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PARAMIS parallel robot for laparoscopic surgery

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Rezumat

Robotul paralel PARAMIS pentru chirugia laparoscopică

Lucrarea prezintă robotul paralel PARAMIS, care s-a realizat în Romania şi este utilizat pentru poziționarea camerei laparoscopului. Pe baza modelării matematice a robotului, s-a construit primul model experimental cu cost redus al robotului chirurgical. Sistemul a fost asfel conceput încât are posibilitatea de a se transforma într-un sistem multiarm comandat de la consola de lucru. Utilizatorul are posibilitatea de a da comenzi de poziționare a laparoscopului într-un spațiu de lucru mare utilizând multiple interfețe de comandă: joystick, microfoane, tastatură&mouse si dispozitivul haptic. Au fost obținute primele rezultate prin realizarea unei colecistectomii folosind robotul chirurgical PARAMIS. Modelul utilizat a fost un ficat de porc extras cu colecist si cai biliare. Datorită modului facil de utilizare a sistemului de comandă, chirurgii se pot adapta foarte rapid să folosească robotul PARAMIS în procedurile chirurgicale. Se pot evidenția avantaje ale utilizării robotului parallel PARAMIS: precizia mişcărilor; absența tremorului natural al operatorului laparoscopului; comanda directă de către chirurg printr-un mod de vizualizare precis, lin şi stabil al câmpului chirurgical; robotul nu oboseşte niciodată; robotul permite utilizarea ambelor mâini de către chirurg; elimină tremorul fin, reduce oboseala ochilor şi elimină necesitatea prezenței unui al doilea chirurg pe tot parcursul unei operații.

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Abstract

The paper presents the parallel robot, which has been developed in Romania and it is used for laparoscope camera positioning. Based on its mathematical modeling, the first low-cost experimental model of the PARAMIS surgical robot has been built. The system has been built in such a way that it has the possibility to transform it in a multiarm robot controlled from the console. The control input allows the user to give commands in a large area for the positioning of the laparoscope using different interfaces: joystick, microphone, keyboard & mouse and haptic device. The first results have been obtained through the performing of an experimental laparoscopic cholecystectomy using PARAMIS surgical robot. The model which was used was a porcine liver, removed with the gall-bladder and the bile ducts. Due to its very easy use control system, surgeons have adapted rapidly to the use of PARAMIS in surgical procedures. Some of its advantages could be emphasized: precision of the movements; absence of the laparoscope operator's natural tremor, direct control over a smooth, precise, stable view of the internal surgical field for the surgeon; no fatigue; allows the use of both hands for the actual procedure; reduces eye fatigue; eliminates the need for a second surgeon to be present for the entire procedure.

Key words: robotic surgery, parallel robot, control system, simulation, interface, cholecystectomy

Introduction

It has already been shown that the progress in engineering and medicine has opened the way for the use of the robots in the operating rooms (1, 2). Robots are useful tools in minimally invasive surgery (MIS), providing benefits such as reduction in hand tremor, navigation, and workspace scaling. Russel Taylor, published a study in 1996 (3), pointing out the pros and cons of using the robotic systems for surgical applications.

There are some investigators focused on exploring the capabilities of robots in the field of medical applications (4,5,6). Jaspers et al. (7) have published a detailed presentation of all camera and instrument holders for MIS. AESOP robotic arm was the first robotic manipulator of laparoscopes used in MIS dating from 1993 (1). The AESOP® robotic arm series (1000 to 3000) have been activated initially by a foot pedal and later by voice control (8-10). After Aesop, Computer Motion created Zeus™ Surgical Robot with three robotic arms attached to the side of the operating table (1). Another robotic system is the ENDOASSIST® which is a console positioned alongside the patient, controlled by an association of foot and head activation through infrared technology (11). Aesop and Endoassit have been compared in experimental conditions (12).

The LAPMAN® (13) is a dynamic laparoscope holder guided by a joystick clipped onto the laparoscopic instruments under the operator's index finger. It has been tested successfully in pilot studies in laparoscopic gynecologic surgery (13,14).

Intuitive Surgical Company designed a fully operational robot, da Vinci™ Surgical System (15). The da Vinci Robotic System is now the most complex robotic surgical system used worldwide for different procedures. Thanks to 7-DOF laparoscopic instruments, this robot allows the surgeon to perform meticulous surgical operations in restricted and difficult-to-reach areas. However, its very high price, its large volume, its technological complexity, and long set-up time, made it not yet entirely won-over the surgical community and its cost-effectiveness still needs to be assessed.

