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PARASURG hybrid parallel robot for minimally invasive surgery

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Rezumat

Un robot paralel hibrid pentru chirugia minim invazivă asistată robotic - PARASURG

În lucrare se prezintă robotul paralel hibrid PARASURG 9M, proiectat şi realizat în întregime în România. Este un robot versatil, fiind alcătuit dintr-un modul de poziţionare şi orientare, PARASURG 5M cu cinci grade de libertate, la capătul căruia poate fi ataşat fie un laparoscop, fie un instrument activ de tăiere/prindere denumit PARASIM cu patru grade de libertate. Pe baza modelării matematice a robotului, s-a construit primul model experimental cu cost redus al robotului chirurgical. Robotul face parte din sistemul chirurgical PARAMIS cu trei brate, unul fiind folosit pentru conducerea laparoscopului, celelate două pentru conducerea instrumentelor active. În situaţia în care este folosit ca şi manipulator al camerei, utilizatorul are posibilitatea de a da comenzi de poziţionare a laparoscopului într-un spaţiu de lucru mare utilizând multiple interfeţe de comandă: joystick, microfoane, tastatură&mouse si dispozitiv haptic. Dacă se ataşează instrumentul activ PARASIM, robotul se poate conduce cu ajutorul dispozitivului haptic. Caracteristicile esenţiale care recomandă robotul PARASURG 9M pentru chirurgia minim invazivă sunt: precizia; eliminarea tremorului natural al chirurgului; comanda directă de către chirurg printr-un mod de vizualizare precis, lin şi stabil al câmpului chirurgical; eliminarea necesitatăţii prezenţei unui al doilea chirurg pe tot parcursul unei operaţii (în cazul utilizării ca şi manipulator al camerei); creşterea dexterităţii chirurgului în cazul utilizării instrumentului PARASIM; ergonomia crescută a utilizării robotului (chirurgul trebuie să adopte o poziţie dificilă timp îndelungat în cazul intervenţiilor laparoscopice clasice, pe când robotul nu oboseşte niciodată). Având un sistem de comandă relativ uşor de înţeles şi intuitiv, doctorii chirurgi se pot adapta foarte rapid să folosească robotul PARASURG 9M în procedurile chirurgicale.

Cuvinte cheie: chirurgie asistată robotic, robot paralel hibrid, instrument chirurgical activ, sistem de comanda, simulare, interfata de lucru

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Abstract

This paper presents the parallel hybrid robot, PARASURG 9M, for robotically assisted surgery, a robot which was entirely designed and produced in Romania. It is a versatile robot, being composed of a positioning and orientation module, PARASURG 5M with five degrees of freedom, having the possibility of attaching at its end either a laparoscope or an active surgical instrument for cutting/grasping, PARASIM, with four degrees of freedom. Based on its mathematical modelling, the first low-cost experimental model of the surgical robot has been built. The robot is part of the surgical robotic system, PARAMIS, with three arms, one used as a laparoscope holder, and other two for manipulating active instruments. When it is used as a manipulator of the camera, the user has the possibility to give commands in a large area for the positioning of the laparoscope using different interfaces: joystick, microphone, keyboard & mouse and haptic device. If the active surgical instrument, PARASIM, is attached, the robot commands are given through a haptic device. The main features that make the PARASURG 9M surgical robot suited for minimally invasive surgery are: precision, the elimination of the natural tremor of the surgeon, direct control over a smooth, precise, stable view of the internal surgical field for the surgeon. It also eliminates the need of a second surgeon to be present for the entire procedure (in the case of using the robot as a camera holder). In addition, there is improvement of surgeon dexterity in the case of using the PARASIM active instrument and better ergonomics in using the robot (in the case of the classic laparoscopy, the surgeon must adopt a difficult position for a long period of time, while the robot never gets tired). Having a relatively easy to understand, intuitive commanding system, the surgeons can rapidly adapt to the use of the PARASURG 9M robot in surgical procedures.

Key words: robotically assisted surgery, hybrid parallel robot, active surgical instrument, control system, simulation, interface

Introduction

Robots are useful tools in minimally invasive surgery (MIS), providing benefits such as elimination of hand tremor, better access, possibility of working in awkward positions, workspace scaling and tele-operation. It has already been shown that the progresses of engineering and medicine have opened the way for the use of the robots in operating rooms (1, 2).

