)
		Allocated(instrument,library_instrument)
	Add list:	Grasped(instrument)
Go_up(x,y)	Preconditions:	Position(x)
	Delete list:	Position(x)
	Add list	Position(y)
Go_down(x,y)	Preconditions	Position(x)
	Delete list	Position(x)
	Add list	Position(y)
Put_down(instrument, Library_instrument)	Preconditions	Position(library_instrument)
		Allocated(nothing,library_instrument)
		Grasped(instrument)
	Delete list	Allocated(nothing,library_instrument)
		Grasped(instrument)
	Add list	Allocated(instrument,library_instrument)
		Grasped(nothing)
Cut(x,y)	Preconditions:	Position(x)
		Grasped(scalpel)
		Patient_status(skin,closed)
	Delete list:	Position(x)
		Patient_status(skin,closed)
	Add list:	Position(y)
		Patient_status(skin,cut)
		Patient_status(skull,intact)
		Patient_status(tumour,present)

Table V. (Continued)

Operator		
Anchor(x,y)	Preconditions:	Position(x) Grasped(retractor) Patient_status(skin,cut)
	Delete list:	Position(x) Patient_status(skin,cut)
	Add list:	Position(y) Patient_status(skin,open) Patient_status(skull,intact) Patient_status(tumour,present)
Perforate(x,y)	Preconditions:	Position(x) Patient_status(skull,intact) Grasped(trepan) Patient_status(skin,open) Patient_status(tumour,present)
	Delete list:	Position(x) Patient_status(skull,intact)
	Add list:	Position(y) Patient_status(skull,hole)
Separate(x)	Preconditions:	Position(x) Grasped(scissors) Patient_status(tumour,present) Patient_status(skull,hole) Patient_status(skin,open)
	Delete list:	Patient_status(tumour,present)
	Add list:	Patient_status(tumour,detached)
Grasping_tumour(tumour)	Preconditions:	Patient_status(tumour,detached) Grasped(forceps)
	Delete list:	Patient_status(tumour,detached)
	Add list:	Patient_status(tumour,absent)
Disanchor_from_to(x,y)	Preconditions:	Position(x) Grasped(retractor) Patient_status(skin,open)
	Delete list:	Position(x) Patient_status(skin,open)
	Add list:	Position(y) Patient_status(skin,cut)

Table V. (Continued)

Operator		
Close(x,y)	Preconditions:	Position(x) Grasped(stapler) Patient_status(skin,cut)
	Delete list:	Position(x) Patient_status(skin,cut)
	Add list:	Position(y) Patient_status(skin,closed)



scalpel position 0.5 -0.5 0.2
retractor position 0.5 -0.4 0.2
trepan position 0.5 -0.3 0.2
scissors position 0.5 -0.2 0.2
forceps position 0.5 -0.1 0.2
stapler position 0.5 0 0.2
robot initial position .45 .15 .23
robot break position 0.2 0.6 1.1
cut from 0.7 0.3 0.8
cut to 0.7 0.3 1
tumour first point .76 .36 0.9
tumour second point .73 .33 .93
tumour third point .73 .33 .87
perforate from 0.7 0.3 0.8
anchor from right 0.7 .32 0.9
anchor to left 0.7 .28 0.9

Figure 3. Inserting parameters before simulation.

Of course, the real operation will have to be executed by a standard medical robotic device, so as to have an adequate level of safety.

4. Planning the Operation

The sequence of steps constituting the operation that was obtained by our planner is described below. Each step is composed of a sequence of actions, which are also described.

Step0: Start-up

Before beginning the operation, the system checks for the preliminary data input by the surgeon. Indeed, these data must have reasonable values and must be contained within some specific range, corresponding to the points in the space the manipulator can physically reach. If the input data do not meet such requirements, the system will prompt the surgeon to input a set of correct coordinates.

Step1: Cut

Following the surgeon's request to cut the patient's skin, the manipulator moves to the scalpel (**move_to**) and takes it (**take**). Then, once the patient's head is reached (**move_to**), the required cut is made (**cut**), and the scalpel is lifted (**go_up**). The manipulator then moves to the tools location (**move_to**), and the scalpel is dropped (**put_down**). During this phase, it would be interesting to analyse the consistency of the position of the cut coordinates.