In Romania, the robotic surgery is only at the beginning, mainly because a robotic surgery system is very expensive and doctors need to be trained to use it. Starting with the 14th November, 2005 Romania has become the first Eastern European country where doctors have successfully performed a cardiovascular robotic surgery using the da Vinci™ system.

In 2008 a "da Vinci S" robotic system was acquired by the Center of General Surgery and Liver Transplantation of Fundeni Clinical Institute. Since 2008, Prof. Dr. Irinel Popescu and his surgical team from Fundeni Hospital operate daily with the da Vinci Surgical Robotic System for various MIS interventions (17). After one year of work, this Center reported 153 surgical operations, which have been perfomed by means of the da Vinci Robot (17-20). 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.

Most of the robots, which assist the surgeons, are serial robots (1). The serial module generates a large operational workspace while the parallel module is steadier and offers a high accuracy during the surgical operation. The actual robotic systems also have some drawbacks such as: they are large and cumbersome, occupying large volumes around the operating table and above the patient; the surgeon's console ergonomics imposes a very high number of training hours; the surgeon relies only on visual feedback losing the tactile facilities; the current systems are limited to certain types of surgery and the market price is prohibitive.

Parallel robots offer higher stiffness and smaller mobile mass than serial robots, thus they allow faster and more precise manipulations (21). In the field of robotics assisted surgery, the drawbacks of serial robots motivate the search of task oriented robot architectures that best fit a specific group of medical applications. In the case of a robotic system for MIS, previous studies have shown that the parallel and hybrid structures are more adequate than serial ones in this field (4,7).

Center 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 Cluj-Napoca, Romania and the Institute of Machine Tools and Production Technology (prof. Jürgen Hesselbach) of the Technical University Braunschweig, Germany aiming to develop parallel robots for surgical applications.

The paper presents the first made parallel robot – PARAMIS (PARAllel Robot for Minimally Invasive Surgery) in Romania, which is used for laparoscope camera positioning.

Material and Method

Description of PARAMIS Robotic System

At first, the requirements for a base robotic module for surgical instruments positioning have been established (22): the robot should have low sizes; the robot structure must be rigid and stable in the Operating Room (OR); the robot assisted procedure must present a minimal damage to the patient.

Starting from these requirements, a new parallel structure – PARAMIS has been developed, which can be used for surgical instruments positioning (23). *Fig. 1* presents the virtual model of the robot. The low-cost structure will allow a wider spread of the robot in the OR, an easier acceptance and a better feed-back for further improvements. The characteristics of the robot motion is the fact that the endoscope will move around a fixed point in space, which is the entrance point of the trocar in the patient's abdominal wall.

Workspace of the parallel robot

The mathematical modeling for the kinematics and dynamics of PARAMIS parallel robot has been already presented in (24, 25,26).

Pisla et al. (27) have proven that the PARAMIS structure has no singularities within the workspace, which represents a great advantage in the development of a safe robot control.

