Review of Robotic Technology for Stereotactic Neurosurgery

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Abstract—The research of stereotactic apparatus to guide surgical devices began in 1908, yet a major part of today's stereotactic neurosurgeries still rely on stereotactic frames developed almost half a century ago. Robots excel at handling spatial information and are thus obvious candidates in the guidance of instrumentation along precisely planned trajectories. In this review, we introduce the concept of stereotaxy and describe a standard stereotactic neurosurgery. Neurosurgeons' expectations and demands regarding the role of robots as assistive tools are also addressed. We list the most successful robotic systems developed specifically for or capable of executing stereotactic neurosurgery. A critical review is presented for each robotic system emphasising the differences between them, and detailing its positive features and drawbacks. An analysis of the listed robotic system features is also undertaken, in the context of robotic application in stereotactic neurosurgery. Finally, we discuss the current perspective and future directions of robotic technology in this field. All robotic systems follow a very similar and structured workflow despite the technical differences that set them apart. No system unequivocally stands out as an absolute best. The trend of technological progress is pointing towards the development of miniaturised, cost-effective solutions with more intuitive interfaces.

Index Terms—Image-guided surgery, Neurosurgery, Stereotaxy, Robotic technology.

I. INTRODUCTION

STEREOTAXIS has been derived from the Greek, meaning a "three-dimensional, orderly arrangement", which is based on the principle that a volume like the brain can be mapped according to a specific coordinate system using precise measurements [1]. The stereotactic technique relates to a Cartesian coordinate system and employs mathematical concepts to identify points in space that result from the intersection of 3 orthogonal planes: the anteroposterior, lateral and vertical [2], [3]. The fusion of mathematical, anatomical and neurological fundamentals enables neurosurgeons to identify and access stereotactic targets without any direct visualisation [4].

The ability to correlate anatomical data with objective spatial mapping has opened the way to minimally invasive and safer structural stereotaxy, also known as "keyhole neurosurgery" procedures such as: biopsies, endoscopy, hematoma/abscess evacuation or radio-surgery, Stereo-Electroencephalography (SEEG) as well as for functional stereotactic procedures based on destructive or augmentative methods – e.g. Deep Brain Stimulation (DBS) [5].

Stereotactic neurosurgery is closely related to the stereotactic frame [6]. Since the first apparatus for human stereotaxy was reported in 1947 by Spiegel et al. [7], stereotaxy rapidly became a subject of interest and over 40 different stereotactic frames were designed and reported in the 1950s [2]. Gabriel and Nashold [1] listed several approaches which were divided into 5 categories: i) translational systems, ii) burr-hole mounted systems, iii) arc-centred, iv) interlocking arcs, and most recently v) frameless [8].

Despite the conceptual differences between stereotactic frames, all share the common goal of establishing a rigid relationship between the patient's head/brain and the operation space where screws, drills, probes and other devices are handled [9]. Frames are often considered to be cumbersome and inflexible devices, which are often uncomfortable to the patient and present limitations in reaching insertion trajectories [1].

Only a handful of robotic systems for assistive robotic neurosurgery were released on the market, although this idea has been a research target since 1985 [10]. Computer-driven technology such as robotic systems, unlike purely mechanical stereotactic frames, enables more intuitive interfaces. Robotic systems excel at handling spatial information and directives, which enables the neurosurgeon to focus entirely on the surgical procedure. The precision, steadiness and endurance of robotic systems are compelling arguments in favour of their use [11]. Additionally, robotic systems enable the precise guidance of neurosurgical instrumentation, as well as motion filtering and the imposition of physical restrictions to avoid "no-go" zones. On the other hand, there is still room for improvement particularly in terms of cost reduction and the development of smaller and more powerful robotic systems [12], [13]. With this in mind, we sought to list the most successful robotic systems developed specifically for or capable of executing stereotactic neurosurgery. The paper aims to provide a current perspective as well as future directions of robotic technology in this field.

The rest of this paper is organised as follows: Section II describes a standard Deep Brain Stimulation (DBS) surgery in order to illustrate the steps involved in a typical stereotactic neurosurgery; Section III addresses the expectations and

demands that neurosurgeons have concerning the potential role of robots as assistive devices; Section IV lists robotic systems and projects that either reached the market or received clinical clearance for assistant stereotaxy (endovascular and radiosurgery enabled robotic platforms not included). Finally, the current perspective and conclusions are presented in sections V and VI, respectively.

II. Stereotactic Neurosurgery

In order to explain when and how a robotic manipulator can be of use, why it would improve both working conditions and the final outcome, we present the traditional workflow of a stereotactic neurosurgery, more specifically for DBS with micro-electrode recording (MER). The bilateral DBS surgery described here was conducted on a patient with Parkinson's disease. More information regarding DBS surgical technique can be found in [14]–[17].

