MECHATRONIC SYSTEM FOR TRANSURETHRAL RESECTION TRAINING

Ángel Asensio, Alejandro Ibarz, Jose Ignacio Artigas, Álvaro Marco
Javier Casas and Roberto Casas
Instituto de Investigación en Ingeniería de Aragón, Universidad de Zaragoza, María de Luna 1, Zaragoza, España
{aasensio,aibarz, jiartigas, amarco, rcasas}@unizar.es

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Abstract: Training the residents who start with endoscopic operations remains a challenge. This paper describes an electromechanical system developed for learning the transurethral resection (TUR) technique. This system can be easily set and cleared up in a classroom, and consists of a supervisor's workbench with a wireless sensing device, connected to several trainees' workbenches with motorised devices. These devices have a resectoscope mounted on an electromechanical structure that is able to reproduce all the movements of an actual endoscopic operation of the prostate.

1 INTRODUCTION

Transurethral resection (TUR) is an endoscopic surgical technique that makes it possible to extract tissue from the prostate in mitigating or corrective operations. It is performed by means of a resectoscope, consisting of a thin cannula that includes an endoscopic lens system and contains a tiny wire loop acting as an electro-scalpel, and operated from the exterior.

Nowadays, video-surgery has simplified TUR training, becoming a common practice among many urologists. However, no urologist hesitates to consider learning this technique difficult and time-consuming. Mere vision of the moving endoscopic image is not enough to acquire the reflexes, manual skill, and mental agility necessary to cope with the recurring occasions in which only solid practical experience will make it possible to handle the situation, and conclude the operation successfully (Pycha, 2003).

Traditional training for novel surgeons is carried out by first explaining the techniques with endoscopic images, to later begin performing very simple operations, directly in the operating theatre.

Work has been done on support for training in endoscopic techniques, and there have also been efforts to devise manipulators for motorised operations guided by the surgeon (Kerfoot, 2004; Gettman, 2003; Katz, 2003; Ottensmeyer, 2000; Ballaro, 1999; Gomes, 1999). However, these systems have certain problems, such as lack of tactile feedback, and their high cost for generalised use in training. Their main objective is to automate operations, not to perform exact imitations of the movements of a surgeon. Our system achieves a great precise reproduction of the movements of an expert surgeon, at a much lower cost.

Another difference with the mentioned line of work is that our proposal aims at low-cost robot systems, specific for this operation, capable of capturing the movements of the resectoscope and reproducing them both in real time and recorded.

For this, we have devised an easy to set and clear up lecture room, practical for use at hospitals. The room has a sensing workbench connected to a computer, and several motor workbenches linked by Bluetooth. All these workbenches are able of reproducing the movements of a hand at the degrees of freedom of the resectoscope. A video monitor shows images of an operation. The sensing workbench senses the movements performed upon it, and the motor workbenches are able of reproducing these movements.

The solution we present in this paper is cost-effective, and has been successfully tested by experienced surgeons. First we detail the specific goals pointed out by the users, which guided us in the design of the solution presented; Next, we analyze in depth each block of the final system.

2 SYSTEM GOALS

The aim of our system is to aid learning of a complex technique of endoscopic surgery, transurethral resection, in order to improve the skill of surgeons and reduce risks for patients. We try to offer a lecture room that permits training in techniques as they are currently performed, in such a way that its structure allows inclusion of more data, and with feasible installation in hospitals (easily set and cleared up in multipurpose halls).

Thanks to the system's modular structure, several different teaching modes are possible:

1. Real time teaching mode: The trainer operates the sensing workbench and movements are repeated in the hands of trainees by means of the motor workbenches. The trainer's explanations can be underlined by videos played on the computer.
2. Recording mode: The trainer watches an endoscopic video on the computer, and simultaneously performs the corresponding movements with the sensing workbench. The movement pattern is stored in the computer, and a video of the operation with embedded information on positions is generated. This video will be used later to control motor workbenches without the presence of the trainer.
3. Recorded teaching mode (without the presence of the trainer): The computer plays a pre-recorded video that controls the motor workbenches.
4. Trainee assessment without trainer: A video is played and trainee operates the sensing workbench; movements are stored in the control board of the sensing workbench. Once the test has ended, data are sent to the trainer's computer, and they are checked against the movement pattern of the expert surgeon.