One of the first robots created for medical purposes is AESOP, produced by Computer Motion, used in MIS dating from 1993 (3). The AESOP® robotic arm series (1000 to 3000) have been initially activated by a foot pedal, and later by voice control (4-6). After several versions of this robot have been developed, they finally developed ZEUS Robotic Surgical System with three robotic arms attached to the side of the operating table (3). EndoAssist (7) is another camera manipulator having four degrees of freedom, produced by Armstrong Healthcare Limited, UK and commercially available. The interesting fact about EndoAssist is the control, as the robot is programmed to detect and follow the movements of the surgeon's head. LAPMAN (8) is a dynamic laparoscope holder with three degrees of freedom guided by a joystick clipped onto the laparoscopic instrument enabling the basic positioning commands for the camera, as shown in Saing et al. in (9).

The most well-known commercial robot is the da VinciTM Surgical System (10) produced by Intuitive Surgical Company. It falls under the category of tele-surgical devices, meaning a human directs the motions of the robot. The da Vinci uses technology that allows the human surgeon to get closer to the surgical site than human vision could allow, and work at a smaller scale than conventional surgery permits. Sitting at the control console, a few feet from the operating table, the surgeon looks into a viewfinder to examine the 3-D images being sent by the camera inside the patient. The images show the surgical site and the two or three surgical instruments mounted on the tips of the surgical rods. The surgeon uses joystick-like controls located underneath the screen to manipulate the surgical instruments. Thanks to 7-DOF laparoscopic instruments, this robot allows the surgeon to perform meticulous surgical operations in restricted and difficult-to-reach areas. Due to its very high price, its large volume, and its technological complexity, this system is not the final solution accepted by the surgical community.

Probably the most important competitor for da Vinci is the system produced by Titan Medical Corporation and called Amadeus (11). Amadeus® uses cutting edge hardware and software from medical, defence, and aerospace industries. New surgical capability is created as a result. Surgeons are able to conduct local or long distance robotic surgery for treatment or training, and can seamlessly switch between the two. The surgical console is a new design, force feedback and enhanced vision system, enabling unprecedented ease of instrument control and system functions.

Another robot that was developed in the research laboratories is Sophie (12) produced at Eindhoven University of Technology and designed by Linda van den Bedem. Sophie is controlled via joysticks on a control panel, which becomes harder or easier to move, depending on how much pressure the robotic surgical instruments are exerting against the patients' tissues. Such a system could be particularly useful for tasks such as making sutures, as it should give surgeons a better sense of how tightly they pull the thread. Van den Bedem's creation is also quite compact and is mounted on the operating table instead of the floor. This means that, when the table is tilted or moved within the room, Sophie will move with it, so no readjustments will be necessary.

The "da Vinci S" robotic system was acquired by the Surgery Clinic and Liver Transplantation of Fundeni Clinical Institute in 2008. Since that time, Prof. Dr. Irinel Popescu and his surgical team from Fundeni Hospital have operated daily with the da Vinci Surgical Robotic System for various MIS interventions (13). By March 2009, 200 surgical interventions with the da Vinci system have been reported, (14-16). In November 2009, a "da Vinci SI" robotic system was acquired by the Municipal Hospital (also known as Surgery Clinic V) in Cluj Napoca. In seven months 70 surgical interventions with this robot were performed, all of them being successful. The Romanian surgeons were trained by an Italian surgery team from Milano. This experience suggests that the robotic surgery is safe, feasible and worth for clinical applications. The use of the robot allows surgeons to perform complex procedures, otherwise performed by laparoscopy, not necessarily the classical procedure.

In (17, 18, 19, 20) the PARMIS parallel robot for minimally invasive surgery was presented. It is a robot with three degrees of freedom, designed as a laparoscope holder. The Research Centre for Industrial Robots Simulation and Testing–CESTER (Prof. Doina Pisla) within the Technical University of Cluj-Napoca, Romania, started in 2005 a joint research with the Surgical Clinic III (Prof. Liviu Vlad), within the

University of Medicine and Pharmacy of Cluj-Napoca, Romania, and the Institute of Machine Tools and Production Technology (Prof. Jürgen Hesselbach) of the Technical University Braunschweig, Germany, aiming at developing parallel robots for surgical applications. PARAMIS was the first product of this collaboration, being also the first surgical robot produced by a Romanian team.