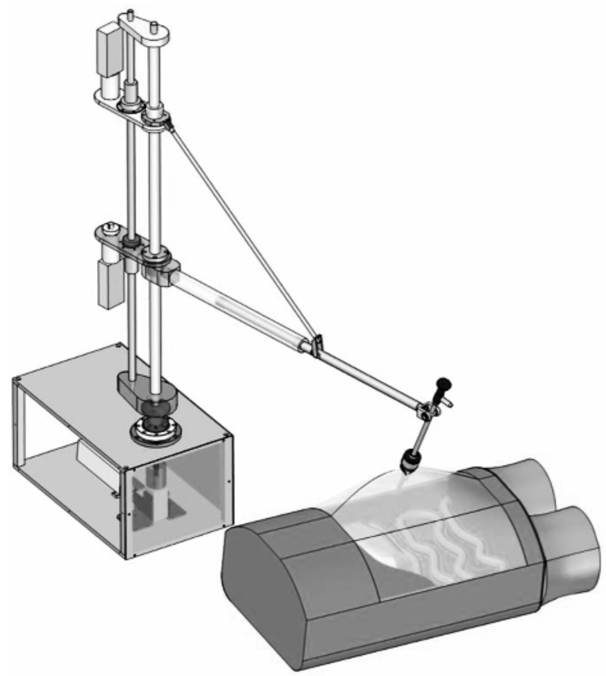


Figure 1. The virtual model of the PARAMIS parallel robot for MIS

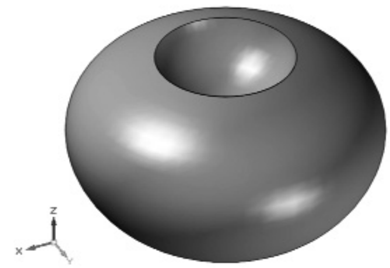


Figure 2. Geometric workspace determination for PARAMIS parallel robot

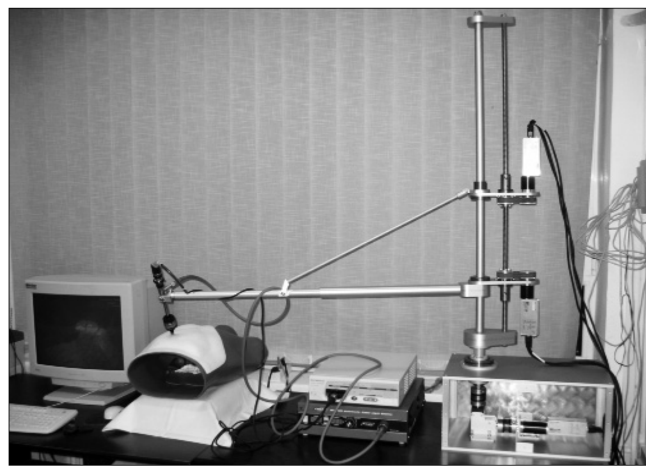


Figure 3. The experimental model of PARAMIS

Figure 4. The electrical panel of the control system for PARAMIS

The overall workspace of the robot, considering that the third robot actuator can perform a 360° rotation, is a cylinder but according to the surgical application, only a small volume of this workspace is used. The workspace of the robot has been generated both geometrically and analytically, these two methods validating each other. During the workspace analysis, the importance of the initial position of the robot with respect to the patient has been emphasized. An improper position would limit the robot reach reducing the area inside the patient that can be viewed with the laparoscope. The laparoscopic camera always passes through a fix point in space (the entrance point in the patient's body) and the position of the robot has to be correlated with the position of the surgeon, the entrance point and the surgical field. *Fig. 2* presents the graphical representation of the PARAMIS workspace by using a geometric determination (26,27).

The experimental model and the robot control system

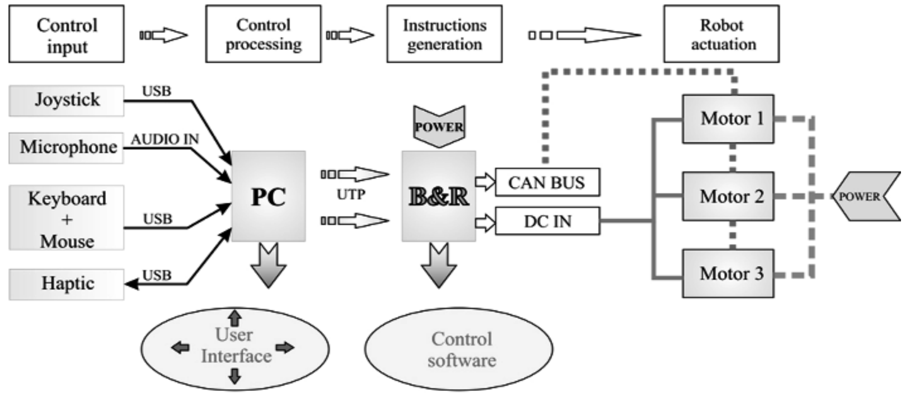
The experimental model of the PARAMIS parallel robot for MIS is presented in *Fig. 3*, which was built in close cooperation with the Institute of Machine Tools and Production Technology of the Technical University Braunschweig, Germany.

Fig. 3 shows (from right to left): the mechanical structure of PARAMIS, the laparoscopic processing unit and the light source, the laparoscope mounted on the robot, a human torso trainer with cholecystectomy model from Simulab (28) with internal organs and a display providing video information from the laparoscopic camera. The parallel robot is modularly built, all the electrical motors are identical with the same control interface. All the robot components have been simply and designed at a low-cost. The control system of PARAMIS has been integrated in a compact box shown in *Fig. 4*. This control system makes the connection between the computer and the surgical parallel robot actuators.