The technical requirements we have had to deal with are the following:

– The workbenches must reproduce movements with the same degrees of freedom that the surgeon has during an actual operation. The initial hypothesis is that the urinary tract sphincter is fixed in space, which leads us five degrees of freedom. The correctness of this hypothesis and the validation of the movement replicator have been checked during the research actions performed by the group.

– Another very important requirement is synchronization of the endoscopic video playing with the movements of the resectoscope.

– To ensure portability, we envisage a radiofrequency workbench data communications structure using Bluetooth (Anastasi, 2003). Bluetooth chips available on the market managed from a microcontroller based system have been used. Both the hardware and the firmware have been original developments aimed at the present final application.

– One last goal is to allow collection of actual movements data in the operating theatre. In this scenario it is not possible to modify the instruments available to the surgeon, nor interfere with his movements. To achieve this, we propose a new method for sensing and capture of the movement of the resectoscope in the operating theatre, based on ultrasound.

3 DESCRIPTION OF THE ENVIRONMENT

3.1 Basic Scenarios

Next we briefly describe the structure of a possible lecture room. It should be pointed out that some systems share certain common blocks, so these will be described only once.

3.1.1 Trainer's Workbench

Its role is that of a general coordinator, and it comprises several clearly distinct subsystems (Figure 1).

The resectoscope or instrument to be used by the medical personnel is mounted on a mechanical system that allows mobility as if an operation were being performed. For this, three turns (coordinate axes) and two sweeps (cannula and resection loop) are allowed. The trainer will introduce the sequence of movements using this workbench. A set of position encoders capture kinetics directly, or by means of the corresponding transmission ratios.

A digital system based on a Field Programmable Gate Array (FPGA) has been developed for data collection tasks, management of communications, motor device control and memory management. Previous developments were based on microcontroller solutions, but the large number of inputs-outputs and the need for concurrence recommended migration to programmable logic devices. The use of FPGA allows for modular and flexible design, which eases the integration of the various subsystems developed.

A Bluetooth device in this workbench acts as a master of the wireless communications system. It is possible to control a complete network, commanding the various devices and modes, and at the same time the various flows of information.

Acting as a central server, the trainer's workbench relies on computer equipment offering various functions: It controls reproduction of the TUR operation video; it allows storage of movement patterns for later analysis or repetition; and it manages communications and state of the devices in the lecture room by means of Bluetooth linking via electronic system.

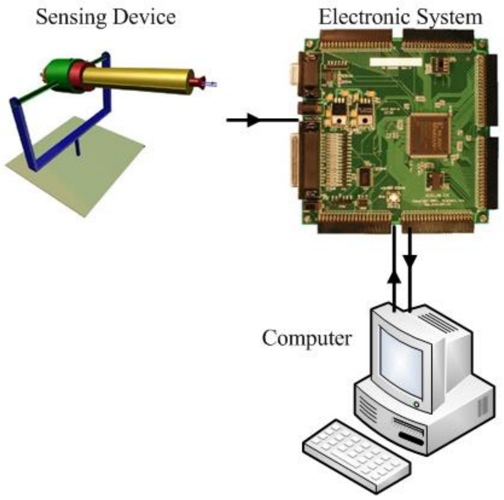

Figure 1: Trainer's workbench.

3.1.2 Trainee's Workbench

The mechanical structure is similar to that of the trainer's workbench (Figure 2). It includes the electromechanical devices allowing reproduction of movements. The student holds the device and feels the movement to be performed. The device retains the position encoders, making available a process of auto-calibration without the need of supervision by the user. A Bluetooth device acts as a slave in the network managed by the trainer's workbench.

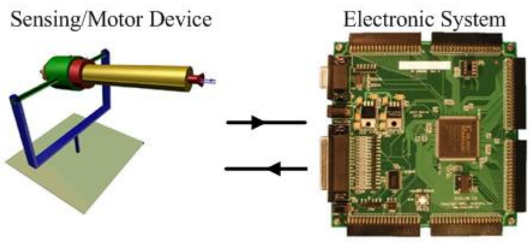

Figure 2: Trainee's workbench.

