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A ROBOTIZED SYSTEM FOR THE EXECUTION OF A TRANSURETHRAL LASER PROSTATECTOMY (TULP)

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Abstract
This paper describes a robotized auxiliary system for the removal of a prostatic adenoma by transurethral means. The system consists of a personal computer with a supervision function, an ultrasound for location of the lesion and a robot for removal of the adenoma.

The operating procedure includes the following phases:
- reconstruction of a three dimensional model of the prostrate starting from some ultrasound images obtained by means of a transrectal probe;
- identification of the volume to be removed:
- removal of this by means of a laser system suitably manipulated by a robot.

This system was entirely developed and tested in the laboratory using a prostatic compressed polystyrene model and a robot with 6 degrees of freedom.

This article also describes a robot project expressly dedicated to surgical application.

1. Introduction

The prostate is a gland, shaped and sized like a nut. It is the organ surrounding the neck of the urinary bladder and beginning of the urethra in the male (prostatic urethra).The bladder continues with a channel, bent forwards towards the root of the penis. which runs throughout the prostate.

Prostatic Adenofibromatosis causes an irregular enlargement of the gland, which projects towards the vesical cavity, and compresses the urethra. This makes the emission of urine difficult and, if the process continues, results in the complete closure of the channel [1]. In this case it is necessary to conduct a prostatectomy which, if the dimensions of the adenoma are not too big (30-60 cc) can be carried out endoscopically.

The endoscopic prostatectomy consists of inserting a cylindrically shaped surgical instrument (8-9 mm in diameter) called a cystoscope into the bladder and performing a series of repetitive movements aimed at removing the tissues that come into contact with the removing device. The latter consists of a laser ray emitted by a fibre inserted in the cystoscope; unlike the classical electric resector this has the advantage of removing the tissues and simultaneously coagulating the lacerated blood vessels.

This type of operation is known as "T.U.L.P." (Transurethral Laser Prostatectomy) as opposed to the acronym "T.U.R.P." (Transurethral Resection of Prostate) in which a resectoscope is used.

The characteristics of the operation (repetitive movements, known a priori) and of the instrument (simultaneous cutting and coagulation action) are both factors that render the development of a robotized instrument possible.

The project consists of simulation of a surgical operation, in the laboratory, by means of an anthropomorphic robot with 6 degrees of freedom (model 1400, of the ABB Robotica company). Modelling is supported by a dedicated robot project.

Many researches deal with robotic and automated surgery (Ref.[1] to [14]). In particular, for TULP, Davies et al. [13], [14] have developed a project for Transurethral Resection of the Prostate, with computer controlled robot and with a graphic interface. The system proposes a model with cones for the interface, for the interaction of the surgeon with the images.

2 Manual T.U.L.P. procedure

The possibility of developing a system to automatically perform T.U.L.P. stems from the collaboration between the Department of Telerobotics at the Politecnico di Milano and the Department of Urology at the Policlinico di Milano.

Endoscopic prostatectomy is one of the operations most frequently performed at this hospital. This pathology affects about 60% of the male population over the age of 55 years. From a survey conducted in the United States it was discovered that a man over the age of forty has a 30% probability of being subjected to endoscopic prostatectomy [2]. In the USA, as many as 100.000 operations of this type are performed each year.

Determination of the seriousness of the situation and therefore of the type of operation to be performed is conducted by means of an ultrasound analysis of the prostate which enables the surgeon to visually identify the adenoma and to quantitatively evaluate its size. The surgical instrument used to remove the adenoma endoscopically is called a cystoscope. This consists of a metal tube (called a mandrel, measuring 400 mm in length and 9 mm in diameter) inside which there is a cylinder housing a laser ray, as well as a system that permits the surgeon to illuminate and photograph the tissue removal operation.

