Future Trends in Robotic Neurosurgery

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Abstract — **Computer Integrated Surgery has only existed for two decades, however it has already spread out world wide, with well over 100.000 operations performed. In the near future, newly developed robotic systems may conquer even the most challenging fields—such as neurosurgery—to provide better patient care and medical outcome. This paper presents the major systems and different strategies applied in robotic neurosurgery. Besides appropriate design, adequate control strategies are required to ensure maximal safety. This makes automated neurosurgery a technologically challenging area for researchers. It is also important during the design phase to consider market aspects. We anticipate that the future trends of clinical applications are outlined by the current leading research directions. The conclusions of the past years of innovation will lead forward on the path of further improvement.**

Keywords — **Computer Integrated Surgery, robotic surgery, neurosurgery**

I. INTRODUCTION

Robotic surgery is entering its adulthood due to the continuous development made by research groups all over the world. From the close co-operation of engineers and physicians great medical robotic innovations were born. It was first proven more than thirty years ago that robotic tools can extend human capabilities, as a brain biopsy procedure (manipulating biopsy cannulae with a PUMA 560 robot) was successfully performed in 1985 [1]. General purpose laparoscopic multi-manipulators—such as the da Vinci—have performed thousands of operations so far; however, more emphasis has been put on gastro-intestinal, cardiovascular and orthopaedic surgery.

Neurosurgery is one of the most demanding areas for Computer Integrated Surgery (CIS), where the complexity of the anatomical regions and the high sensitivity of the tissues require fine accuracy and high precision. In the mean time, robot-aided procedures offer remarkable advantages both for the patient and the surgeon. The ability to perform a surgery in smaller scale with robots makes microsurgery a reality. The use of mechatronic devices can increase the stability and robustness of the system, give increased accuracy to navigate based on medical images and help positioning the surgical tool to the target point. Furthermore, there is the option to introduce advanced digital signal processing and control or to record the spatial points-of-interest and motions. This can be useful for surgical simulation and risk-free training. Finally, robotized equipment can greatly add to the ergonomics of the procedure, especially in the case of minimally invasive surgery (MIS).

CIS promises significant results in the case of brain procedures mainly for two reasons: the skull gives a rigid frame, therefore it is easier to register real word structures to preoperative scans of the patient. (This is the basis of effective image-guided surgery). Second, the compactness of the head allows less soft tissue motion during the intervention, enabling a more accurate use of pre-operative planning. However, once the skull is open during the procedure, there may be significant tissue motion. Compensating for brain shift is a major field of research.

We can categorize surgical robots based on their different roles in the OR [2]. Passive robots only serve as a tool holding device once directed to the desired position. Semi-active devices perform the operation under direct human control (e.g. in compliant mode). Active devices are under computer control, and automatically perform certain interventions (e.g. bone machining). Beyond this, surgical robots can be involved in the procedure with different level of autonomy [3]. Systems that are able to perform fully automated procedures—such as CT-based biopsy or cutting—are called autonomous, or supervisory controlled. (A human supervisor would always be close to the robot, but does not intervene, as long as everything goes according to the surgical plan.) On the other hand, if the robot is entirely remote-controlled, and the surgeon is in charge of every single motion of the robot, we may call it a teleoperated system. The latter can be realized by a master-slave manipulator system for example. Modifying this control paradigm, we can introduce compliant (co-operative) control. It means that the surgeon is directly giving the control signals to the machine, while leaving some space for automation. This is called the hands-on technique, as the human is always in contact with the robot.

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Table 1. Major neurosurgical robotic projects and most important features. (CA = commercially available)

Project [ref.]	Category	Institute, company	Main features
Alpha robot [1]	Active, teleoperated	MicroDexterity Systems Inc.; Albuquerque, NM, USA	5 DOF parallel manipulator mounted on the stereotactic frame, CA
Cranio [11]	Active, automated	RWTH-Aachen / Lehrstuhl für Biomedizinische Technik; Aachen, DE	Craniectomy with 6 DOF hexapod robot
Cyberknife [12]	Active, automated	Accuray Inc.; Sunnyvale, CA, USA	Image guided radiotherapy, tumor irradiation, CA
Evolution 1 [13]	Semi-active, automated	Universal Robot Systems; Schwerin, Germany	6 DOF hexapod robot for pedicle screw placement and adenoma dissection, CA
JHU project w/ NeuroMate [9]	Co-operative control	Johns Hopkins University; Baltimore, MD, USA	Skull base drilling with force based co-operative control withVirtual Fixtures
KineMedic [15]	Active, teleoperated	DLR / BrainLAB AG, Feldkirchen, Germany	Light-weight, high payload 7DOF robot for MIS neurosurgery, CA
MARS robot (SmartAssist) [16]	Active, automated	Mazor Surgical Technologies Inc.; Caesarea, Israel	FDA approved, light-weight, head mountable robot for needle insertion
Minerva [17]	Active, automated	Lab. of Microengineering, Swiss Federal Inst. of Tech.; Lausanne, CH	Real time frameless stereotactic instrument guidance in CT scanner
MRI compatible robot [7]	Semi-active, automated	Harvard Medical School; Boston, MA, USA	5 DOF robot for percutaneous procedures, driven by ultrasonic motors
neuroArm [8]	Active, teleoperated	University of Calgary; Canada	MRI compatible complete multi-manipulator
NeuRobot [18]	Active, automated	Computer Integrated Medical Intervention Laboratory; Singapore	Instrument guidance, skull-base surgery
NeuroMaster [19]	Active, automated	Robotic Institute Beihang University; Beijing, China	6 DOF robot for stereotactic procedures
NeuroMate [10]	Passive, automated	IMMI / ISS / Schaerer Mayfield NeuroMate Sarl; Lyon, France	Cannulae positioning for biopsy, neuroendoscopy, CA
PathFinder [6]	Active, automated	Prosurgics Ltd. (formerly Armstrong Healthcare Ltd.); High Wycombe, UK	6 DOF manipulator for instrument guidance, CA
Raven [20]	Active, teleoperated	University of Washington; WA, USA	6 DOF general surgery, automated suction
RAMS [21]	Active, teleoperated	NASA JPL; Pasadena; CA, USA	6 DOF manipulator for eye and brain surgery with motion scaling and tremor filtering
Steady Hand System [14]	Co-operative control	Johns Hopkins University; Baltimore, MD, USA	7 DOF robot with advanced tremor filtering for MIS needle driving