3.1.3 Installation in Operating Theatre

Figure 3 shows the block diagram of the installation in operating theatre. Encoder-based position capture is not possible in the operating theatre, since the set of instruments cannot be modified (figure 4). We have therefore developed a novel positioning technique based on ultrasound (US) pulses, with the aim of applying it to the capture of the movements performed by the surgeon on the resectoscope in the operating theatre. In this way, it will be possible to document fragments of actual operations with the video information, movements, and other parameters that may be considered relevant. We should point out that the training video is obtained by an endoscopic camera during the operation. Later on, and as a previous step to its use in the training system, it is processed by the computer system.

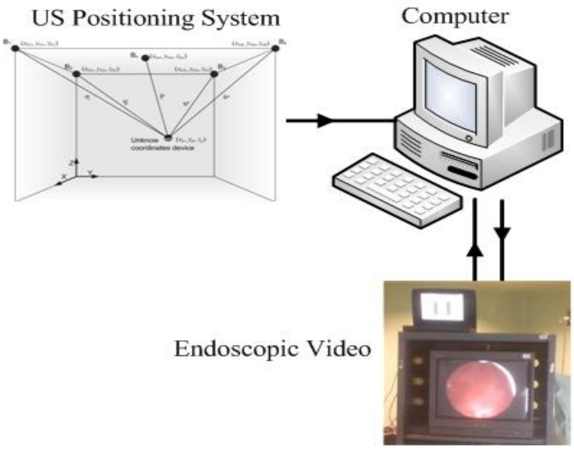

Figure 3: Installation in operating theatre.

3.2 Mechatronic System

Initially, the typical movement of the resectoscope in an operation was studied. Considering the results, to express the movement as parameters, the following hypothesis is adopted: "The point of the resectoscope oppressed by the sphincter is considered still, and this point does not vary throughout the operation".

To all practical effects, it is considered as the origin of the coordinates of the mechanical system. On the basis of this hypothesis, the conclusion reached is the need to design a mechanical system allowing three angular movements, one forward movement for the cannula, another for the cutting-loop, and two for the switches of irrigation and coagulation. To sum up, seven coordinates are used to define the state of the device at a given moment. Four of them reflect the point in space where the end of the resectoscope is, another the state of the cutting loop, and the remainder refer to the state of the switches the resectoscope is equipped with (generally pedal-operated).

According to the explanation offered, the mechanical system should allow the movements detailed in Figure 4.

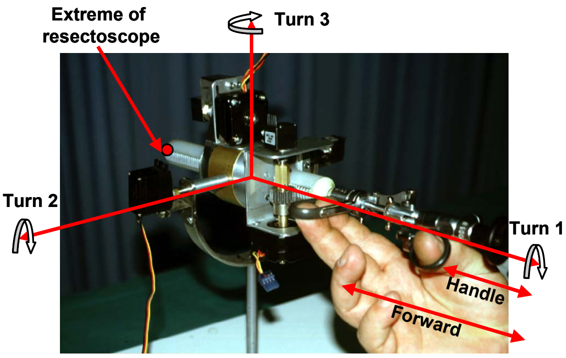

Figure 4: Kinetic diagram of the resectoscope.

The final system has been the result of several different prototypes. At the moment of designing the mechanical system, we have two different kinds of devices:

Sensing device: Conveniently equipped with encoders in order to capture the movements performed with it.

Motor device: Fitted with servo-motors to reproduce movement. In the design phase, this device is also equipped with sensing elements in order to carry out calibration and performance measurements.

The present design is capable of completely valid mobility. The sensing workbench can most realistically imitate any type of operation. Both the sensing and motor workbenches share a similar design, so that they may or may not include motors and sensors, that they may have the required functionality on the basis of a single development. The mechanical similarity between them likewise eases the generation of movements from the stored kinematics.