The cystoscope is inserted in the urethra until its extremity reaches the prostate and consequently removal of the

adenoma initiated. The tissues to be removed are distinguishable from the healthy ones because they are whitish in colour while the healthy tissues are pinkish.
The operation consists in the progressive enlargement of the urethra which, from a practically null diameter before the operation, in the area of maximum tissue removal, can reach a diameter of 60 mm [3]; [7].
The tissue removal trajectories are parabola arcs whose first starting point is situated just beyond the veru-montanum and whose second is situated just beyond the bladder neck; the intermediate point, that defines concavity, is established in an empirical way. The location of the first point is maintained constant while the distance of the second point is progressively increased moving away from the centre of the urethra. To begin with the trajectories shown in figure 1 are determined; these trajectories are repeated in order to generate a revolution solid by rotating the plane in which the tissue removal occurs by a suitable arc, around the urethra.
The step of increase between two successive rotations is usually several tens of degrees; the accuracy of movements is about 1-2 mm and the speed about 1-2mm/s. Before going on to develop the trajectories indicated by apex "2" the same series of arches along the entire revolution angles must have been completed. Over and above a certain diameter the range of rotation of the operation plane is limited according to the entity of the prostatic gland; as can be seen further on, the prostatic urethra is not situated in the centre of the prostate meaning that it is therefore necessary to keep account of the wall dimension according to the direction in which one is working [4]. The next trajectories are created by making a complete rotation of the operation plane before proceeding with the next enlargement; the enlargement ends when the pink tissues (sign of healthy tissues) are reached

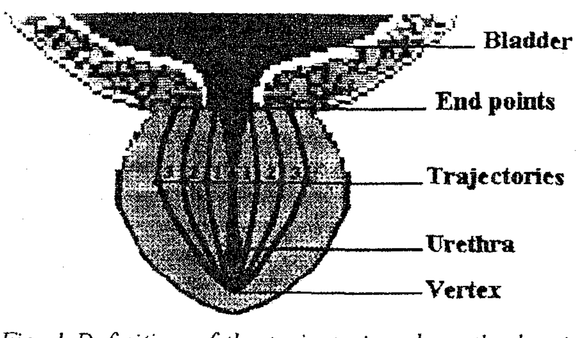

Fig. 1 Definition of the trajectories along the longitudinal plane

With regard to the intermediate point, which defines the concavity of the single parabolas, a ultrasound image which represents a section of the prostate is used.

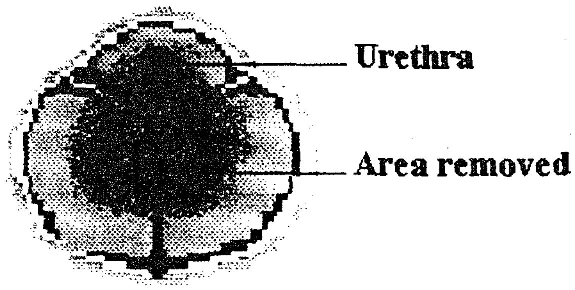

Fig. 2 Transverse prostatic section

As can be seen from Fig. 1, the urethral channel is situated in the middle of the prostate; it is therefore necessary to bear in mind different penetration in the prostate according to the rotation angle. In fact, the surgeon only looks at the upper part of the prostate to verify the need for surgery. This is due to the fact that under normal circumstances, removal only takes part in the lower part (with respect to the urethral axis). The channel is enlarged to reach a maximum diameter (in the areas where this is possible) of 6 cm; this value is generally higher than the real dimensions of the pathology. This is done to ensure that the patient enjoys a long period of good health; the adenoma could in fact reform, thus forcing the patient to undergo another operation [5].

3. Robotized system

The transurethral prostatectomy consists in the development of a sequence of well defined movements that can be established prior to the operation. A transrectal ultrasound probe can be used to perform a series of prostatic ultrasound, from which it is possible to reconstruct a three dimensional image of the adenoma [6]. This project develops a reconstruction methodology based on the analysis of two ultrasound images interpolated with a fixed point.

