Robotic Surgery: State of the art and challenges for the future

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***Abstract*—In the last decades, the use of technology in medicine has been massive. One of the areas in which it has been a huge development is in the surgical interventions. A lot of robotic platforms have been developed and used in order to enhance surgeon skills and make easier, quicker and more effective procedures. This paper presents a review of the state of the art of robotic surgery, the gold standard equipment, the features of their implementation and the challenges for the future in the area.**

***Index Terms*—Robotic microsurgery, medical instrumentation, laser surgery, Da Vinci equipment, Zeus equipment.**

I. Introduction

The evolution of medicine has been incredible in the last century, a lot of inventions have made possible easier procedures with better results regarding to recuperation times, smaller mortality rates, eradication of certain diseases, among others. One of these big steps towards a better health management, is the development of robotic equipments capable of enhance the surgeons abilities for a better performance in the operating room making possible less invasive surgeries, better access to the operating sites in the body and smaller recovery times, principally, in microsurgical procedures.

Robotic Surgery can be defined as a surgery that uses the assistance o robotic platforms for its execution, nowadays this kind of procedure is applied to different areas principally, phonomycrosurgery, cardio, neural, orthopedics and lymphedema surgeries, but also urology, ophthalmology, neurology, oncology and otology among others [10].

In most of the cases the standard robotic equipment for surgery is constituted by a microscope or a virtual substitute of for it, a set of robotic instrumentation that includes the camera for the microscope, sensors and actuators, a software and a hardware interface [17]. In this document a brief summary of the most relevant equipments developed in the area, along with the challenges for future development will be presented.

This paper will be organized as follows: in the section two a brief summary about the most relevant robotic platforms for microsurgery will be presented, in section three information about the different tools and features of robotic surgery equipment is displayed, then in section four some of the tasks of the robotic platforms will be exposed, finally in section five the current challenges in the area will be pointed out.

II. State of the art

Robotic surgery is becoming common in developed countries now and has being used in different kind of procedures. The most common, the laparoscopic procedures performed by the AESOP and the Da Vinci equipments, some of these surgeries include cholecystectomies, mitral valve repairs, prostatectomies, antireflux procedures, hysterectomies and several others of this nature. There are also orthopedic interventions, in this field the gold standard is ROBODOC used to assist during hip replacement surgery [13]. The advances have made possible robotics assistants in neurology as the Neuromate, the Pathfinder and the SpineAssist; as well as in catheterisation with the Amigo, Niobe, Magelan and CGCI [3], among other areas.

The first incursion of robotics in surgery was with the PUMA robot in 1985 it was a robotic arm used for holding, since then, a number of robotic platforms for robotic surgery assistance have been designed, here a brief review of the more relevant platforms, considering the number of procedures performed and its status as commercial equipments, is presented. The most recognized ones are the Robodoc, the Zeus and the Da Vinci equipments, this last one was the first commercial equipment widely used in the operating rooms around the world. Recently (2012-2015), the microralp project that took place in Europe developed a number of techniques and devices, providing new perspectives in the area of robotic microsurgery. Here some of the achievements of these platforms will be presented.

A. PUMA and ROBODOC

The PUMA robot is part of the first generation of robotic equipments for microsurgery, the development of these equipments was focused on the surgical accuracy. The PUMA 200, particularly, was an industrial robot used by Known for a surgical procedure, its function was to determine the entry orientation and location of a surgical needle, it used to offer accuracy bellow 1 mm [3]. After the PUMA some other equipments with similar characteristics were developed, some of them were used for surgery planning and preparation as for example the ROBODOC capable of using CT images and make a surgical plan for the total hip replacement procedure, it used to work in a with high accuracy and is the only orthopedic robotic assistant approved by the FDI [13], at the date more than 25000 have been done around the world with this equipment.