Various alternatives have been checked for movement generation, among which we could feature step-motors and servo-motors. The latter presents suitable speed-torque characteristic curves, which together with their simple handling have made them the chosen solution. Different kinds of movement must be generated, angular for the three coordinate turns, and longitudinal for the cannula and resection movements. In order to achieve linear movements, mechanical transmission chains have been designed, based on the turning of the servo-motor.

The measurement of the three angular movements is performed with angular encoders. The linear movements are indirectly measured from the electromechanical rotation system. In this way we can use the same kind of sensor for the different movements, with all the advantages of uniformity and simplicity. Specifically, the encoder chosen will be of the digital type and incremental.

Once the mechatronic system implemented, the performance, both kinetic (speed, accelerations, movement ranges and sensitivity) and dynamic (torque) of the system was tested. For this, automated tests have been devised to check the step and ramp response of each motor device.

Finally, several tests were carried out by the medical team, with the goal of simulating the different kinds of movements that actual operations might require. Two models were simulated: cystoscopy (inspection) and resection (operation), as well as a mixed model including various types of movement. On the basis of these tests, we can state that our system correctly replicates a model operation.

3.3 Synchronization

In the system, various temporal distortions may appear, which can generically be grouped as two different sets of problems:

– Data delay: An ideal design in the FPGA will make this negligible in the context of the time intervals operated with.

– Loss of synchronization and regularity between video frames and mechanical positions: Critical aspect. The computers might be unable to send the movement data in a totally regular and predictable way while it reproduces a video or is handling other processes.

Different alternatives have been checked: synchronization by means of video subtitles, real-time operative systems, and modulation in audio channel.

The solution finally adopted is based on use of the video's audio channel. To include the digital information of positions on an analog audio signal, Manchester encoding has been chosen. It has been decided to encode and send the sampling number corresponding to each video frame, rather than all the data for each frame. A Hamming code with distance 4 is applied, to minimize environmental noise. This strategy will make it possible to detect up to three bit errors, and correct up to one bit. The frame under the Hamming format is Manchester encoded and modulated upon the audio channel. Both processes have been carried out with Matlab. The final application generates an audio file containing the sampling numbers, spaced the exact time needed. This file is included in the video, so that we have a video with exact time marks indicating a sampling number. In normal use, an audio channel carries the frame number we are at, and the other channel may include trainer's comments.

Before the use of a trainee's workbench, a massive download of positions in each motor system is performed from the computer to the local FPGA. During the video playing, the time marks are extracted and the local memory is searched for the associated positions.

3.4 Computer System

The computer system presents two layers. One of them is opaque to a certain degree for the end user, and collects the data of the different blocks and integrates them. Also, it calculates the kinematics of the resectoscope during the operation, using the obtained data from the ultrasound location system. Finally, it generates the movement references for the device, synchronized with the endoscopic video.

The computer system has another aspect, intended for the end user in the training context. A simple and friendly user interface is offered for interaction in the lecture room (Figure 5). It includes a video player and a manager of the various operation modes that the trainer may request. The more tedious tasks, such as Bluetooth node management and processes with data files have been completely automated.

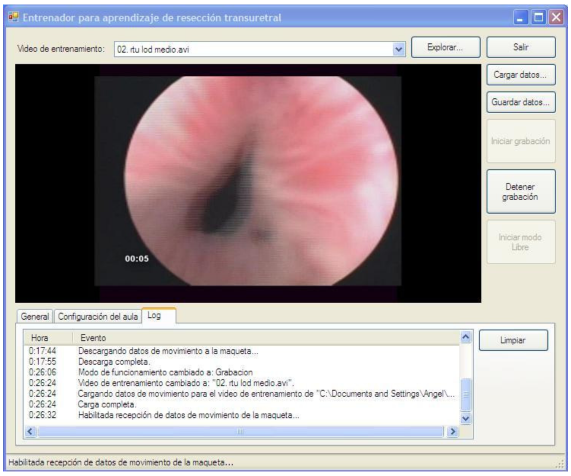

Figure 5: Computer system. User interface.