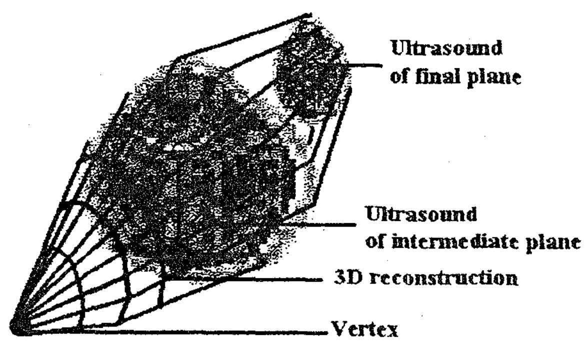

Fig. 3 3D reconstruction of the adenoma

The system reconstructs a sort of paraboloid, with an angular vertex, by interpolating the fixed point with points that have been suitably identified by means of an ultrasound section of the prostate. These points, which defined the

outer section of the adenoma. are indicated by the surgeon on the ultrasound. displayed on the screen of a personal computer. by means of suitably interfaced software.
Asking the surgeon to provide more images would involve a somewhat laborious and pointless memorization sequence due to the fact that a second degree interpolation. on a maximum length of 50 mm. is more than sufficient. Furthermore. the accuracy of the manual operation is of the order of 1-2 mm. a value that can be obtained and improved through use of a robot. The first part of the project foresees the use of an anthropomorphic robot with 6 degrees of freedom capable of simulating all the movements performed by the cystoscope during surgery. Nevertheless. this type of robot has proved to be ineffective on account of being too cumbersome (situated between legs of the patient) and not particularly reliable in reaching position with particular orientations. The presence of specific points and the lack of knowledge about robot positioning procedures in various configuration, are not able to guarantee patient protection. [8]. A dedicated robot, capable of overcoming these limitations, was therefore designed. The main features of this robot, designed as a robt for transurethral surgeries by laser. are the following: presence of 3 active degrees of freedom. presence of one passive degree of freedom for self-determination of the anatomical characteristics of the patient. reduced dimensions (40x40 cm), realization of any type of trajectories (in one's own work space) and mechanical safety system to guarantee patient protection.

4. Components of the system

The complete system is shown in figure 4 and comprises the following modules:

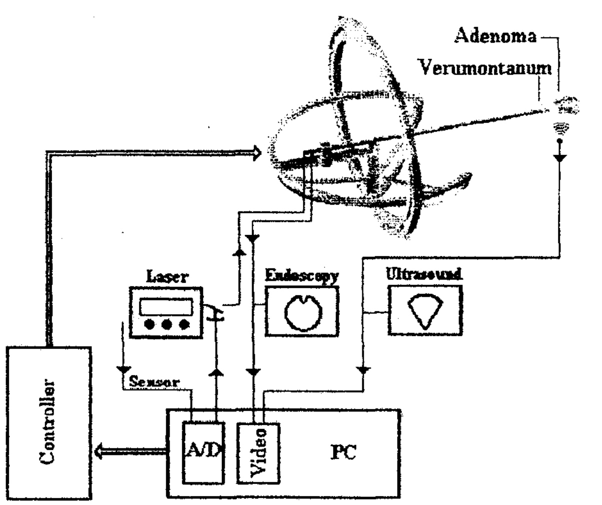

Fig. 4 Components of the system

Personal computer: supervision of the entire system is entrusted to a PC. This is capable of acquiring the ultrasound and endoscopic images in both real time and continuously. Furthermore. the PC not only handles positioning of the robot but also acquires the deformation state of the tissues and provides for laser ray generation during surgery.

Video card: the video card is inserted in the PC and enables the PC to acquire and display the ultrasonic and endoscopic images on the screen. Furthermore. it is possible to store the images acquired on a disc.

Ultrasound: this is the instrument used to identify the characteristics of the adenoma. The prostate can be reached in two ways: either transurethally or transrectally. By performing an ultrasound with a transrectal probe and a transurethral endoscope it is possible to effectively reconstruct the shape of the pathology. The ultrasound provides the transverse section of the adenoma while the endoscope provides the position of this image in the event of the extremity of the cystoscope coinciding with the ultrasonic scan plane [9].
This situation can be obtained by positioning the cystoscope in the desired scan plane and by moving the ultrasonic probe until this point is identified. Identification of this point occurs when the cystoscope appears on the ultrasound image. Because the cystoscope is made from metal it is immediately distinguishable because it is much lighter in colour than the rest of the image. The video output of the ultrasound is connected in input to the video card of the PC.