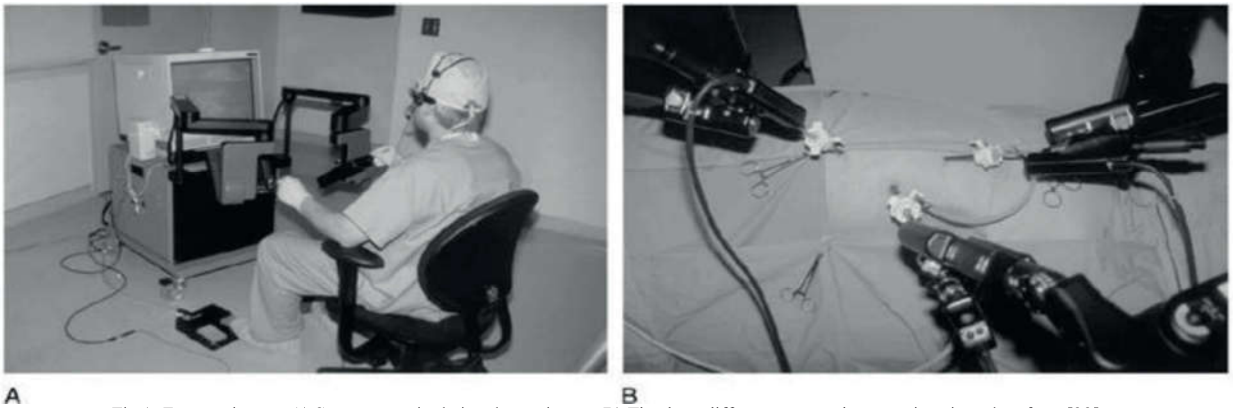

Fig 1. Zeus equipment A) Surgeon manipulating the equipment B) The three different arms at the operating site, taken from [28]

B. Aesop and ZEUS

The next generation of robots appeared in the decade of the 90s, one of the emblematic equipments was the Automated Endoscopic System for Optimal Positioning (AESOP), they were a series of robotic arms used for visual aid and control of different surgical instruments. In 1995, the Zeus unit with four DOF appeared, it was developed by y Computer Motion, Inc., Santa Barbara, CA, it was a robotic platform constituted by three AESOP arms. The main components of the equipment are the surgeon console, the dedicated computer and the three robotic arms, as shown in figure 1, the information about the surgeon movements is processed through the dedicated computer and then transmitted to the manipulators in the arms the camera is controlled by one of the arms using voice activated automated endoscopic surgical optimal positioning, the other two arms control the 5mm instruments [28]. Some of the features of the later developments were a micro joint and a micro wrist that made possible to hold and manipulate 28 instruments, and the filtration of tremor among others [29]. In the 2001 the Zeus system was cleared by the FDA, however it was taken out from the market at 2003.

C. The Da Vinci Equipment

Another equipment for surgical interventions widely used is the Da Vinci System developed by Intuitive Surgical, Inc., Mountain View, CA, it was approved by the FDA for human use in 2000. The equipment is used for different types of laparoscopic interventions. Its is a dual handed system provided with six DOF in tools at the end of the arms and a 3-dimensional imaging system. The Da Vinci is constituted by a console with integrated display for visualization of the operation site, four robotic arms, one for holding the camera and the other three for manipulation of the tools with enough dexterity for imitating the movements of the surgeon [29], as is shown in figure 2, the dexterity is achieved by the novel EndoWrist that will be presented in the next section. The visualization is obtained by two tiny cameras mounted in a 12 mm stereo endoscope with two separated optical channels.

