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ROBOTIC SYSTEMS FOR SURGICAL APPLICATIONS

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Abstract: *This paper presents a survey of various solutions regarding robotic implementation in surgical application. The approach are based on several common concepts of assisted robotic surgery, however, for each one a number of particularities have been highlighted in order to provide a background for further research in this area. Afterwards, the paper illustrates authors' approach for robotic surgery system design, by illustrating the development of a complete, functional system based on four suspended robotic arms carrying surgical instruments and one additional arm supporting a remote controlled lighting lamp. The robots are controlled by two operators, while the process is supervised by another three assistants.*

Key words: *medical robot, assisted robotic surgery, master system, suspended robotic arms, remote control.*

1. INTRODUCTION

The robots are the first tools in history that are designed not only to help humans in certain activities, but to replace them entirely in some aspects. Although this goal is far from being reached, these machines are used today in more types of applications than ever, requiring only a minimal level of human supervision.

The main reason for which robots are gaining more and more ground in various modern activities resides in their versatility. Their various architectural structures are characterized by high mobility, allowing the robotic systems to have a very generous working space, especially when external axes are used. Also, due to programming flexibility, much more capabilities of parameter customization and feedback are available, making robots more suitable for different sensorial systems implementation [1].

The above mentioned aspects are coming in addition to the advantages that every machine has over human workers: higher precision, improved repeatability and productivity. These are the main arguments for which the robots are used frequently even in non-industrial applications, such as surgical interventions. The main reason for which the robots are widely used in various medical applications is that, when it's about human health, any mistake can have very grave consequences. Since the beginning, the medical robots were intended to dramatically reduce the error probability and to extend the surgical limits beyond the conventional limits.

Traditionally, one of the main hurdles in medicine was the low precision of the human arm. Even with the continuously development of the medical tools, these were still driven by the hand of a surgeon, which was subject to stress, tiredness, and various unpredictable events. Typically, a man cannot maintain high levels of concentration for extended periods of time, an important aspect if considering that some surgical operation can take well over eight hours to complete.

The robots are reliable solutions to overcome these issues. But, unlike the industrial applications, the surgical processes are not predictable, nor repetitive, so that the robotic systems cannot rely solely on their programming to successfully perform operations on humans. A human-machine interface is needed in order to allow surgeons a fast and easy control over the robots without any physical contact. In the last twenty years, the emerging of virtual reality technologies leaded to the development of a particular category of human controlled systems: remote controlled robots. This concept has become the central objective in robotic medical systems research.

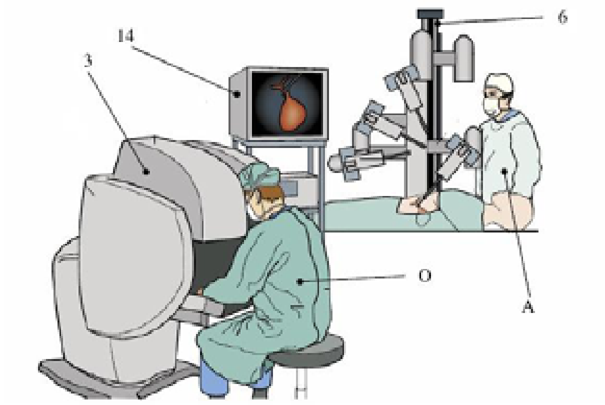
One of the main advantages of medical robots is their high precision. However, compared to the human arm, the mechanical systems provide a low flexibility. A solution to this issue consists of complex structures comprised of multiple robot arms with redundant degrees of freedom in order to achieve increased dexterity and to avoid singularities. Another solution is haptic technology implementation, which represents a method interfaces to the user via the sense of touch by applying forces, vibrations, and motions [3].

2. A COMPARATIVE STUDY OF SEVERAL ROBOTIC SURGERY SYSTEMS

2.1. Robotic surgery system based on robots fixed on the floor

Figure 1 illustrates a robotic system that performs medical operations on a patient lying in an appropriate position on a table (this solution is in fact a representation of the Da Vinci system developed by Intuitive Surgical Inc.).

The human operator (usually a surgeon) is conducting a minimally invasive procedure (for example laparoscopy) manipulating the handles of a command console. According to operator's actions, a microprocessor is controlling the movement of the endoscopic instruments or other possible accessories [4].



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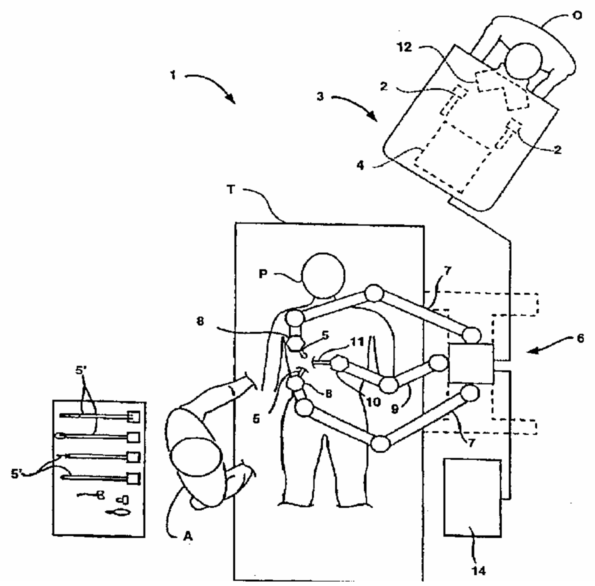

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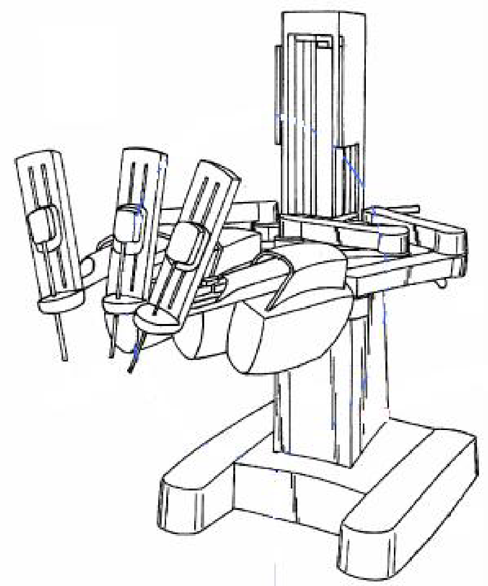
Fig. 1. Robotic surgery system based on a robot fixed on the floor: a) perspective view; b) above view; 1 – overall layout; 2 – handles; 3 – command console; 4 – console microprocessor; 5,5' – surgical instruments; 6 – robotic system; 7, 9 – robotic arms; 8, 10 – end effector orientation system; 11 – video camera; 12 – console monitor; 14 – central monitor; *O* – human operator (surgeon); *A* – human assistant; *T* – table.