4 OPERATING THEATRE POSITIONING

It is interesting to see how different data are obtained in the operating theatre, such as the endoscopic video of the operation and the actual in situ trajectory followed by the resectoscope. Obtaining the endoscopic video is possible with commercial equipment, so we will concentrate on the analysis of the problems regarding highly accurate location. The different alternatives allowing a sufficiently exact positioning were analyzed, with the main focus on optical, radiofrequency and ultrasound solutions. Several aspects, such as economy and environmental constraints pointed to ultrasound positioning as the ideal method.

Through high precision positioning by ultrasound waves, it is possible to locate an object within a given volume with a tiny error margin, simply and quickly, without any necessary physical contact with the point to be referenced (Fukuju, 2003; Casas, 2004; Mahajan, 2001; Prigge, 2000). The initial idea was to obtain a system allowing capture of the position of the resectoscope during an actual operation in the operating theatre; the system should therefore have very restrictive features.

In the case of our application, there are certain key aspects defining the location system, due to the characteristics of work in an operating theatre.

The range of the system must agree with the dimensions of the operating theatre (in our case, up to 3.5 metres).

Given the need for a precise reading of the kinematics and of the position of the resectoscope, the positioning refresh rate must be as high as possible. It has been possible to obtain up to twenty references per second.

In order to achieve millimetric errors in the position of the resectoscope, it was necessary to analyze other factors of the design: the possibility of background noise, disadjustment of probes, environmental factors (temperature and humidity), and reflected ultrasound waves due to reflecting surfaces.

The probes of the emitter modules (Figure 6) are joined to the resectoscope in fixed positions. Three probes are usually necessary in order to later infer the position and direction of the instrument from them.

The receiving probes will be attached to the ceiling of the operating theatre in positions with known coordinates, with the necessary precision to later give references for the emitting probes in the

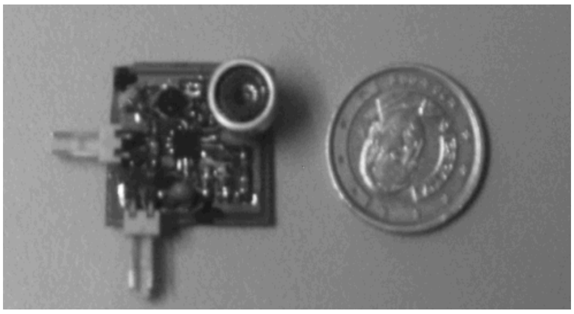

Figure 6: Emitter probe.

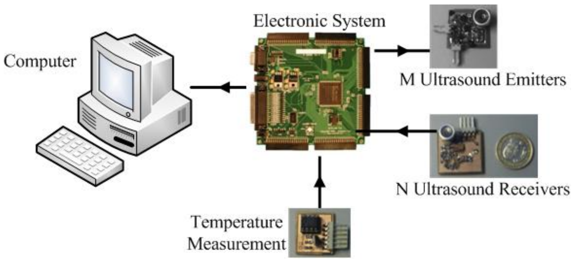

Figure 7: Precision positioning block diagram.

space. A redundant number of probes make possible to minimize the effects of occlusions.

The system includes the blocks shown in figure 7.

The control system will send a signal to the corresponding emitter modules, to generate the ultrasound pulse train, and simultaneously the time-of-flight of the ultrasound waves to the receiver modules will be measured. During the time-of-flight of the ultrasound pulses a measurement of the temperature will be obtained, to compensate the data. The features and pattern of the pulse trains generated are critical for the system. Their generation is based on a self-interference strategy, in which the optimum phase and counter-phase periods have been obtained analytically and empirically. In the receiver, filtering is an equally delicate process, articulated around a second order Rauch filter followed by a high speed comparator.

The receiver modules will send the received signal, filtered and conditioned, to the FPGA, which will capture and process the data in order to calculate the times-of-flight of each emitter-receiver pair, as well as reliability indicators of each measurement for their later processing. Once all of the data have been processed, it will send all the information obtained to the computer together with the temperature measurement. The computer will calculate the distances between each of the emitter-receiver pair.