D. The Microralp Project

Between 2012 and 2015 the project microralp took place in Europe with the participation of five different institutions: the Istituto Italiano di Tecnologia (Italy), the Institut FEMTO ST (France), Leibniz UniversitÃd't Hannover (Germany), the UniversitatdegliStudi di Genova (Italy) and the Centre˘ HospitaloUniversitaire (France). Product of this project a number of developments in the robotics for microsurgery were done, for example in the areas of development of interfaces between the surgeon and the robotic instruments, in [15] and [16] for example, the author implement a virtual scalp that let the surgeon to work interactively in an interface in a tablet specifying what part of the tissue needs to be removed, the instructions from the surgeon are then implemented by the robotic tools, new techniques for identifying cancer tumors in the larynx [2] were also developed, and even microrobotic systems for laser phonomicrosurgery, [7], among others.

The main product of the project was an entire surgical system, that plays as interface between the surgeon and the patient, with features such as, interfaces for visualization and control, a size of 20 mm of diameter at the distal end containing the microrobotic laser, a channel for the micro tools, cameras tools and necessary illumination for the performance of successful phonomicrosurgeries [12].

III. Tools and features of robot surgical equipment

A. Tremor cancellation tools

One of the big challenges existent in robotics microsurgery is the tremor of the surgeons while performing different tasks, in order to avoid errors in the surgery for this cause a number of tools and techniques have being developed, their principal function is to cancel undesired movements. Tremor is an involuntary movement similar to a sinusoidal wave. One of the solutions to this problem is the Micron developed in [24], this apparatus senses the amount of tremor using a six DOF inertial sensing module, the inverse of the estimated error is used as input of the piezoelectric manipulators for compensating the undesired motion, these manipulators have 400 micrometers range of motion and 1 N force capability [18]. The figure 3 shows the control scheme of the developed tool. A similar device was developed by [1].