A typical layout of the robotic system comprises of two robotic arms for positioning and orienting the surgical tools and an arm used to manipulate an endoscopic video camera for stereoscopic image acquisition. The images are simultaneously displayed on the console's screen and on a central monitor that allows an assistant to supervise the operation. The assistant also has the role to perform a preliminary positioning of the robotic arms with respect to the patient and to change the end-effectors.

The specific layout of the surgical robotic system can vary according to the application, but a common solution is the DaVinci robot developed by Intuitive Surgical Inc [5]. The DaVinci modular robot is a surgical system designed to facilitate complex surgery using a minimally invasive approach. It is used especially for laparoscopy, prostatectomy, cardiac valve repair and gynecologic procedures. As shown in Fig. 2, the robot is comprised of two elements: the positioning system and the surgical



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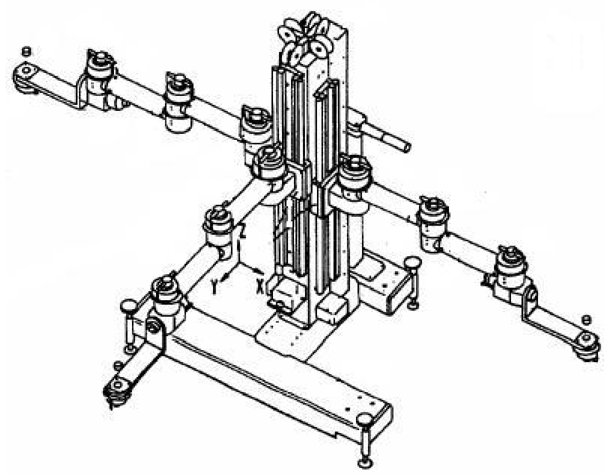

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Fig. 2. The DaVinci modular robot: a) general layout; b) the positioning system.

robotic arms. The positioning system has a SCARA-type general architecture with multiple arms, and is attached to a mobile trolley. Through several special linking elements, a surgical robot is attached to each of the positioning. The surgical robot is actually a parallelogram mechanism which can be rotated with a roll-type motion, and it manipulates an end-effector with the role to hold the surgical instrument.

The number of arms included in the robotic system may vary, but an overloaded mechanical structure may create visibility and manipulation problems. A partial solution of this issue is the implementation of an auxiliary device with an additional robotic arm (as shown in Fig. 3). The overall system is functioning similarly to the one previously presented. The difference is that, in this case, two operators are needed: one that controls the main surgical robot and one that controls the auxiliary robot. The auxiliary device implemented in Fig. 3 can take the form of a trolley carrying one or more additional robotic arms, manipulated by an assistant through a supplementary command station.

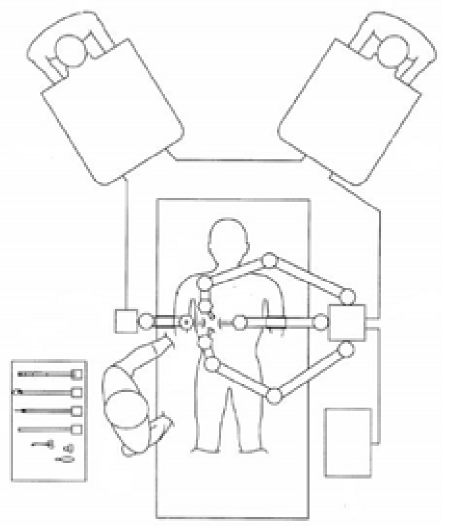
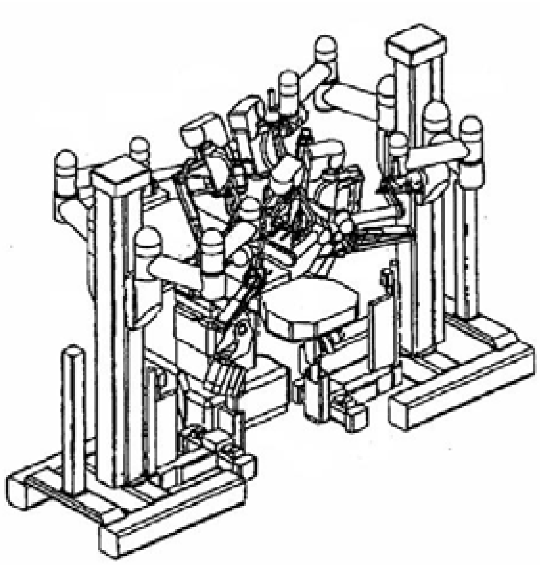


Fig. 3. Robotic surgery system based on a robot fixed on the floor and an auxiliary device including an additional robotic arm.



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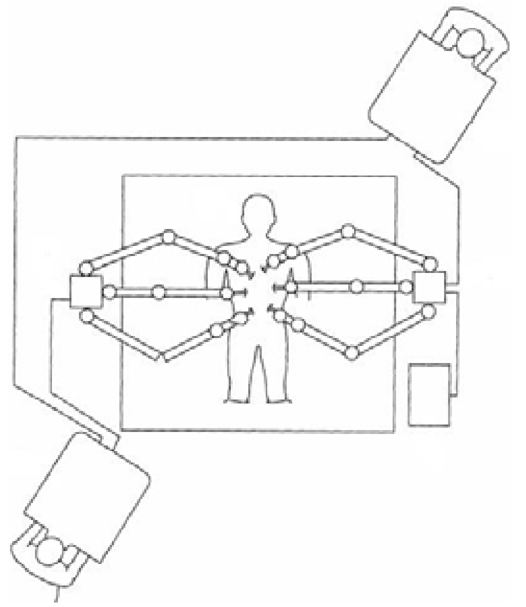

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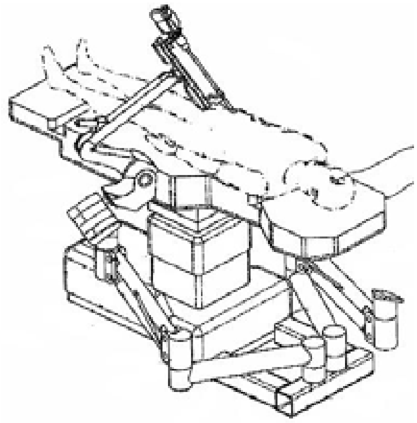
Fig. 4. Robotic surgery system based on two robots fixed on the floor: a) perspective view; b) above view.