Material and Method

Description of PARASURG 9M Robotic Arm

Among the main requirements that surgeons impose for a surgical robot used for minimally invasive surgery, following may be mentioned (21): the robot control has to be accurate, the robot has to be stable and rigid in the operating room, the robot should have low size, maximum speed of 1 cm/s, robot precision 1 mm, maximum rotation (left/right): 90°, etc.

A surgical robotic system, PARAMIS, is being developed within CESTER – *Fig. 1*. The robotic system consists of: one arm used as laparoscope holder and another two arms for the active instruments. The first arm, presented in (19) (PARAMIS) had actually all of the characteristics presented above, but practice has proved that there are situations when the abdominal wall is under a lot of pressure in certain positions when using the robot as a laparoscope holder, in this way reacquiring a mechanism that will hold the camera and release some of that pressure. As observed from *Fig. 1*, the PARASURG 9M robotic arm is composed from the PARASURG 5M parallel robot and the PARASIM active instrument used, among others, for grasping, cutting, suturing.

As it has already been presented, the structure presented in this paper has nine degrees of freedom: three degrees of freedom for general positioning of the camera/instrument, two degrees of freedom for the orientation module, so that the camera will not have to rely on the abdominal wall, and four degrees of freedom for the active surgical instrument. The robot structure is based on an already registered patent (23). The robot has a hybrid parallel mechanism assuring high rigidity due to its closed chain. *Fig. 2* presents the virtual model of the PARASURG 5M robot as a laparoscope holder, and *Fig. 3* shows the PARASURG 9M robot.

The advantage of PARASURG 5M compared to PARMIS is the better camera guiding and the avoidance of a certain pressure on the abdominal wall. But, and perhaps the most important fact, is that this robot can be used to guide an active surgical instrument.

The experimental model of PARASURG 9M

The experimental model of PARASURG 5M is presented in *Fig. 4*. The robot was entirely designed and built in Romania, aiming to achieve a low-cost structure. The system has 9 motors, three of them being placed in the box (base of the robot), all being identical, a module with another two identical, but smaller than the others, at the end of the robot arm, used to position and orient the active instrument

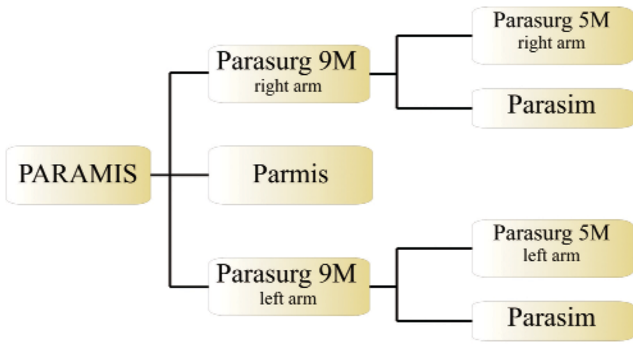


Figure 1. *The PARAMIS robotic system for MIS*

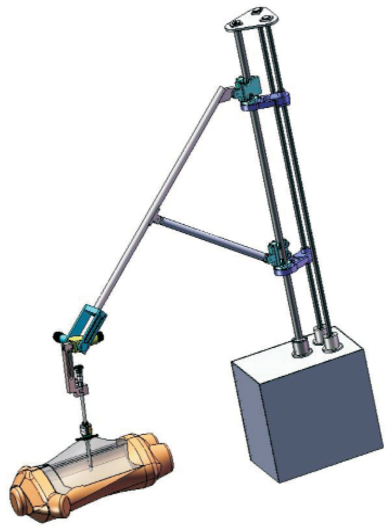


Figure 2. *The virtual model of the PARASURG 5M parallel robot for MIS as laparoscope holder*

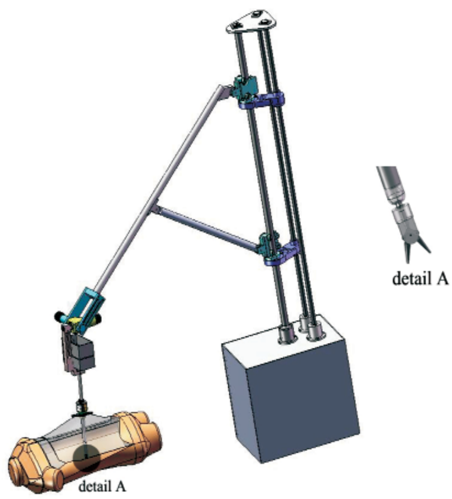


Figure 3. *The virtual model of the PARASURG 9M parallel robot for MIS as active instrument holder*

Figure 4. The experimental model of PARASURG 9M

(or laparoscope), and the PARASIM surgical instrument with four degrees of freedom, three of the used to orient the head of the instrument and another one for the active function. The figure also presents a human torso trainer with cholecystectomy model from Simulab (24) with internal organs.