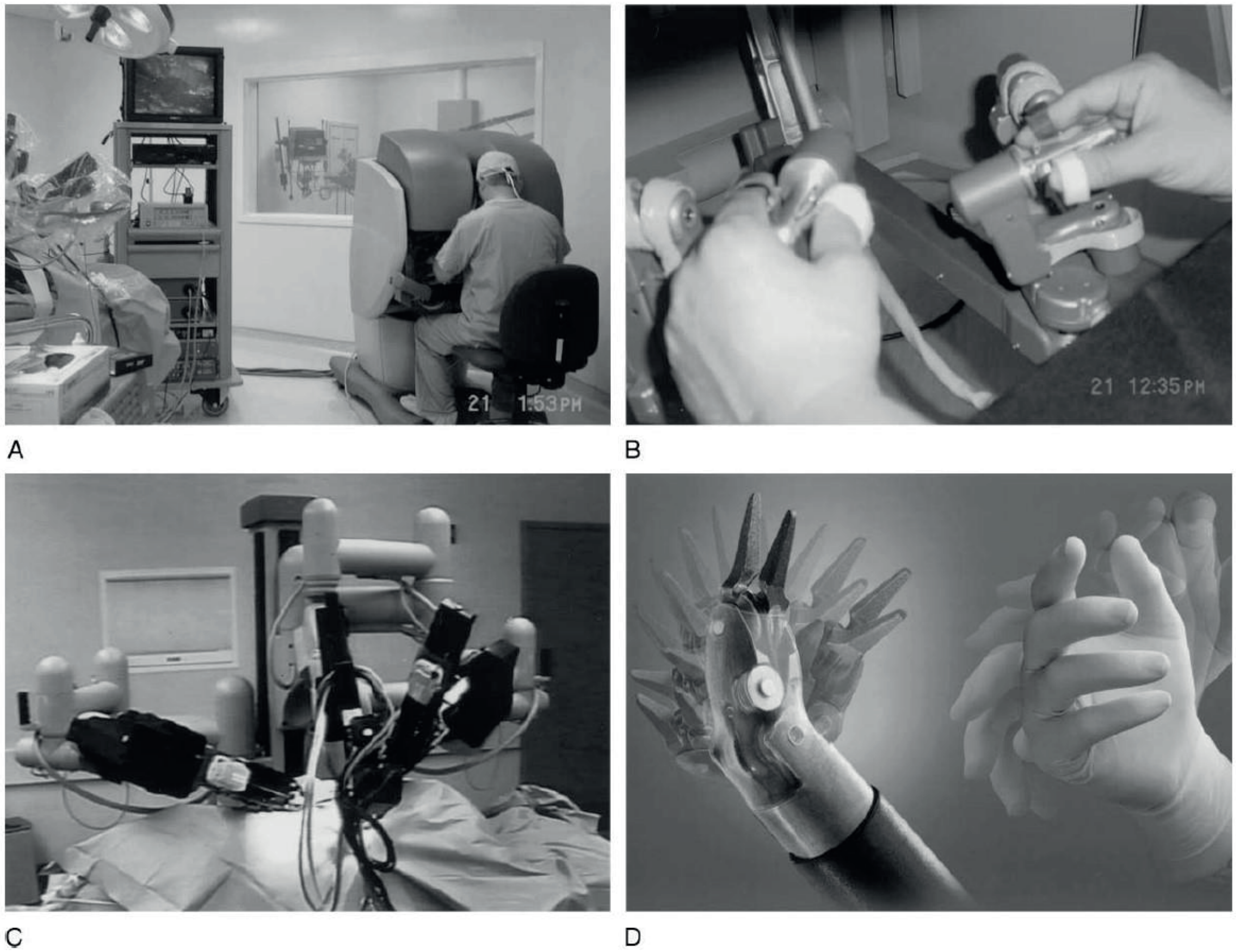

Fig 2. Da Vinci equipment A) Surgeon console, B) Surgeon manipulation C) Cart with the different arms at the operating site D) Final Actuator of the arms.

B. Imaging tools and techniques

In robotics surgery the visualization is critical, because depending on the site of the operation in most of the cases the surgeon do not have direct visual information about the procedure being performed. Therefore, different tools are used for assisting visualization. Early in the 90s the common approach was the use of small cameras that provide visual information about the intervention site, however the results were not outstanding as the surgeons need information about depth. As consequence new techniques have been developed for 3 dimensional visualization most of these techniques use sensors for identifying location and previously taken images from CT, MRI [5] and ultrasound [25].

C. Force and tactile sensing tools

The feedback about the textures in the operation site is very important for the surgeon, it allows him to determine the conditions of the tissues. It is also important to determine the force applied for the different tools in order to prevent damage of the tissues. [9] One big problem is the size required for the tools at the surgery site, therefore the solutions in the area of sending become very important. Some of the techniques implemented for tactile and force sensing are based on LVDTs, current monitoring to deduct torque, optic measurements, capacitive sensors, piezoelectric based sensors and evendynamical vibrating sensors that evaluate the response of the tissue in order to determine its texture [23].

D. Actuators for surgical platforms

The actuators used in robotic surgery, need to be maneuverable as they imitate the surgeon movements for developing different tasks such as grasping, clamping, sewing among others. However the small space in the operation site makes impossible to have normal motors on the tools, rater what is used are wires, which are strategically located to make possible different movements when they are pulled in the right direction. These kind of tools are called steerable tools and the gold standard is the EndoWrist, utilized in the Da Vinci robot, the figure 4 shows how it works, another alternative is the DragonFex, whose design minimizes the fatigue of the wires compared with the EndoWrist [11]. Mechatronics is slowly involved in the final effectors for robotic platforms beginning with the use of servomotors for controlling the wire behavior and sensors in the final effector for close loop feedback. Two of the developed actuators for robotic surgery that use mechatronics can be found on [6], [20] and [26].