Equipment for endoscope: this equipment can be used to display the image provided by the endoscopic camera on the screen. The video output of this equipment is connected in input to the video card of the PC to allow for display and processing.

Laser generator: this enable a laser beam of variable power to be generated. The power normally used in the surgical context is 30-35 watts according to the patient's tissue type. The optic output is connected to a fibre measuring approximately 1 mm in diameter and is inserted in the cystoscope. Activation of the ray takes place by means of a command automatically handled by the PC.

The cystoscope: the surgical instrument is the same one used in manual operations. Inside there is a fibre. which has to be blocked with the cystoscope so that it does not project more than 2-3 mm outside the instrument. The internal cylinder must be attached to the external one so that. during movement. there is no change of position due to the relative displacements between the two cylinders. Finally. the video connector must also be connected for internal visual control of the cavity.

Sensor/data acquisition card: this card is directly inserted in the PC and is used to acquire the deformation state of the tissues during removal. A force sensor. capable of detecting the pressure to which the instrument is subjected, is mounted on the robot's effector. The output signal given by the sensor, after being suitably amplified. is connected to the analog input of the A/D card. At this point the signal is converted from analog to digital and directly read by the PC.

The robot: The design is of two circular concentric rings, rotating one against the other and arranged on a vertical plane. The outside ring is fixed and acts as a support for the rotation of the inside ring. Inside the latter there is a subsystem consisting of a circular ring sector situated in an orthogonal plane with respect to the former. This ring acts as a guide for a rotating system arranged in such a way that it represent the radius (variable) of the aforementioned guide. In this way circumferences with variable radii for the composition of curvilinear places can be obtained. The curvilinear trajectories can be considered as sections of the variable radius circumference. This type of structure reduces deviations to a minimum during the passage from one radius to another for composition of the various geometric places. This not only allows for greater fluidity of movements but also more speed.

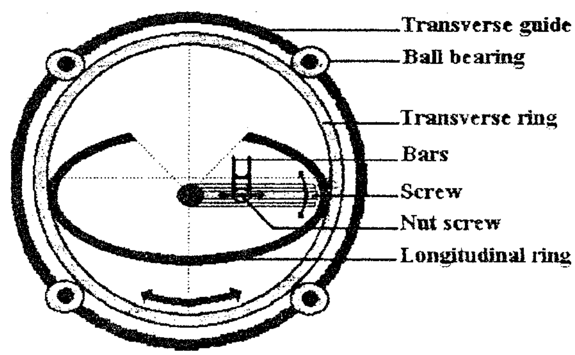

Fig. 5 Design of the TULP Robot

Movement control: robot control is entrusted both to the PC and the controller of the robot itself. The PC processes the parameters imposed by the user and calculates the tissue removal trajectories. These geometric places are communicated via serial, to the robot controller which provides for positioning. The control and implementation of movement is effected by means of a cc motor and two motors of the Brushless type, which offer high performance levels combined with compact dimensions. Position control is obtained by means of three optic type encoders which offer high resolution combined with a high level of immunity from electromagnetic disturbances. A fourth encoder, placed on the robot's effector, is also present. This is necessary to allow the robot to self-diagnose the patient's anatomy (especially for determination of the veru-montanum).

5. Safety system

A very important factor in the design of a robotized system for the performance of surgical operations, is patient safety. In order to guarantee this characteristic, it is necessary that all the parts of the system are kept under control in order to allow for intervention in the case of malfunctioning. The robot structure has been studied to guarantee the creation of any trajectory combined with the relative complexity of the management organs. Sensors to monitor orientation of the cystoscope and the force to which it is subjected are located on the robot [10].