The control system and user interface of PARASURG 9M

The control system structure of PARASURG 9M is presented in *Fig.* 5. It is mainly composed of four levels (stages):

The introduction of the command (the user inputs). The control structure of the system is designed in such a way that the robot can be controlled by using mouse & keyboard, haptic (25) and vocal commands. The last type of control is used when positioning and orienting a camera, the haptic being used to control the instrument, while the mouse & keyboard is an alternative mostly to the voice control.

The whole processing is achieved within a personal computer that provides a user interface and processes the data from the input controls, or in other words, the commands given by the user. Based on the parallel robot kinematics and its current position, the motion parameters of the robot are calculated. Knowing the workspace of the robot, eventually other obstacles that might appear and each robot displacement is first calculated, verified and validated and only afterwards, the actual motion of the robot is executed.

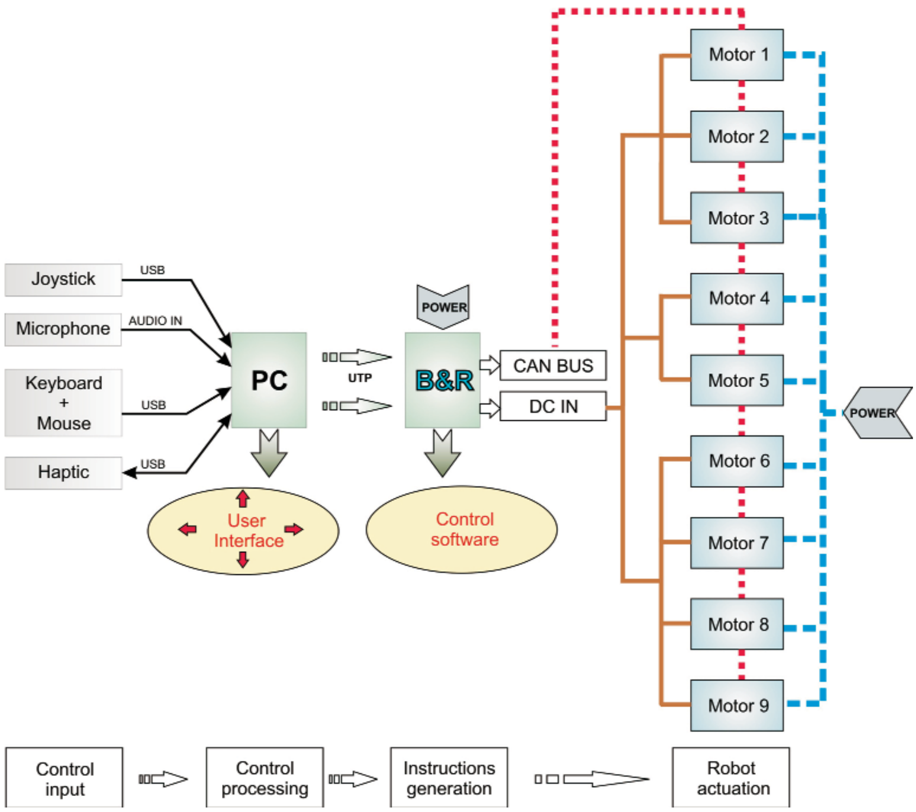
The calculated motion parameters are then transmitted via an Ethernet interface to the programmable logic controller (PLC) where the instructions are generated.

The PLC generates the control code for the motors of the robot and through the Controller–area network (CAN) the robot actuators will be positioned based on the calculated data.

There is a network of proximity sensors between the motors and the PLC that are used to establish the zero position of the robot. To increase the security level for the exploitation of the robot, there are control elements, both to the level of the commands processing and to the level of the assembly PLC – robot.

At each session of work with the robot, the running of the

Figure 5. The control system structure of the PARASURG 9M robot



initialization commands is necessary. The first command would be the one of initialization of the sensors system that determine the position of the actuators and allows the control over the position of the robot. This is obtained by running the NEST command. By running the ORIGIN command, the robot is positioned in such a way that it is ready for the insertion of the laparoscope/active instrument into the abdominal cavity. The coordinates of the incision point at the top of the abdominal cavity of the patient are also saved. This position is crucial, since all the movements of the robot will be relative to this point.