Control system structure

The control structure of the PARAMIS parallel robotic system

Figure 5. The structure of the PARAMIS robotic system



is presented in *Fig. 5*. The control input allows the user to give commands for the positioning of the laparoscope using different interfaces: joystick, microphone, keyboard & mouse and haptic device *(Fig. 5)*.

The control processing stage is achieved within a personal computer (PC) that provides the 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. As a safety measure, each robot displacement is first calculated, verified and validated and only afterwards, the actual motion of the robot is permitted. The calculated motion parameters are transmitted via Ethernet to the programmable logic controller (PLC) where the instructions generation takes place. The PLC through the Controller–area network (CAN) will position the robot actuators based on the calculated data. The digital input module (DC IN) receives data from the proximity sensors mounted on each axis of the robot.

For safety reasons, the system is equipped with an automatic lock in case of power failure.

Fig. 6 presents the PARAMIS robot control using the keyboard/mouse and the developed graphical interface while *Fig. 7* presents the voice controlled interface of the robot. The joystick/haptic interface, which was newly developed is presented in *Fig. 8*.

Figure 6. The robot control through the keyboard

Figure 7. Voice controlled parallel surgical robot

Graphical user interface

The user interface was developed in close collaboration with the team of surgeons from Surgical Clinic 3, University of Medicine and Pharmacy "Iuliu Hatieganu" Cluj-Napoca, which presents the important commands required during a surgical procedure (29). The information integrated in this interface is very important, as the user of the robotic system, the surgeon, has no technical knowledge regarding the robotic system.

The set of commands for PARAMIS can be divided into five main categories: Initialization, Mode selection, Parameters configuration, Positioning and Position saving *(Fig. 9)*.

Initialization

The first set of commands is used for the reset of the actuator encoders and for the positioning of the robot relative to the patient. Once the desired position is reached, the laparoscope is fixed on the robotic arm with the tip touching the incision point. Once this point is saved, the robot cannot be moved relative to the patient, as it will save the point of contact

Figure 8. The robot control through the Joystick (haptic device)

between the laparoscope tip and the patient as the fixed point in its working space.

Mode selection

These commands refer to the selection of the desired command mode for the robot. This can be changed at any time during the procedure.

Parameters configuration

The user is able to set up the motion parameters of the laparoscope (increment, speed and acceleration) as well as to define a safety zone within the surgical field. The system allows the definition of the cuboid inside, 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. Once these limits are set the robot will not allow the laparoscope to go beyond these limits.

Positioning

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.

Position saving

In every surgical procedure there are several positions of the laparoscopic camera used (preferred) by the surgeon. In that case the surgeon can save up to three positions within the surgical field, where the parallel robot will return from any position.

In the case of the voice control mode, a speech tool developed by Microsoft, Speech SDK (Software Development Kit) has been used. 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);

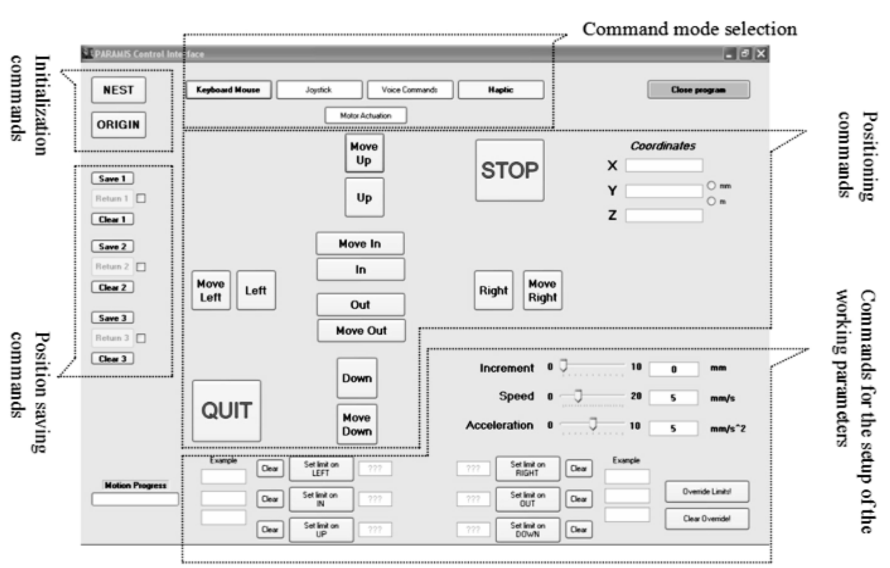
Parameters setup: Increment Plus/Minus, Speed Plus/ Minus, Acceleration Plus/Minus;

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.