II. CURRENT ROBOTIC APPLICATIONS IN NEUROSURGERY

In the past decades, several different robotic neurosurgical devices have been created, and a couple have reached the market (Table 1).

In fact, none could move on towards real mass production and achieve the success of the well-known da Vinci teleoperated system. We cannot talk about a major financial breakthrough because of certain functional limitations and the higher investment/ maintenance costs. However, the new systems offer even more significant clinical advantages that may well compensate for their high cost.

Table 1. lists the major neurosurgical robotic systems and their main features. Beyond these, several other research projects exist, as listed in the MEdical RObotics DAtabase (MERODA [4]).

III. FUTURE OF NEUROSURGICAL ROBOTS

Present research projects are focusing on three major areas for improvement. One is to increase the overall accuracy and/or efficacy of the classic stereotactic systems, another is to increase the added-value of the equipment and the third is to further enhance the capabilities of the human surgeon. The following ongoing research examples give a good insight how these trends are realized and what are benefits for future patients. Safety is paramount, and may always determine the way research is conducted. In the discussed three cases, patient safety is addressed differently in each system.

A. Improvement of stereotactic surgery

The European Union's most recent initiative, the Robocast project aims to augment existing image-guided surgery techniques and to find new ways to perform high-precision keyhole neurosurgery [5]. The Robocast systems will use optical trackers for patient safety (to monitor and compensate for any change in the patient's position) and provide visual information of the surgical field. Given an accurate registration, the controller will use the preoperative diagnostic information to plan the path of the intervention. The modular system to be built will consist of two manipulators and one smaller probe, actively cooperating in a biomimetic sensory-motor integrated framework. The PathFinder system (Prosurgics Inc., UK) forms the basis of the bigger positioning robots. The stereotactic 6 degree-of-freedom (DOF) PathFinder is already available on the European market. It works with the CT or MRI images of the patient and automatically registers the position of the probe (with at least 1.25 mm accuracy). In general practice, it is capable of aligning the surgical tools within 1 mm to the target. In 2003, real-life experiments showed that the application accuracy was 0.44 ± 0.02 mm (mean ± standard deviation) using the robot, 0.98 ± 0.02 mm with stereotactic frame and the error was 1.96 ± 1.6 mm in with a standard (frameless) navigation system [6].

Improving the efficiency and precision of stereotactic surgery will lead to more gainful treatment of certain brain tumors and lesions. Deep brain stimulation electrodes could be placed very accurately with this kind of system, resulting in the routine treatment of Parkinson and similar diseases. Effective percutaneous brachytherapy could be achieved, where radioactive seeds are implanted to kill the cancer cells. Based on the preoperative images, blood clots could also be removed. Robocast is planned to be used to inject stem cells into the brain to treat Alzheimer's and other diseases [7].

B. Integrating imaging devices

The other main direction of development is to integrate the robots with advanced imaging devices to increase their utility by allowing intraoperative imaging. This can be very challenging technically, but offers the highest level of added-value to the procedure. Magnetic resonance imaging (MRI) gives a fine resolution picture of soft tissues, with acceptable rate, while it does not expose the patient and the surgeon to radiation. MRI compatible robotics has been in the focus of research interest since the mid 90s.

NeuroArm [8] is a recent teleoperated anthropomorphic robot from a University of Calgary led consortium. The MRI compatible robot (up to 1.5 Tesla magnetic field) is made for stereotaxy and microsurgery. Beyond motion scaling and high definition visual feedback, the neuroArm is able to provide very accurate 3D information of its two 7 DOF arms. It uses three displays to give a complete visual coverage on the operating environment, showing in parallel the 3D stereoscopic view of the operation, the MR image of the patient and the control panel. The system has been used on one human patient so far, further clinical trials will begin shortly, and the robot may hit the market in the next years.