After initializing the system, the user has to be able to set up the motion parameters for the tip of the active instrument (the increment for the displacement, the speed and acceleration) as well as to define a safety area within the surgical field. The latter one is highly intuitive, since the volume of the robot workspace inside the abdominal cavity and its correctness is up to the surgeon that conducts the operation. The safety workspace is defined as a cube, where the laparoscope will be forced to remain. This is done by positioning the laparoscope inside the patient and saving the limits on left, right, up, down, in and out. A special function of temporary cancelling the workspace limits of the laparoscope/instrument inside the patient was added in order to allow the surgeon to move beyond the safety limits.

The positioning of the laparoscope/active instrument inside the patient will be done by using a set of commands that will be kept, irrespective of the type of commands. These commands are used for the actual displacement of the laparoscopic camera, using time based commands or increment based commands in order to obtain the best view of the surgical field. The displacement increment may be any value between 1 and 20 mm (for the camera again).

In certain cases, during an intervention, the surgeon has to visualize a certain area, or avoid certain obstacles, and, in order to do this as easily as possible, there was introduced a set of commands that allows to save up to three positions in the safety workspace of the robot where it can go back from any current position. There are three buttons with which the saving command will actually be achieved: Save, Return and Clear.

A speech tool developed by Microsoft, Speech SDK (Software Development Kit) has been used in the case of the voice control mode. Easily integrated in Visual Basic, a voice recognition module has been developed. The PC allows the configuration of individual voice profiles that, with little training, can offer over 99% correctness in speech recognition.

Emergency stop: Stop;

Positioning: Go Up, Go Down, Go Left, Go Right, Go In, Go Out (incremental) Move up, Move Down, Move Left, Move Right, Move In, Move Out (duration);

Parameters setup: Increment Plus/Minus, Speed Plus/Minus, Acceleration Plus/Minus;

Position saving: Save One, Return One, Clear One (two and three) – for saving, going to and clearing a position of the laparoscope in the surgical field.

When at the end of the robot arm one attaches an active surgical instrument for cutting/grasping/suturing, the best way to command the robot is through the haptic device Omega 7 with seven degrees of freedom. Using this device, the instrument will follow the movements of the haptic device. Three degrees of freedom of the Omega 7 will be enough to position and orient the instrument, while the others will be necessary to actuate the head of the instrument that has four degrees of freedom. A very important function will be the scaling of the motions, since the haptic workspace is much smaller than that of the robot. In this way, a small motion of the haptic will be translated into a wider motion of the robot or vice versa. It is also important to be able to change the scaling according to the surgeon's requests. Changing the scaling according to the surgeon's requests is another important feature for this robot. Another important function will be the capacity to move the haptic independently of the robot. This is also related to the fact that the robot workspace is much larger than that of the haptic device. This will be done by pressing a button that will interrupt the connection between the haptic and the robot, so that the robot will not follow temporarily the motions of the haptic until the surgeon decides otherwise.

The robot can be covered in a plastic sheet, due to its compactness, so there is no contact between the robot and the outside world. The only part of the robot that has to be sterilized is the instrument.

A fast connecting device was added at the end of the robot arm, in order to be able to detach as fast and easily as possible the camera or the instrument from the robot in case of emergency. This was possible by using a helicoidally arc that presses on a ball that, at its turn, presses on the camera/instrument. After detaching the instruments from the robot arm, the robot is moved apart from the operation table (since it will be placed on a separate wheeled table) to create space for the medical personnel to approach the patient.

The PARAMIS surgical system

Both the PARMIS and PARASURG 9M robotic arms will be integrated into a three arms robotic system (the PARASURG 9M robotic arm and instrument will be doubled – one for each arm of the surgeon), system called PARAMIS. The structure of the system is presented in *Fig.* 6. If in the case of PARMIS (and PARASURG 5M), several ways of controlling the system