Due to the compactness of the robot arm, it can be covered in a sterilized plastic sheet, so that it has no contact with the outside. The instruments are sterilized so overall one can say that there is no problem concerning the sterilization of the robot.

The camera and/or instruments attachment to the robot arm is made in such a way that it can be removed quickly without having to pull out the instrument from the patient abdomen.

Figure 9. The user interface



After the instruments are detached from the robot arm, the robot is moved apart from the operation table (since it is placed on a separate wheeled table) to create space for the medical personnel to approach to the patient.

Results

Laparoscopic cholecystectomy using the PARAMIS parallel robot

The first results have been obtained through the performance of an experimental laparoscopic cholecystectomy using PARAMIS surgical robot *(Fig. 10)*.

The model used was a porcine liver, removed with the gall-bladder and the bile ducts (30). The user-friendly control interface of the robotic system allows the surgeon to command the robot movements using voice commands, along with other modalities of controlling the robot (mouse, keyboard, joystick). During the procedure, up to three key-positions can be saved using specific command allowing the surgeon to return rapidly to these points. The movement amplitude can be modified using different commands, allowing the surgeon to get a large or a short movement of the laparoscope.

The use of the PARAMIS parallel robot as positioning system for the laparoscopic camera has been evaluated acknowledging its advantages and drawbacks.

Discussion

Based on the first experimental tests using PARAMIS robot, some of its advantages could be emphasized: precision of the movements; absence of the laparoscope operator natural tremor, rapid returning in key-positions, open architecture allowing a simple and fast introduction of new commands or modification of the existing ones, direct control over a smooth, precise, stable view of the internal surgical field for the surgeon; no fatigue; there are few misinterpreted commands from the surgeon; permits the use of both hands for the actual procedure; eliminates the fine tremor; reduces eye fatigue; eliminates the need for a second surgeon to be present for the entire procedure; can save three anatomical positions and return to them by a single voice command.

Figure 10. *Cholecystectomy on a pork liver using the PARMIS Robot*

An identified problem is the necessity of an initialization and registration of the robot with the surgical model. The open architecture control software allows continuous improvements and customization. A three-arm robotic system is planed to be developed in the near future.

Conclusion

The paper presents a simple and a lightweight parallel robot for laparoscopic surgery. The developed low-cost PARAMIS parallel robot prototype is the first step toward a multi-arm robot, which can be used in laparoscopic surgery. A first cholecystectomy on a porcine liver has been successfully performed. The experimental results recommend PARAMIS as a useful tool in MIS. The cost of such a robot is lower (about 20.000 Euro) compared to the other commercial laparoscope holder assisting robots, and with some small improvements it could be a current participant in laparoscopic interventions.

Acknowledgments

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References

1. http://biomed.brown.edu
2. Plitea N, Hesselbach J, Vaida C, Raatz A, Pisla D, Budde C, et al. Innovative development of surgical parallel robots. Acta Electronica, Mediamira Science (Cluj-Napoca). 2007. p. 201-206.
3. Taylor R, Stulberg S. Medical Robotics Working Group Section Report. In NSF Workshop on Medical Robotics and Computer-Assisted Medical Interventions, Bristol, England, 1996.
4. Ben-Porat O, Shoham M, Meyer J. Control design and task performance in endoscopic teleoperation. Presence, Massachusetts Institute of Technology. 2000;9(3):256-67.
5. Glozman D, Shoham M, Ficher A. A surface-matching technique for robot-assisted registration. Computer Aided Surgery. 2001;6:259-69.
6. Grace KW, Colgate JE, Glucksberg MR, Chun JH. A six degree of freedom micromanipulator for ophthalmic surgery. Proc. of IEEE International Conference on Robotics and Automation. 1993. p. 630-635.
7. Jaspers JE, Breedveld P, Herder JL, Grimbergen CA. Camera and instrument holders and their clinical value in minimally invasive surgery. Surg Laparosc Endosc Percutan Tech. 2004; 14(3):145-52.
8. Kraft BM, Jäger C, Kraft K, Leibl BJ, Bittner R. The AESOP robot system in laparoscopic surgery: Increased risk or advantage for surgeon and patient? Surg Endosc. 2004;18(8):1216-23. Epub 2004 Jun 23.