6. Software interface

The software was developed in Visual Basic, integrated with suitable DLL (Dynamic Link Library) for the management of the video card and the data acquisition card. The development environment is the typical Windows environment and is based on the display of an icon and windows which are presented to the user in their various situations. The instructions regarding management of the system are both simple and guided in that only information connected to the type of surgery being performed is given or requested of the user [11]. Two methods are foreseen: manual and automatic. With the manual method the surgeon can develop a single removal trajectory by defining the extremities, the speed and the precision in tissue removal. With the automatic method prostatectomy can be performed. The surgeon must define the removal trajectories by modifying the characteristics of suitable figures displayed on the video. The software interface that allows for this insertion is the following:

The default figure is an ellipse: the doctor can change the definition by acting on the scrollbars and viewing the changing images in real time. The transverse and longitudinal dimensions, the angle of initiation and termination, to preserve the upper part of the gland, the number of progressive enlargements of the urethra and the number of rotations of the operation plane, can be modified. The typical solids generated are shown in figure 8. Other menus can also be chosen. These allow the operator to control the images, to move the robot and to always have a guide that notifies the surgeon of the functions that have been performed and those that need to be performed in order to complete the definition of the operation. The imposition of the immobility of the veru-montanum takes place in a way that can be seen by the user: the cystoscope is automatically oriented by the system according to the current point.

7. Automatic TULP

The operation begins with placement of the patient on the operating table with legs divaricated and turned upwards. The robot is placed between the patient's legs in a symmetrical position with respect to the urethral axis. The cystoscope is manually inserted into the urethra and pushed just beyond the veru-montanum thus connecting the instrument to the robot.

The system proceeds with auto-determination of the veru-montanum: the robot is automatically positioned in a series of points by processing the information provided by the force sensor and by the orientation sensor. When the error associated with the process is a tenth of a millimetre. calculation is terminated. At this point the transrectral probe is inserted and two prostatic ultrasounds are performed: determination of the ultrasonic plane is determined by the internal extremity of the cystoscope which. on account of being made from metal. is much lighter than the rest of the image. After memorizing the two ultrasonic images. the location of the paraboloid vertex of removal. which can be reached by the surgeon by means of an analysis of the endoscopic image. must also be memorized. Before starting surgery, the surgeon must define the trajectories in the two previous sectors and impose both the operating speed and precision. The system therefore constructs a three dimensional model of the adenoma and imposes the removal sequence. The typical operation sequence is shown in Fig. 6.

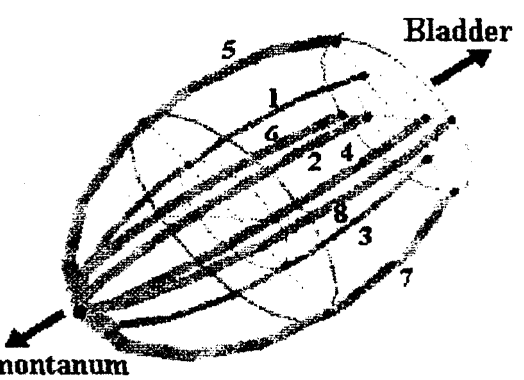

Fig. 6 Sequence of the removal trajectories of the prostatic adenoma

Typical solids which describe the volume to be removed are reported in Fig. 7.
The default figure is an ellipse; the doctor can change the definition by acting on the scrollbars and viewing the changing images in real time (Fig. 8). The transverse and longitudinal dimensions. the angle of initiation and termination. to preserve the upper part of the gland. the number of progressive enlargements of the urethra and the number of rotations of the operation plane. can be modified. The typical solids generated are shown in Fig. 8. Other menus can also be chosen. These allow the operator to control the images, to move the robot and to always have a guide that notifies the surgeon of the functions that have been performed and those that need to be performed in order to complete the definition of the operation. The imposition of the immobility of the veru-montanum takes place in a way that can be seen by the user: the cystoscope is automatically oriented by the system according to the current point.

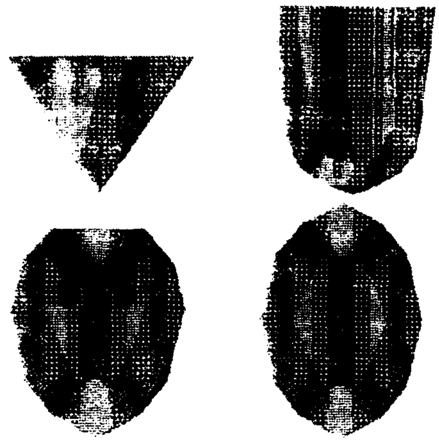

Fig. 7 Typical solids which describe the volume to be removed

The methodology applied consists of the execution of a succession of parabola arches which originate from the vertex and reach the final ultrasound plane. The system positions the robot at the paraboloid vertex. Interpolation of the points constituting trajectory number is then carried out by communicating the coordinates of the points that constitute this place to the robot controller. The succession of points is gradually calculated with a step that depends on the precision imposed by the surgeon. After terminating trajectory no. 1. no. 2 is then calculated and so on.