After obtaining the distances between emitter and receiver probes, the coordinates of the emitter probes are calculated by an algebra resolution

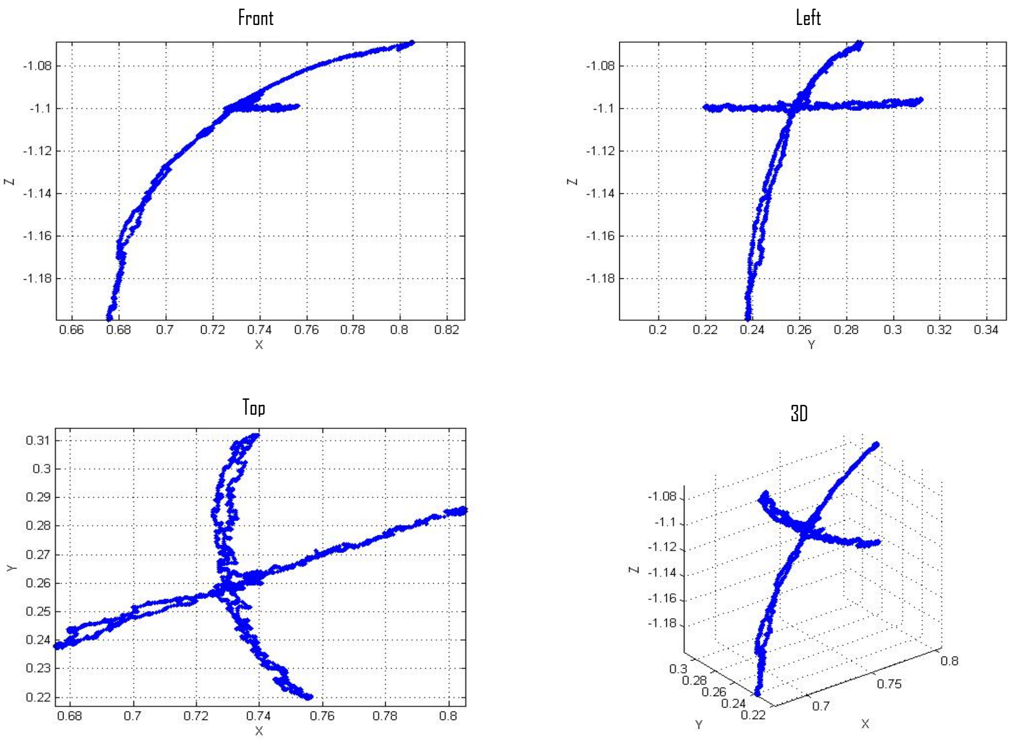

Figure 8: Positions of the end of the resectoscope.

method (Casas, 2004) and a solution filtering algorithm based on the least median of squares (Casas, 2006). Once the positions of the emitter probes have been obtained, the trajectory of the resectoscope is obtained as well.

In order to verify the system, an experiment set-up has been designed with the motor workbench managed by the computer system in auto-calibration mode. Figure 8 illustrates the results obtained. It shows the position of an emitter probe located at the end of the resectoscope. An emitter transducer is attached to the mock up, which moves using a predefined pattern. With three receivers, the results are very accurate (few millimetres), and even the bounces and oscillations of the mechanical system itself can be detected.

5 CONCLUSIONS

Training surgery residents who start with endoscopic operations remain a challenge. This paper has described an electromechanical system developed for learning the TUR technique. It consists of a trainer's workbench with a wireless sensing device connected to several trainees' workbenches with motorised devices. These devices have a resectoscope mounted on an electromechanical structure able to reproduce all the movements of an actual endoscopic operation.

The system has several operating modes that will make it possible to:

– Reproduce the movements of an expert surgeon in the hand of the trainee.

– Reproduce the pre-recorded movements of an actual operation in the hand of the trainee.

– Assess the level reached by the student before participation in any operations or in solving problems requiring a certain degree of experience.

As a complement, a millimetrically accurate, ultrasound-based positioning system has been developed. This will be mounted on a resectoscope in order to capture the movements performed in an real operation. The management software of the training room allows easy integration of these data with the endoscopic video, to rely on an adequate operations database.

What remains is to assess this tool in the practical conditions of training urology residents in the use of medical equipment, which will doubtless offer most interesting data regarding the use or need for modifications of the global system.

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