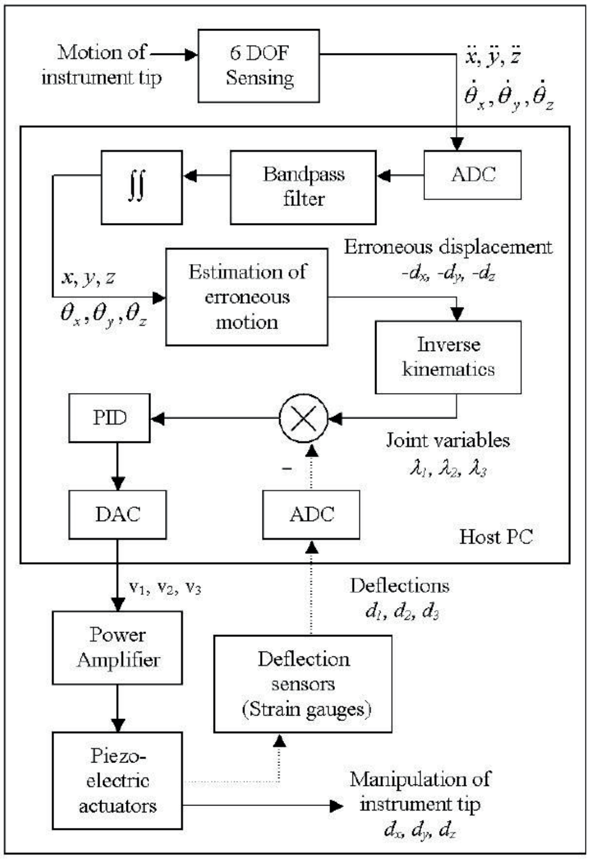

Fig 3. Block diagram of Micron, taken from [24]

IV. Tasks of the robotic equipment in surgery and microsurgery

There are a number of tasks that robot equipment performs due to its precision, some of them include holding instruments, sewing tissue, motion and force scaling among others [31].

Precise needle insertion is needed in Neuro surgical and optical procedure. Tasks related to holding and moving are also performed by these type of equipments, they position lights and cameras, additionally they help with tools such as retractors and suctions tools. In some cases the structures of the body are very sensitive and fragile, robotic tools are used to scaling the human force in order to manipulate certain tissues and physiological structures. As it was said before, robots also compensate undesired motion and therefore are excellent tools for delivering radiation or applying laser to tissues that need to be destroyed without affecting the surrounding tissues.

Surgical robots are used for heavy task as for example supporting and guiding equipment such as x-rays equipment or linear accelerators. Even to perform tasks related to drilling and bolting in trauma surgeries in which is required a big amount of force but also delicate precision.

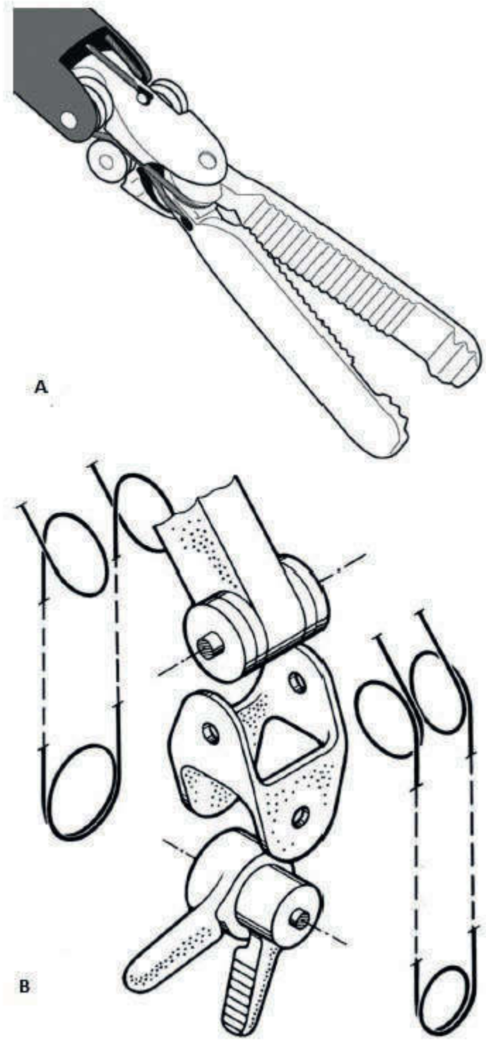

Fig 4. EndoWrist. A) Final actuator, B) Assembly of the actuator based onwires, image taken from [11]

When there is need of identifying abnormal tissue smart robotic platforms are used, they take information about the tissues and using different techniques determine its type, if the tissue is harmful, the robot removes it in an smart way.