C. Hands-on surgery

The ongoing neurosurgical research project at the Johns Hopkins University (JHU) is a good example of the cooperative control concept. The system is based on a modified NeuroMate surgical robot that is capable of helping and increasing the performance of human surgeons [9].

The NeuroMate robot was the first neurosurgical robotic device to get CE mark in Europe, and then the US Food and Drug Administration's (FDA) approval in 1997 for stereotactic neurosurgical procedures. (After having performed over 3000 operations, it was approved for frameless stereotactic surgery as well in 1999.) It also has a CE mark for neuro-endoscopic applications. Originally developed at the Grenoble University and produced by Innovative Medical Machines International (Lyon, France), the 5 DOF NeuroMate provided an accurate and trusted assistance for supervised needle positioning for brain biopsy. The technology was bought and commercialized by Integrated Surgical Systems Inc. (Sacramento, CA, USA) in 1997 and later acquired by Shaerer Mayfield NeuroMate Sarl (Lyon, France). The robot's reported intrinsic accuracy is 0.75 mm, with a repeatability of 0.15 mm. In real-life stereotactic surgical setup, the overall application accuracy was measured to be 1.95 ± 0.44 mm [10].

Beyond the robot, the JHU system (Figure 1.) consists of an FDA approved, widely used treatment guidance system—StealthStation (Medtronic Navigation, Louisville, CO, USA)—and the 3D Slicer open source software (www.slicer.org). To the last link of the Neuromate robot, a 6 DOF force sensor (JR3 Inc., Woodland, CA, USA) was attached, and the end-effector is a high-speed bone drilling surgical instrument (Anspach eMax drill, Palm Beach Gardens, FL, USA). Optical tracking is made possible by passive visual markers mounted on the robot and on the patient.

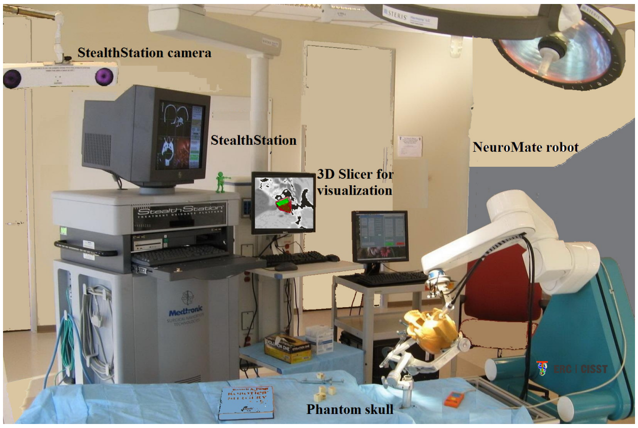

Figure 1. Robotic neurosurgery setup at the Johns Hopkins University with a modified NeuroMate robot, a StealthStation surgical navigation system and the 3D Slicer software.

The NeuroMate is guided in cooperative control mode for removal of cranial bone on the skull base. This means that the readings of the force sensor are directly coupled back to control the robot. Depending on the direction of the force applied by the surgeon, the robot moves in the defined direction, and its speed is proportional to the force.

The JHU system has three major advantages. It offers the visualization features used in stereotactic surgery: the tool's position can be followed on the 3D model of the patient, acquired from pre-operative CT scans. Second, the surgical tool is mounted on the rigid robot, thereby improving its stability. The surgeon is still holding the classic drill tool, and directs its movement; he or she can release the tool any time, take a rest, or position it arbitrarily. The most important advantage, and the real novelty of the application, is that the surgeon can define virtual boundaries on the CT scan, prior to the operation. These are called Virtual Fixtures (VF), and once registered to the robot, they are used to prevent the tip of the tool from going beyond the defined safe area in any direction. The VFs are defined using the editing and model creation tools of the 3D Slicer software. These features together greatly increase the safety and the reliability of the procedure, easing the surgeon's task, and therefore potentially reducing the operating time.

Experimental results have been acquired through foam block cutting and cadaver tests. The application accuracy of the system was measured to be 0.79 ± 0.82 mm in phantom experiments with foam blocks, and the typical overcut on cadaver test samples was 1.5 mm, with a maximum of 2.5 mm. This shows that the system can be considered for serious applications, especially with the further improvement of the registration procedures' accuracy.

Hands-on surgery is providing an ergonomic and safe way for surgeons to operate. Force readings can be effectively used to control such a system, allowing the introduction of advanced computer control. Further extensions of the concept will allow the integration of dynamic Virtual Fixtures that may be used for automated motion compensation of human body organs.

IV. CONCLUSION

Robotic neurosurgery has already proved its utility in the case of several applications from biopsy to skull base drilling. Systems currently under development are about to deliver high clinical advantages and improved safety features providing better procedures for both the patient and the surgeon. Three directions of development presented in the paper, the improvement of accuracy in stereotactic procedures, the close integration with imaging devices and the use of hands-on surgery concept will greatly improve the overall quality of computer integrated neurosurgery. It is believed that through improved quality of future healthcare, the higher costs of robotic interventions will pay off.

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