Step2: Anchor

After the surgeon commands to anchor the cut, the manipulator moves to the retractor (**move_to**), takes it (**take**) and moves to the patient's head (**move_retractor**). After taking the right side of the retractor to the distance commanded by the surgeon (**move_to**), the manipulator anchors (**anchor**) the left side where required, and finally leaves the patient's head (**go_up**). A check for consistency could be set before this phase, namely: the retractor must be anchored to a point lying inside the cut, and the width of retraction must stand within a suitable values range.

Step3: Perforate

The next command function is to perforate the patient's skull. For it, the manipulator moves to the tools location (**move_to**), takes the trepan (**take**) and moves to the cut on the patient's head (**move_to**). Then, the manipulator perforates (**perforate**) the patient's skull up to a certain depth threshold set by the surgeon (it is strongly required that the depth of the perforation does not extend beyond such a threshold, otherwise permanent brain damage can result). Finally, the manipulator leaves the patient's head (**go_up**), moves back to the tools location (**move_to**) and drops the trepan (**put_down**).

Step4: Detach

During this step the manipulator is to detach the neoplasma along the borders of the zone whose coordinates are given by the surgeon. The manipulator first moves to the tools area (**move_to**), where it takes the scissors (**take**); then it moves into the perforation (**go_down**) to cut the brain at the first location (**separate**). Then the manipulator moves to the second location (**move_to**), where it cuts the brain again (**separate**); then, it moves to the third location (**move_to**) and repeats the cutting operation (**separate**). Finally, the manipulator moves back to the first location (**move_to**), then leaves the patient's head (**go_up**), returns to the tools (**move_to**) and drops the scissors (**put_down**).

Step5: Extract

After the command of tumour extraction, the manipulator moves to the forceps (**move_to**), and takes them. Once the patient's head is reached (**move_to**), the manipulator moves towards the neoplasma (**go_down**), grasps the tumor (**grasping_ tumour**) and extracts it (**go_up**). Then, the manipulator moves back to the tools (**move_to**) and drops the forceps (**put_down**).

Step6: Disanchor

Following the surgeon's command to disanchor the retractor from the cut, the sequence of actions taken by the manipulator starts with the motion to the point where the retractor has been fixed (**move_to**); then, the manipulator disanchors the retractor, by closing it up to the point where it has first been put (**disanchor_from_to**), takes it (**take**)and extracts it (**go_up**). Then the manipulator moves to the tools location (**move_to**) and drops the retractor (**put_down**).

Step7: Close

This step follows the final command to close the cut. The manipulator moves to the tools location (**move_to**), takes the stapler (**take**), moves to the patient's head (**move_to**) and closes the cut (**close**). Then, it leaves the patient (**go_up**), moves to the tools (**move_to**) and drops the stapler (**put_down**). Finally, the manipulator moves back to its home position (**go_up**).

The operation is over.

The above described sequence was input to the robotic simulator and successfully executed in the virtual environment. The results of the simulation tests have been satisfying, in the sense that the surgical operation can be effectively reproduced in the virtual environment starting only from the requirements expressed by the surgeon in his natural language.

The possibility of monitoring the operation allowed the user to modify, whether necessary, the trajectory generated by the intelligent planner, so as to take into account possible additional kinematic and dynamic constraints of the robot. Once the trajectory is definitely checked and validated in the virtual environment, it can be finally input to the robot and executed.

5. Conclusions

In this paper, an application of Artificial Intelligence to medical robotics is presented. Namely, AI techniques based on all ontologies, a linear planner algorithm and logical predicates have been used to obtain a sequence of operations to be input to the control system of a robot in order to perform a specific neurosurgical task according to the requirements expressed by the surgeon the natural language.

The AI techniques employed to this purpose have been described both in their theoretical approach and in their implementation. Moreover, a robotic simulator has been built so as to be able to test the developed technique in a virtual environment by monitoring the trajectory generated by the intelligent planner. The robotic manipulator chosen to perform the operation undergoing the test phase is a commercial Puma 560 whose kinematic features are well known. Of course, the real operation will have to be executed by a standard medical robotic device, so as to have an adequate level of safety.

The results of the simulation tests have been satisfying, in the sense that the surgical operation can be effectively reproduced in the virtual environment starting only from the requirements expressed by the surgeon in his natural language.

Further developments of the work will be aimed at implementing the neurosurgical operation in a real operating room and using an existent medical robotic device, so as to get a working prototype of the whole surgical robotic system, that will then be thoroughly tested.

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