The need of using multiple surgical instruments at the same time in certain applications, while a mobile image acquisition system is required, has lead to alternative solutions, such as using two parallel-operating robots. The system presented in Fig. 4 is similar with that from Fig. 3, the only difference being that, instead of the auxiliary trolley, another complete Da Vinci robot is used.

The system includes a total of six robotic arms, one of the robots being manipulated by the operator and the other by an assistant. As an example of application for this system, one robot can manipulate two surgical instruments and an endoscopic video camera, while the other robot can manipulate a stabilizer and another two surgical instruments (or a surgical instrument and an endoscopic camera). Thus, the operator and the assistant can cooperate to perform an operation with stabilized heartbeat or other procedures in which a robot is holding two parts of tissue and the other is performing a stitch. Nevertheless, such a system is still overloading the space surrounding the patient because of the multiple robotic arms used.

Another approach regarding ground robots used in surgery is represented by mechanisms that are mounted on a special type of supports attached directly to the surgical table. This solution allows the robotic arms to retract under the table when not operating, freeing the space around the patient if intervention from the operators is required. Fig. 5a illustrates this approach with one arm oriented towards the patient's abdomen, while Fig. 5b shows two arms oriented towards the patient's torso.



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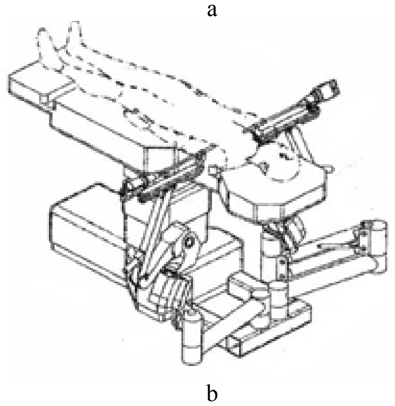

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Fig. 5. Robotic surgery modular system based on two robotic arms attached to the surgical table: a) the arms oriented towards the patient's abdomen; b) the arms oriented towards the patient's torso.

2.2. Robotic surgery modular system based on four robotic arms fixed on the ceiling

Certain applications such as complex laparoscopy require a number of several surgical tools. Considering the disadvantages of previously illustrated solutions, a modular system was developed including four suspended robotic arms and the possibility of adding two or more auxiliary arms fixed on the floor. This combined solution provides an optimal usage of the working space, allowing efficient cooperation of the surgical tools.

Fig. 6 illustrates the four suspended robotic arms grouped in two pairs placed on the opposed sides of the surgical table. It can be observed that the positioning mechanisms have a parallelogram structure. Fig. 6a shows the system in operating configuration, while Fig. 6b shows an above view of the system. This concept allows the operators full access to the surgical table and its surrounding area [6].

2.3. A robotic system that includes offset rotary joints and rotation correction mechanisms

Another approach was developed by the National Aerospace Laboratory of Japan for various applications, including surgery. The general architecture of this robotic arm is presented in Fig. 7, with two variants, the difference being the angles between the numerical controlled axes.

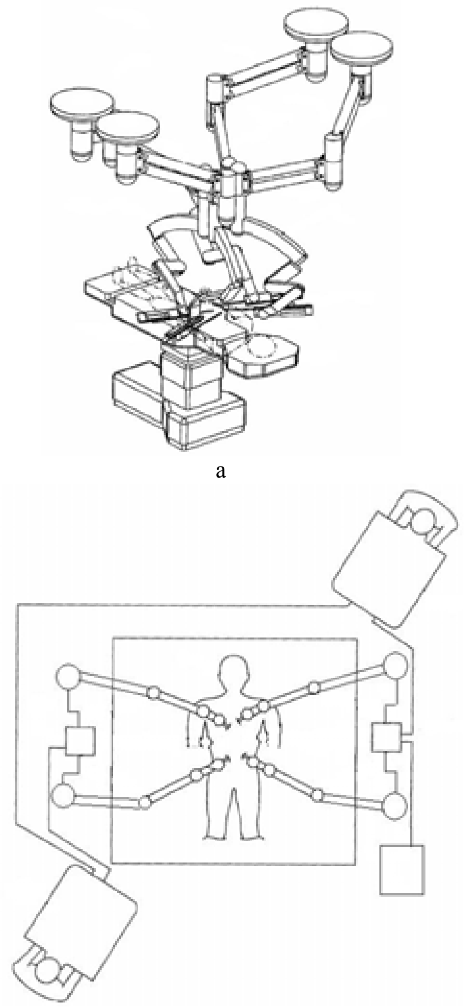

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Fig. 6. Robotic surgery modular system based on four suspended robotic arms: a) operating configuration; c) above view.

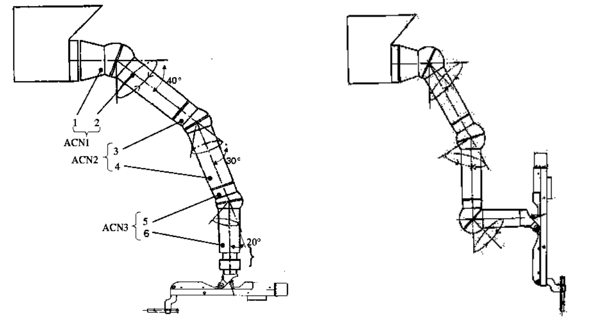

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Fig. 7. Robotic system with offset rotary joints: a) first variant; b) second variant.