8. Conclusions

The experiments conducted in the laboratory demonstrated the validity of this project. Simulations were carried out by using an anthropomorphic robot with 6 degrees of freedom. which although capable of simulating the operation has strong limitations in terms of use on a human patient.
On the one hand. the biggest problems concern the overall dimensions of the robot (80 x 120 cm^2) and. on the other. the occurrence of anomalous situations in positioning the robot (due to the presence of specific points and unreachable configurations).
The methodology designed for surgery gave excellent results when the operation was performed with a rotation of $\pm 45^{0}$ in horizontal and $\pm 60^{0}$ in vertical. The accuracy reached is < 1 mm with a speed of several tenths of a millimetre per second, thus improving both precision as well as length of the operation (it takes about half the time). Another two important problems. which led to the development of a dedicated robot. were also evidenced. These consist of the impossibility of physically limiting the robot's work space (if not via software) and the difficulty of identifying the position of the veru-montaunum. The idea of mounting a force sensor on the robot's effector would make the entire system more complex and therefore even less reliable.

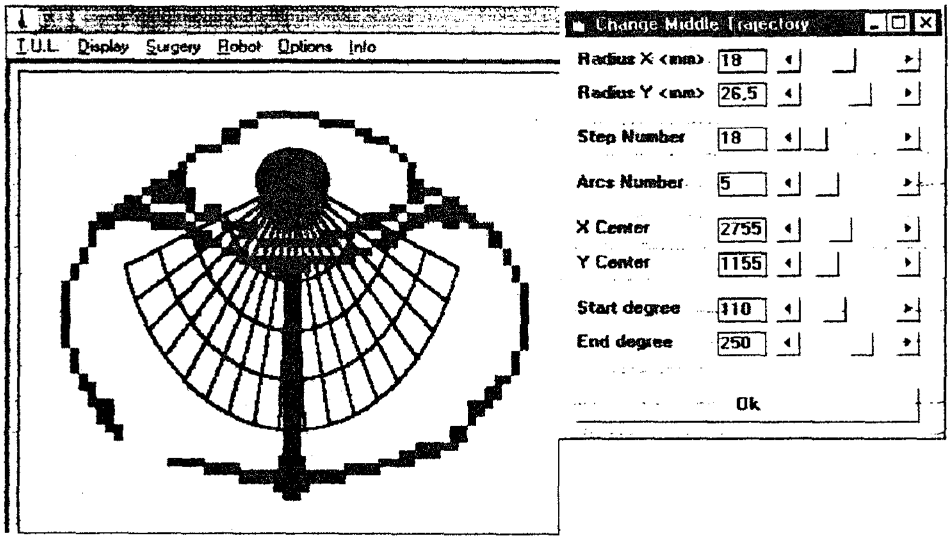

Fig.8 Video interface for definition of the removal trajectories of the prostatic adenoma

The new system was designed to eliminate all the problems evidenced in the previous conception, while simultaneously trying to create an easy-to-use system for the surgeon. Consequently a surgeon/computer interface was developed. Not only is this easy-to-use but also complete. The movement of the robot is handled in a way that is transparent to the surgeon since, the different orientation of the cystoscope, according to the restraint imposed by the veru-montanum, is automatically imposed by the control system. Furthermore the cost of the new robot is much lower than the previous one, thus allowing for a more rapid development and use.

This research wants to increase also the capabilities of graphic interface [14] and it offers an interface for the volume of resection which is familiar for the surgeon, because it presents many shapes, reported in Fig. 7. The surgeon may prepare volumes with an easy interface for the prostatic adenoma resection .

The possible continuation of this work is the application to other robotic surgery, like possibly to the liver and to the bones operation. The robotic system is on development also towards these applications.

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