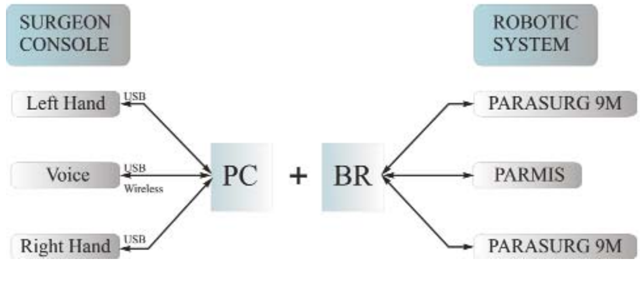


Figure 6. *The general control structure of PARAMIS robotic system*

Figure 7. *The robots PARMIS and PARASURG 5M working together*

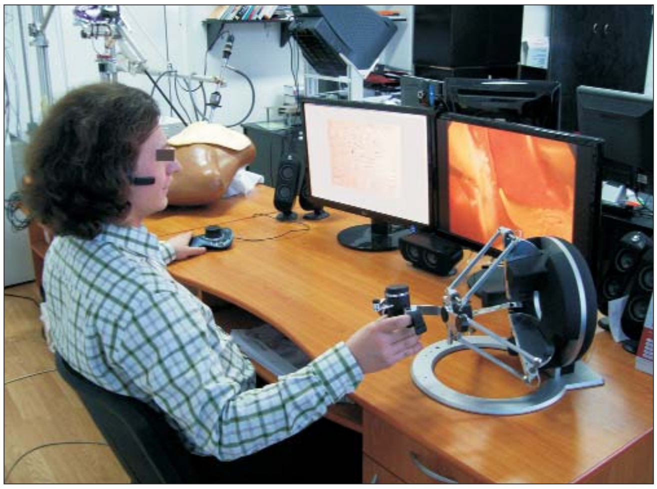


Figure 8. *The robots PARMIS and PARASURG 5M controlled by voice, respectively by the haptic device*

were possible – by voice, mouse & keyboard, haptic, in the case of using the whole system, for the arm that positions the camera, only the voice command (as requested by the surgeons) will be used. But, the PARASURG 9M can be controlled only by the haptic device. Sometimes, for a more precise positioning of the camera, the surgeon can use the haptic device by pressing a commuter button that interrupts the communication between the haptic and the active instrument arm and connects it to the camera arm. If for the PARMIS robot, the PLC had to control three motors and for the PARASURG 9M nine motors, in the case of the integrated system PARAMIS, there are 21 actuators that the PLC will have to control. In this system, the timing of the instruction executions is essential, since the number of motors that the PLC has to control is very large. At present, an algorithm to allow the best positioning of the camera and instruments in such a way that they do not collide is being developed. In *Fig. 7* are presented the robots PARMIS and PARASURG 9M working together and in *Fig. 8* the voice and haptic command of the PARMIS system is presented.

Results

Laparoscopic Cholecystectomy using the PARAMIS robotic system

The PARAMIS robotic system has been tested on a human torso provided by Simulab on which a cholecystectomy has been performed.

The used model was an artificial liver, with the gall-bladder and the bile ducts (24). The PARMIS arm was controlled by the surgeon using vocal commands, while the PARASURG 9M was controlled by the same surgeon using the haptic device as the right arm of the robotic system. The left arm of the robotic system was supplied by a surgeon. During the procedure, up to three key-positions can be saved using specific command allowing the surgeon to return rapidly to these points. The movements for both the PARMIS and PARASURG 9M can be scaled, allowing the surgeon to get a large or a short movement of the laparoscope. The tests allowed acknowledging the advantages and disadvantages of the robotic system.

Discussion

As compared to the classical laparoscopic surgeries, the PARAMIS robotic system solution has several advantages: absence of natural tremor for the laparoscope/active instrument; absence of eye fatigue; direct control over a smooth, precise, stable view of the internal surgical field for the surgeon; no fatigue; motion scaling; increased ergonomics; the existence of supplementary functions that allow certain positions to be saved for easy returning; elimination of the fine tremor; the active instrument will not lean on the abdominal wall of the patient, in this way increasing the positioning precision of the tip of the tool, the large motors are placed at the base of the robot, reducing the weight that these have to carry, plus the elimination of the translational joint that might self-block (as in the case of PARMIS); increased dexterity by using the PARASIM active instrument; open architecture allowing continuous improvements and customization.

In the near future, a second robot identical with PARASURG 9M, will be added, in order to complete the PARAMIS robotic system.

Conclusion

The robot presented in this paper has a hybrid parallel, lightweight and simple structure for minimally invasive surgery. One of the main tasks of the project was to develop an affordable and compact solution for the use in the operating room, using force-feedback. The estimated costs for the PARAMIS robotic system would be of about 150.000 Euro, a much lower price compared to the commercial systems already existing on the market.

Acknowledgments

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