The basis is connected with the first element by a conventional rotary joint, while the next joint has the axis inclined at a different angle. The third segment of the robotic arm is linked to the second through a rotation correction element, a solution that is also used between the third and the fourth segments.

The main characteristic of this kind of system is that all the degrees of freedom are achieved through rotary joints. A degree of freedom is ensured by two associated rotary joints, of which one has the axis inclined with respect to the other one. Both joints can be driven by the same motor, so that a plane movement can be achieved easily, or they can be driven by two motors for more complex trajectories. The angles between the joint axes are chosen in the design phase of the system development according to the surgical application in which the robots will be implemented.

2.4. A robotic system that includes rotary joints with perpendicular axes

This type of robot can operate in a large space, being driven by small command movements. The implementation of a secondary system for general coordinates transformation is necessary to allow the operator to command the "slave" robot (providing the required scaling between the "slave" and the "master" robots). The "master" robot can contain the control function of the system so that singularity can be avoided for both robots. The general layout of this type of robot is presented in Fig. 8.

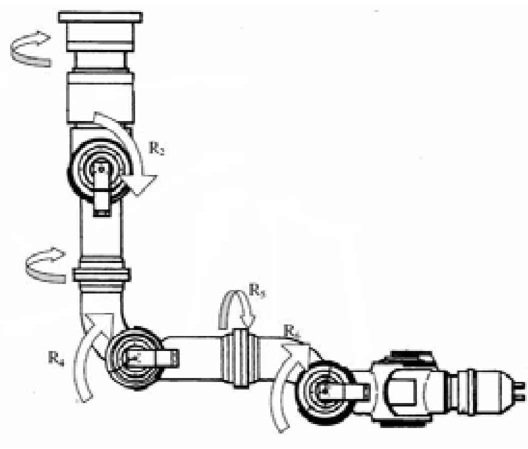

Fig. 8. A robotic system that includes rotary joints with perpendicular axes.

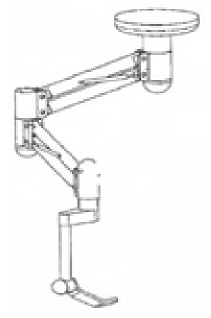

Fig. 9. Positioning system for a suspended robotic system.

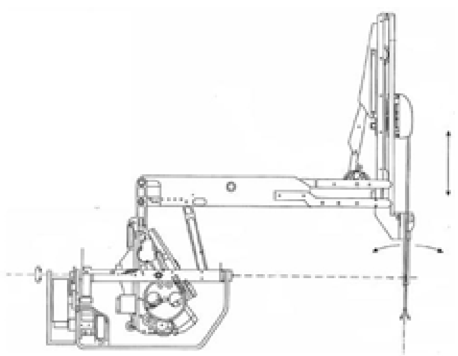

Fig. 10. End-effector orientation system.

2.5. A suspended robotic system that includes a positioning system and an orientation system

The positioning system for this type of robot is composed of two turning parallelogram mechanisms which can execute horizontal rotary movements or vertical movements (see Fig. 9). The vertical movement is counter-balanced by two springs with a force that can be adjusted by a screw-nut system. A retracted position can be configured to allow the arm to clear the area surrounding the surgical table. The structure stiffness can be improved by additional structural elements.

The end-effector orientation system is illustrated in Fig. 10. The end-effector is mounted on a support attached to a sliding joint. The support allows electrically actuated surgical tools that require feedback from the operation area. The end-effector can perform a roll and a sliding movement, as well as a rotation provided by a parallelogram mechanism so that the characteristic point of the tool doesn't change its position.

3. PRELIMINARY CONCLUSIONS

The systems presented above are intended to provide various options to override the issues of robotic surgery, as well as a solid background for further research in this area.

Based on the actual development status of the robotic medical systems and adopting several solutions presented above, the authors have developed a concept that will combine the advantages of the existing approaches. The system is based on four robotic arms suspended on two gantry systems, with one additional arm carrying a remote operated lighting lamp to provide video feedback of the operation. The robots are controlled by two operators, while the process is supervised by another three assistants. The conceptual scheme of the system is illustrated in Fig. 11 [2].

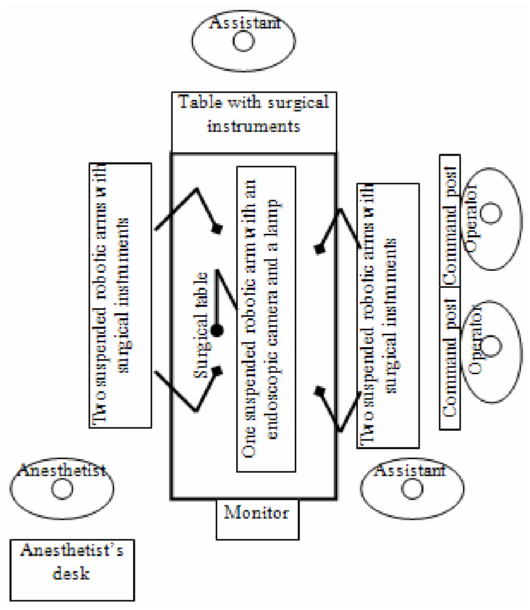

Fig. 11. Scheme of the developed robotic surgical system.

4. THE BASIC CONCEPTS OF THE PRESENTED ROBOTIC SURGICAL SYSTEM

The developed solution is a modular surgical system based on multiple suspended robotic arms. This approach allows multiple surgical tools manipulation while, at the same time, it saves important space around the table, making easier for the operators to closely supervise and coordinate the operation.

The general structure chosen for the developed system is illustrated in Fig. 12. It includes four modular robotic arms suspended on a gantry structure which offer them the possibility to slide above the surgical table [1, 3, 4]. The surgical tools are stored near the table, inside the working space of the robots. Two command stations are separated from the operating area by a safety transparent wall. These consoles allow the surgeons to supervise the process and to make decisions in critical moments.