9. Mettler L, Ibrahim M, Jonat W. One year of experience working with the aid of a robotic assistant (the voice-controlled optic holder AESOP) in gynaecological endoscopic surgery. Hum Reprod. 1998;13(1O):2748-50.
10. Long JA, Descotes JL, Skowron O, Troccaz J, Cinquin P, Boillot B, et al. Use of robotics in laparoscopic urological surgery: state of the art. Prog Urol. 2006;16(1):3-11. [Article in French]
11. Aiono S, Gilbert JM, Soin B, Finlay PA, Gordan A. Controlled trial of the introduction of a robotic camera assistant (EndoAssist) for laparoscopic cholecystectomy. Surg Endosc. 2002; 16(9):1267-70. Epub 2002 Jun 14.
12. Nebot PB, Jain Y, Haylett K, Stone R, McCloy R. Comparison of task performance of the cameraholder robots EndoAssist and Aesop. Surg Laparosc Endosc Percutan Tech. 2003;13(5): 334-8.
13. http://www.medsys.be/surgical-robots/
14. Polet R, Donnez J. Using a Laparoscope Manipulator (LapMan©) in Laparoscopic Gynecological Surgery, Surgical Technology International XVII, Universal Medical Press – 2007.
15. http://www.intuitivesurgical.com
16. http://www.renaltransplant.ro
17. Popescu I. The role of Romanian Society of Surgery in the development of surgery in ourcountry. Chirurgia (Bucur). 2008;103(4):375-6. [Article in Romanian]
18. Vasile S, Sgarbură O, Tomulescu V, Popescu I. The robotic-assisted left lateral hepatic segmentectomy: the next step. Chirurgia (Bucur). 2008;103(4):401-5.
19. Tomulescu V, Stănciulea O, Bălescu I, Vasile S, Tudor S, Gheorghe C, et al. First year experience of robotic-assisted laparoscopic surgery with 153 cases in a general surgery department: indications, technique and results. Chirurgia (Bucur). 2009;104(2): 141-50.
20. Vasile S, Sgarbură O, Tomulescu V, Popescu I. The robotic-assisted left lateral hepatic segmentectomy: the next step. Chirurgia (Bucur). 2008;103(4):401-5.
21. Merlet J-P. Parallel robots, Kluwer Academic Publisher, 2006.
22. Plitea N, Hesselbach J, Pisla D, Raatz A, Vaida C, Wrege J. et al. Innovative development of parallel robots and microrobots. Acta Tehnica Napocensis, Series of Applied Mathematics and Mecanics. 2006;49(5):5-26.
23. Plitea N, Hesselbach J, Vaida C, Raatz A, Pisla D, Budde C, et al. Innovative development of surgical parallel robots. Acta Electronica, Mediamira Science (Cluj-Napoca). 2007. p. 201-206.
24. Pisla D, Plitea N, Vaida C. On kinematics of a parallel robot for minimally invasive surgery. The International Congress on Industrial and Applied Mathematics. ICIAM 2007, Zurich, DOI 10.1002/pamm.200700850.
25. Plitea N, Pisla D, Vaida C, Gherman B, Pisla A. Dynamic modeling of a parallel robot used in minimally invasive surgery. Eucomes 2008, Springer, 10.1007/978-1-4020-8915-2_71, 595-602
26. Vaida C. Contributions to the development and kinematic - dynamic modeling of parallel robots for minimally invasive surgery. 2009, PhD Thesis, Technical University of Cluj-Napoca, Romania.
27. Pisla D, Plitea N, Vaida C. Kinematic modeling and workspace generation for a new parallel robot used in minimally invasive surgery. In: Advances in robot kinematics: analysis and design 2008.
28. www.simulab.com
29. Vaida C, Pîslă D, Plitea N, Gherman B, Gyurka B, Stancel E, et al. Development of a control system for a parallel robot used in minimally invasive surgery. International Conference Advancements of Medicine and Health Care Through Technology - Meditech. 2009, IFMBE Proceedings, 2009;26: 171-7.
30. Graur F, Plitea N, Vlad L, Pîslă D, Vaida C, Furcea L, et al. Experimental laparoscopic cholecystectomy using PARAMIS parallel robot. The 21st SMIT International Conference, Sinaia, 7-9 Octombrie 2009.