V. Challenges in robotics microsurgery

Even though the last 25 years have implied a huge development in robotic equipments for microsurgery assistance, due to the small spaces where micro surgery is performed and the fact that the surgeon is not operating over the patient, rather a robotic platform acts as an interface between the surgeon and the patient, a number of challenges appear in the area of robotic surgery. These challenges are related to the mechatronics of the instruments, the planning of procedures and coordination between them, the need of certain kind of feedback for the surgeon about the actions performed, the existence of appropriate interfaces between the instruments at the operation site and the surgeon and the need of better visualization options [10], [17], [14].

There are a number of challenges related to the mechatronics of the robotic instruments involved in microsurgery, due to the need of excellent dexterity and maneuverability for the realization of delicate actions implied in surgical procedures. Additionally, there is a need for instruments with enough flexibility to be adapted to the different structures of the human body, that have the appropriate size but are also strong enough to manage the complicated conditions that could exist in the operation site.

Regarding to the planning is important for the set of tools involved in the realization of a microsurgery , to be capable of working collaboratively as a group and in a coordinated manner, even though the objective of the robots for microsurgery is not to replace the surgeons, they should have certain amount of intelligence in order to coordinate their actions, alert when a dangerous action is taking place and be capable to adapt themselves to the extreme conditions existing in the operating site.

One of the biggest problems in the area of robotic assisted surgery is the lack of feedback regarding to texture and force applied to the tissue under treatment, information that is veryimportant for the surgeon, as the excess of applied force can cause damage on the tissue or suture [8]. Some solutions have been proposed as the use of virtual reality [30], force and haptic feedback [19], piezoelectric sensors [9], [22] and mathematic methods for force estimation [27], among others to give to the surgeon feedback about the area being treated. However the area is still under development and there is a lot to be done for better feedback to the surgeon in order to achieve a natural feeling for him/her during the procedure.

Another challenge is related to the need of more comfortable interfaces between the surgeons and the robotic instruments, in which the surgeons perform the procedures in a natural way. Developments as the virtual scalpel system [15] and the robotic interface presented in [16] have partially achieved a degree of comfort for the surgeon. However, there is need for better robotics platforms to cover this aspect of the robotics microsurgery.

Finally, there is need of the application of better techniques and instruments in order to get better visual information of the site of operation, there are still a bunch of limitations related to the resolution of the cameras and the limited range of view that they provide.

VI. Conclusion

A simple review of the most relevant equipments developed for robotic surgery have been presented here, additionally some information about the techniques utilized in the area and the future in robotic surgery has been exposed in order to give an overview of what has been done in the area and what needs to be done in the future. There is a lot to be done in the area yet, therefore this topic opens a lot of possibilities of research topics to be explored.

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VIII. Biography

Carmen A. Carabali Carmen got her degree in 2011 as Electronics and Control engineer at Escuela Politécnica Nacional in Ecuador, was working in the industry for two years. Then got a scholarship for post graduate studies which took place at Flinders University in Australia, where she got the degree of Master in Biomedical Engineering, during her time in there she got awards for her performance and had the opportunity of working in two research groups, the first one related with advanced computing and the second one with brain signal analysis were shedeveloped her thesis which lead to a scientific publication. Currently she is working as a full time lecturer at Escuela Politécnica Nacional, and is interested in research in areas such as, artificial intelligence, multi-agent systems, signal processing, medical devices, medical imaging and cognitive neuroscience.