5. THE COMPLETE LAYOUT OF THE DEVELOPED ROBOTIC SURGICAL SYSTEM

After an extended analysis of the basic structure presented above, and considering the specific issues and requirements of the application, a detailed layout of the robotic cell has been developed (see Fig. 13) [2]. For increased precision, the surgical robots have been attached to four corresponding positioning robots with parallelogram configuration. The robotic arms are controlled from the command posts by two surgeons. The operation is attended by three assistants:

- the first assistant is usually a surgeon, that stands beside the surgical table and is directly supervising the process; he is usually the only one who has direct, close visual contact with the operation, and also changes the surgical tools in certain situations; he can also visualize the process on a monitor, for better coordination with the other operators;
- the second assistant stands near the tool storage table and hands the necessary surgical instruments to the first assistant if he needs to change an end-effector,

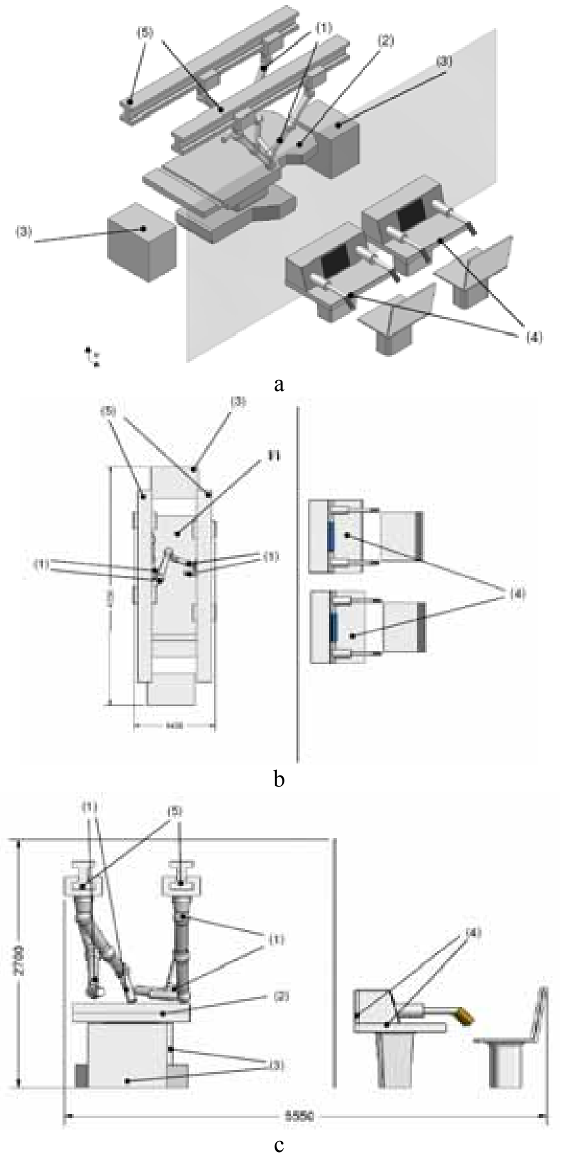

Fig. 12. The basic layout of the presented robotic surgical system: a) perspective view; b) above view; c) side view; 1 – robotic arms; 2 – surgical table; 3 – surgical tools; 4 – command posts; 5 – gantry structure.

or is performing the replacement himself in some situations;

- the third assistant performs the anesthesia of the patient.

The surgical table has a structure with a few degrees of freedom in order to set an appropriate height or to allow the orientation of the patient in certain positions. The necessary amount of light is provided by a lamp manipulated by an auxiliary robotic arm [5].

In Fig. 14 an alternative solution is presented, in which two of the four robotic arms are placed on a support system attached to the surgical table [6]. This approach allows the two remaining suspended arms better movement possibilities, since they are using separate slides for translation. The disadvantage is that, although the two arms mounted on the ground can be retracted under the surgical table when not operating, they are still taking some space around the patient during surgery, possibly interfering with the operators' supervision or movements.

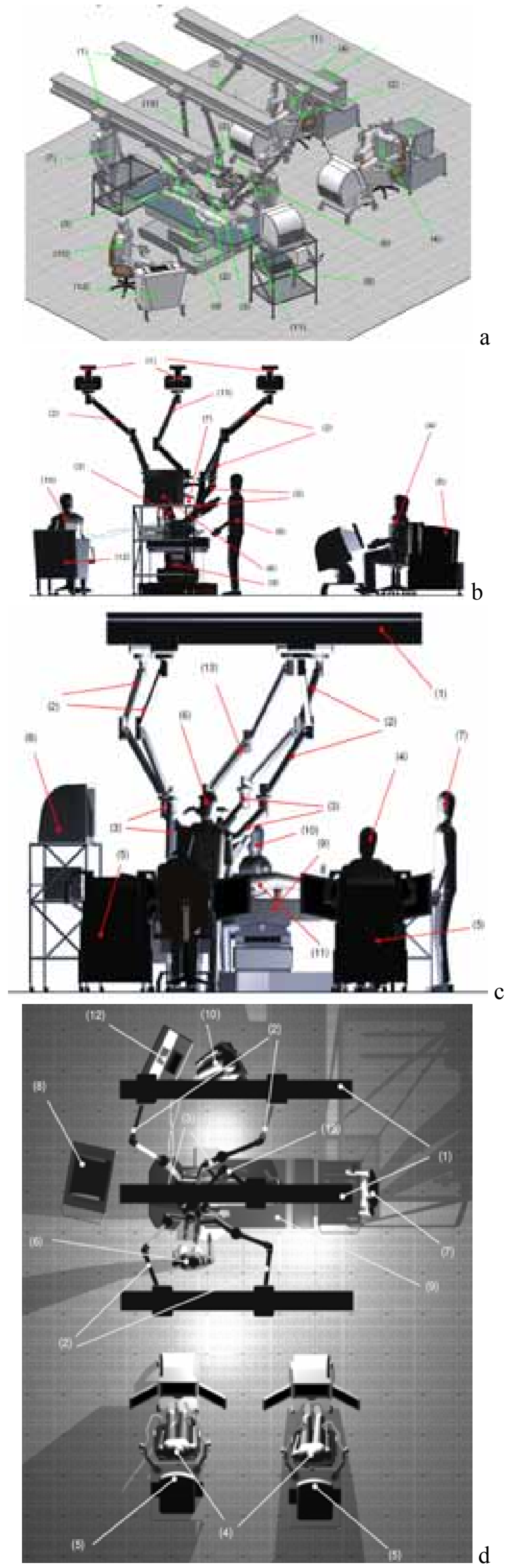

Fig. 13. The complete layout of the presented robotic surgical system: a) perspective view; b) front view; 1 – gantry system; 2 – positioning robotic arms; 3 – surgical robots; 4 – surgeons; 5 – control posts; 6 – first assistant; 7 – second assistant; 8 – auxiliary display; 9 – surgical table; 10 – anesthetist; 11 – patient; 12 – anesthetist's control post; 13 – lighting robotic arm; c) side view; d) above view; 1 – gantry system; 2 – positioning robotic arms; 3 – surgical robots; 4 – surgeons; 5 – control posts; 6 – first assistant; 7 – second assistant; 8 – auxiliary display; 9 – surgical table; 10 – anesthetist; 11 – patient; 12 – anesthetist's control post; 13 – lighting robotic arm.

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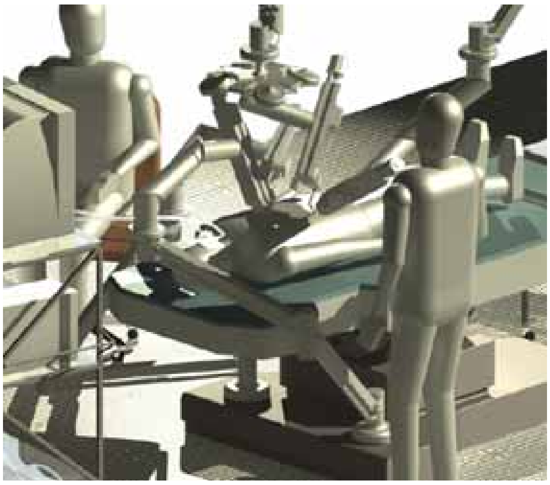

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Fig. 14. An alternative approach with two robot arms placed on a support system attached to the surgical table: a) general view; b) detail.

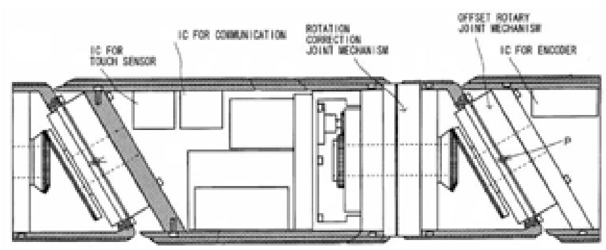
6. THE STRUCTURE OF THE ROBOTIC ARM INCLUDED IN THE SURGICAL SYSTEM

The general layout of the developed robotic arm is illustrated in Fig. 15. The robot is suspended on a gantry structure, with the basis attached to a translation joint. The mechanical structure includes a positioning system (with two parallelogram mechanisms) and an orientation system (with offset rotary joints) [4].

Fig. 15. The suspended surgical robot.

A comparative analysis has been made regarding the driving approach for the orientation rotary joints. In Fig. 16, a pinion powered by an electrical motor is simultaneously rotating both segments of the arm in a contrary direction. The resulting trajectory is a plane movement with an angle smaller than the angle between the axes of the two rotary joints. This behavior is similar with that of a simple rotary joint, the only advantage being that this solution allows a greater load capacity (however, this is not necessary for a surgical robot) [5].

A second approach is presented in Fig. 17, in which the third element can be rotated around its inclined axis, around the first rotary joint or it can execute a plane movement. The movement is transmitted from the motor to a spindle through a belt system. The cinematic flexibility is obtained through an electromagnetic device.



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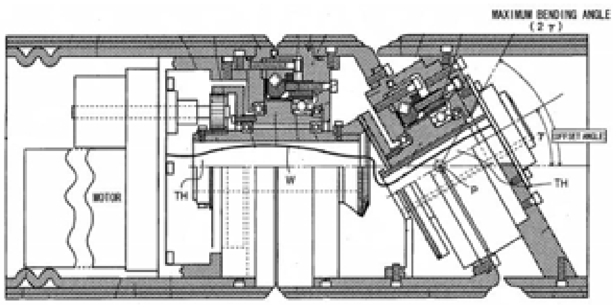

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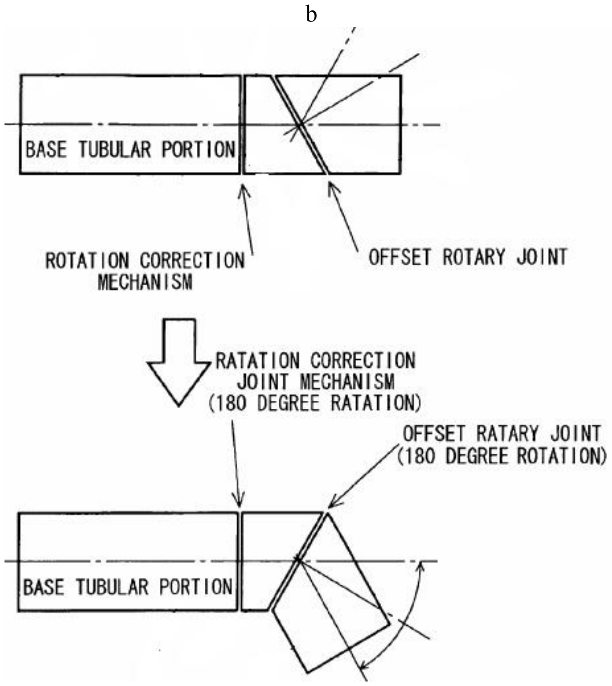

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Fig. 16. An approach for the orientation system: a) general view; b) detailed view; c) the movement of the rotary joints.

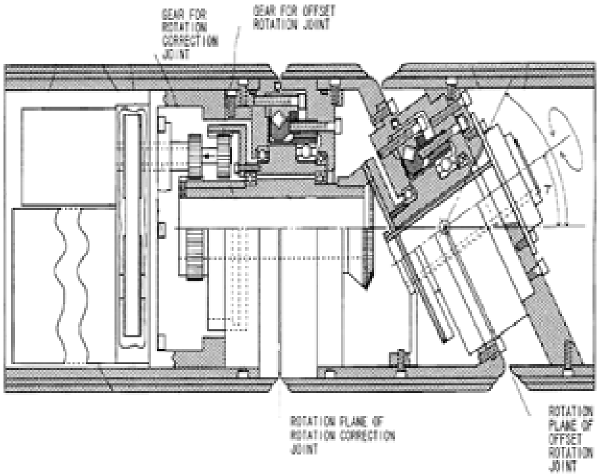


Fig. 17. The second approach for the orientation system.

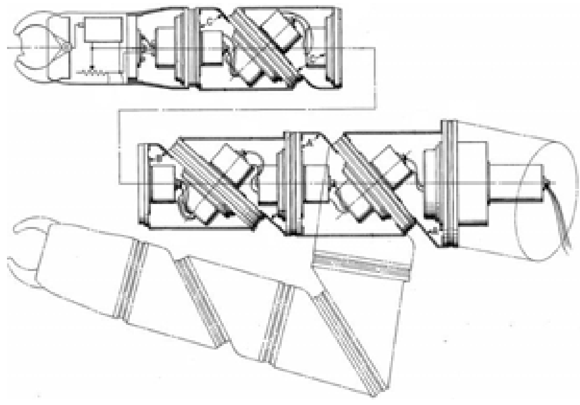


Fig. 18. The approach chosen for the surgical robotic arm.

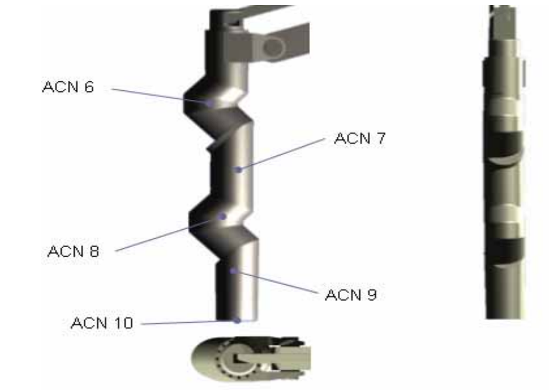
Although the second approach has the characteristics required for surgical applications (especially dexterity and flexibility), the implementation of the electromagnetic device leads to a very complex mechanism. This is the reason for which the final solution integrated in the developed surgical system has the two rotary joints of the orientation system driven by separate motors. The motors are placed grouped at the beginning of the arm, or directly in the actuated joints, as shown in Fig. 18.

The virtual model developed for the orientation system is illustrated in Fig. 19.

The orientation system is attached to a positioning system composed of two parallelogram mechanisms (see Figs. 20 and 21). This structure has been chosen because it allows the robot to clear the area surrounding the surgical table, so that the operators can have free access to the patient.

The end-effector can perform a roll-type rotation, but also a sliding movement, as shown in Fig. 22. A ball bush device is used for movement transmission. Fig. 23 illustrates several end-effectors that can be used in surgical applications. The instrument used in the developed application is presented in Fig. 24.

In order to analyze more efficiently the positions, speeds and accelerations of the mechanical structure elements, the positioning system and the orientation system have been analyzed separately. The inertial ad gravitational loads have been determined by approximating a model of the robot based on the existing documentation.



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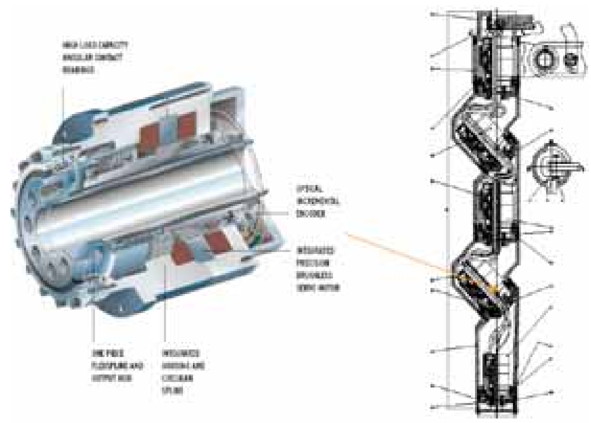

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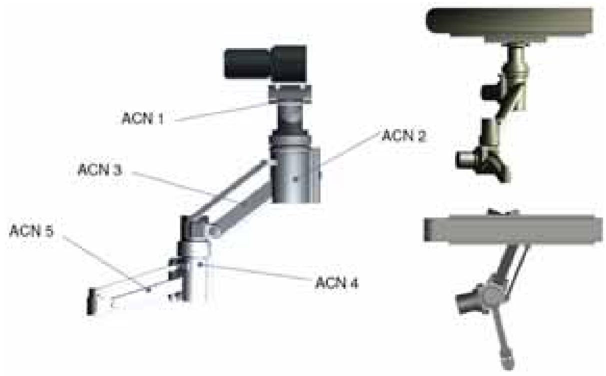
Fig. 19. The virtual model of the orientation system: a) general view; b) section.



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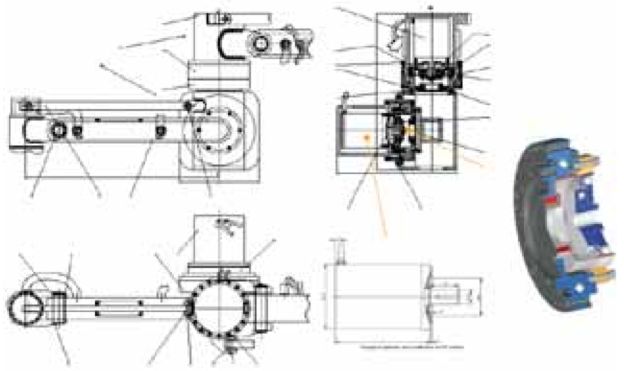

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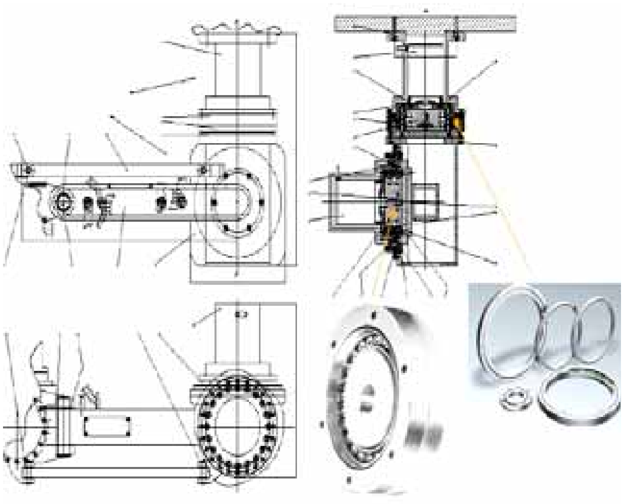
Fig. 20. Fist part of the virtual model of the positioning system: a) general view; b) 5th and 4th axes.



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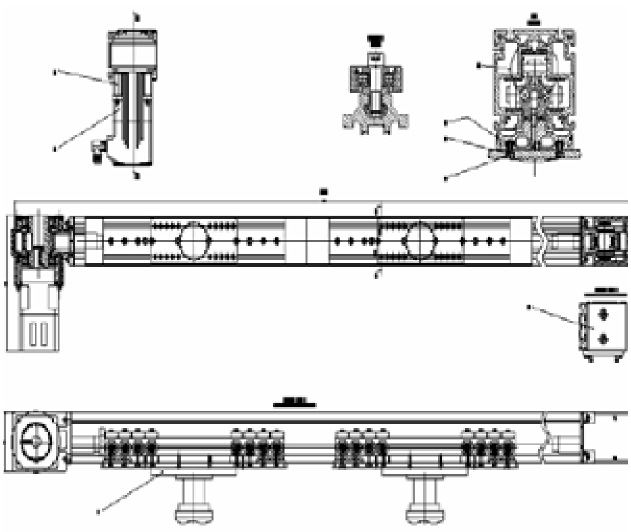

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Fig. 21. Second part of the virtual model of the positioning system: a) 3rd and 2nd axes; b) first axis.

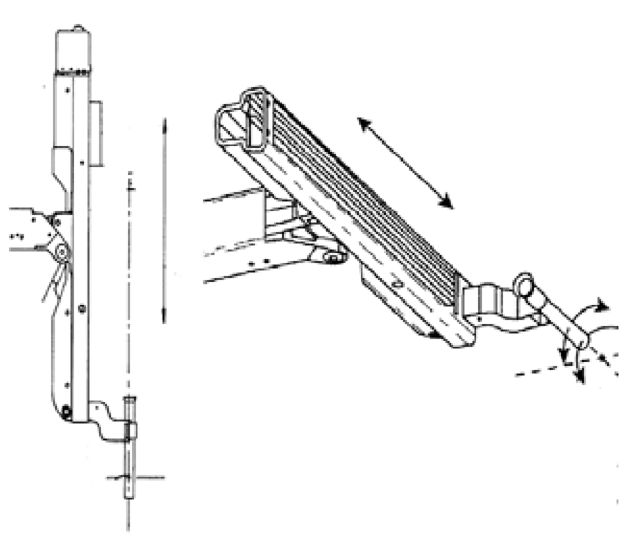

Fig. 22. The translation movement of the end-effector.

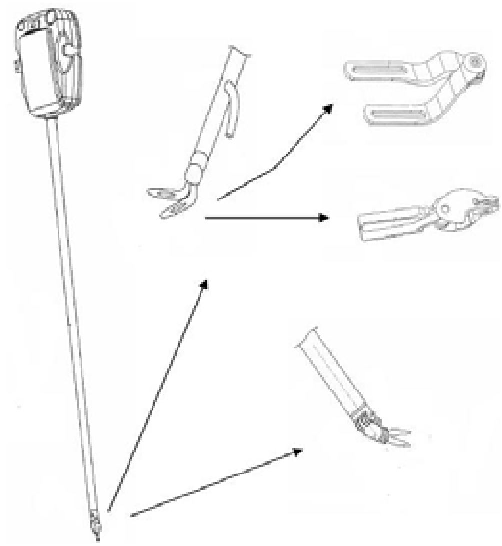

Fig. 23. End-effectors used in surgical applications.

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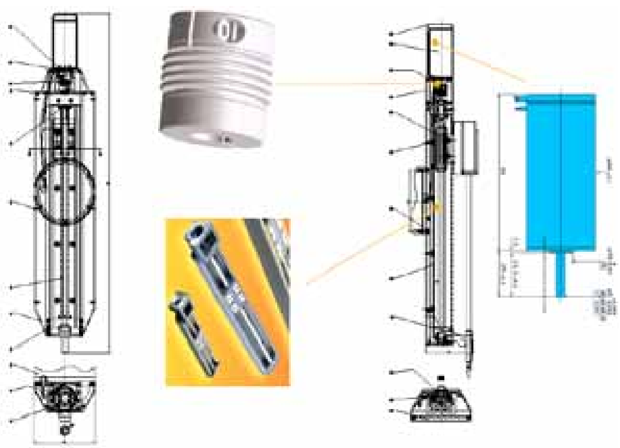

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Fig. 24. The end-effector used in the developed application: a) general view; b) sections.

In order to determine the most unfavorable configuration, the loads have been calculated for two different positions of the robotic arm (the greatest loads have been considered).

7. CONCLUSIONS

Since the beginning, the medical robots were intended to dramatically reduce the error probability and to extend the surgical limits beyond the conventional limits. The most important aspects of this approach in medical applications are precision, miniaturization, smaller incisions, decreased blood loss, less pain and quicker healing time. These arguments are solid justifications for continuous research in robotic medical systems, attempting to find new solutions to overcome specific issues.

The introduction of automated systems (especially robotic cells) in surgical applications allowed the development of specific techniques, such as remote and unmanned surgery, minimally invasive surgery and haptic control of medical systems.

This paper presents a fully developed robotic surgical system that is capable of minimal invasive and precise operations. The implementation of virtual reality technology allows the robotic arm to be remote controlled by surgeons, which have full control of the process. The architecture of the system allows full mobility of the manipulators, while keeping the space around the surgical table clear. This characteristics offer maximum access to the patient for both the robotic arms and the operators, efficiently combining the mechanical and the human factors.

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