Following the paradigm of Image-Guided Surgery (IGS), the patient initially undergoes a Magnetic Resonance Imaging (MRI) and/or any anatomo-functional imaging scan. On the day of surgery, and after attaching the stereotactic ring (Fig. 1a) to the patient's head, a Computed Tomography (CT) scan is taken. The MRI and CT scans are *registered* to the stereotactic space, i.e. – the transformational relationship between the two three-dimensional spaces is determined [18]. Four fiducial localisation plates, attached to the stereotactic ring during the CT scan (Fig. 1a), allow for the calculation of the transformation between the image space, with reference to the anterior-posterior commissure line, and the stereotactic reference frame.

In the planning software, the medical team selects the target and entry points of the electrode insertion trajectory, avoiding vessels and ventricles. Based on the selected trajectories, the planning software computes the stereotactic coordinates for each electrode.

A phantom device is used in the operating room to visually confirm the stereotactic coordinates (Fig. 1b). The phantom is attached to a stereotactic ring (similar to the one fixated on the patient's skull) and simulates the target point to be reached by the electrode. The stereotactic frame is mounted onto the phantom's stereotactic ring and is adjusted to the desired coordinates. A stylet is then placed in the stereotactic frame guide and if the stylet tip and the phantom tip are coincident the computed coordinates are confirmed.

The frame is subsequently removed from the phantom, placed in the patient's stereotactic ring and the stylet is used to mark the scalp entry point. Then the frame is moved aside to make the scalp incision and to drill the hole in the skull to access the brain (Fig. 1c-1d). Afterwards, the frame is adjusted once again in order to advance the electrodes/cannulas to the defined depth (1e).

Multi micro-electrodes are used to map the sensorimotor region by recording the neuroelectrical activity near the planned target. Initially, these electrodes are positioned along the planned trajectory with the aid of guiding cannulas, 10mm to 15mm before the target. After this, they are iteratively lowered – millimetre by millimetre – until they are positioned

5mm from the target and then half a millimetre between iterations, recording the neuroelectrical signals during each step. At the end, the data recorded are analysed to select the closest location to the sensorimotor region within the nucleus (Fig. 1e).

The same recording micro-electrodes have a macro-stimulation lead, which is used to stimulate the previously located sensorimotor region. Following an iterative approach once more, the current and the depth of leads is increased (Fig. 1e-1f). During each step, the team of neurologists qualitatively evaluates the patient's symptoms, seeking the best response and verifying side effects.

After finding the ideal electrode placement and stimulation signal properties, the micro-electrodes are replaced with a definitive quadripolar macro-electrode. Intraoperative imaging is used to check if the macro-electrode placement coincides with the micro-electrode position. The macro-electrode is later connected to an Implanted Pulse Generator (IPG) or neuropacemaker. If bilateral brain stimulation is required, all the intraoperative processes must be repeated for the other side. Due to the long duration of the procedure, the neurosurgeon may choose to implant the IPG afterwards or in the following day.

III. Robotic assistant: neurosurgeons' expectations and demands

How do robotic systems improve the work conditions for neurosurgeons, neurologists and other staff? What tasks can be delegated to the robot? What are the benefits for the patient? What can be expected of a neurosurgical robot? These are some of the most common and fundamental questions often posed to and by developers regarding robotic neurosurgery, which will be addressed below.

As stated previously, typical stereotactic surgery lasts several hours, throughout which the surgical team must remain completely focused. After attending stereotactic surgeries and *brainstorming* with neurosurgeons and robotic engineers, we were able to answer the first two questions (which are somewhat related) and concluded that a simple and intuitive robotic system may improve the standard procedure in various aspects and thus:

- Enable the coordinates and electrode's path information to be managed between the planning software and the robotic controller software, instead of manually handling this information.
- Avoid stereotactic frame and mechanical driver slacks or loose parts.
- Avoid the slow process of repeatedly mounting and setting the frame and driver coordinates for both the phantom and patient.
- Allow neurosurgeons to select and insert electrodes in eccentric trajectories, overcoming the constraints imposed by the stereotactic frame apparatus. This is extremely helpful when more than a single trajectory is needed, such as during SEEG, where up to 20 electrodes need to be inserted in a single procedure.
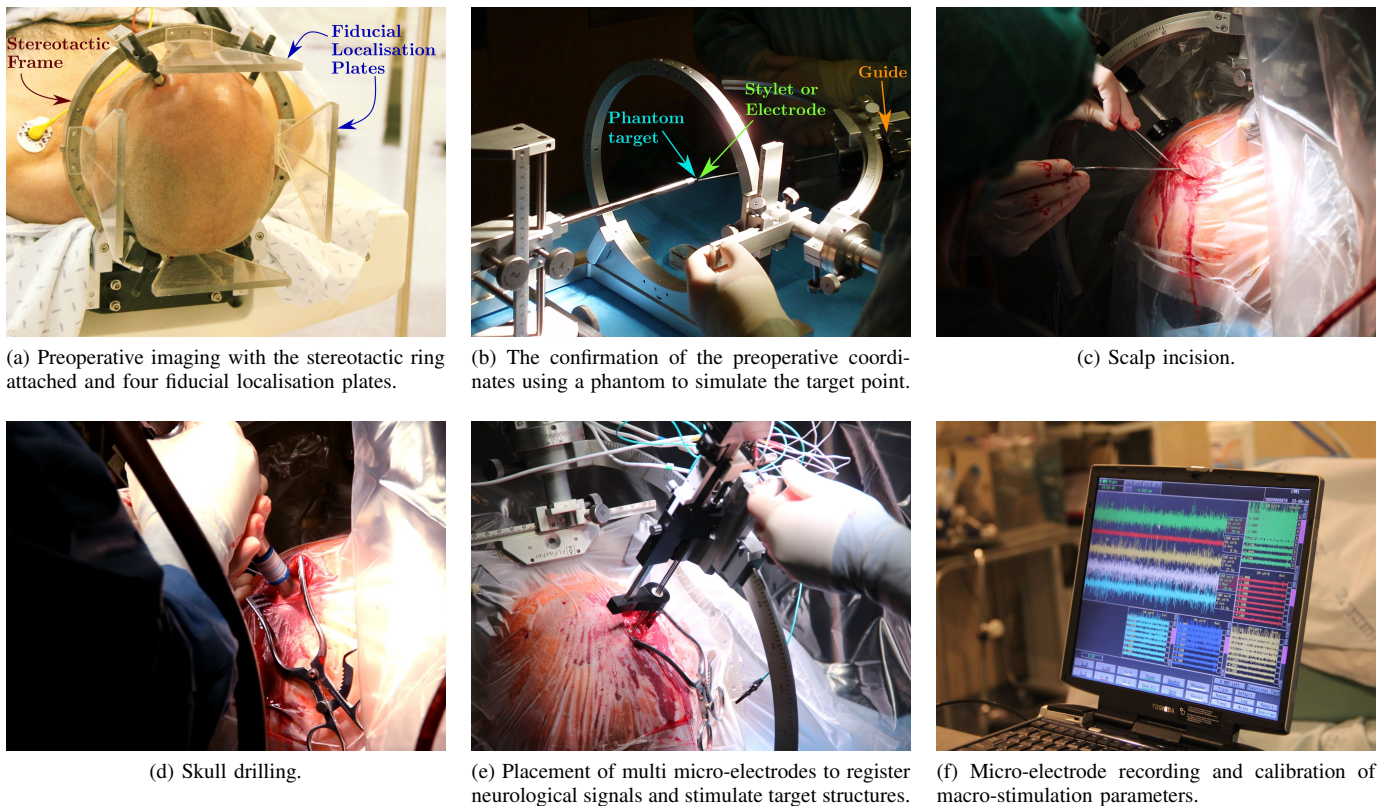
(a) Preoperative imaging with the stereotactic ring attached and four fiducial localisation plates.

(b) The confirmation of the preoperative coordinates using a phantom to simulate the target point.

(c) Scalp incision.

(d) Skull drilling.

(e) Placement of multi micro-electrodes to register neurological signals and stimulate target structures.

(f) Micro-electrode recording and calibration of macro-stimulation parameters.

Fig. 1.   Steps in the procedure for Deep Brain Stimulation surgery.

- Enable the robotic manipulator to handle multiple end-effectors and surgical instrumentation to execute re-strained skull drilling and the swift positioning of electrodes with improved precision. The manipulator can limit these tasks so that they are executed specifically along the predefined path, instead of executing them on the basis of a marked entry point.
- Enable medical teams to easily take control over the task of increasing the depth of electrodes - while evaluating the patient's symptoms - by simply interacting with a robot graphic interface, which aids neurosurgeons with that task.
- Ensure flexibility and ease in changing the entry point once the burr hole is performed and in the event of encountering an unexpected vascular structure after opening the dura matter.
- Reduce the risk of data loss or human errors.
- Enable online monitoring of the absolute coordinates of the instrumentation tips, based on their physical dimensions and on the manipulator position in relation to the base referential.
- Finally and most importantly, making frameless surgery under robotic guidance possible.

It is important to note that, even though frameless surgery implies no frame, the transformation between the instrument guiding device and the patient must be constant. The most common approach to this problem relies on the use of a Mayfield 3-point pin fixation device (Integra LS, Plainsboro, New Jersey), in order to immobilise the patient's skull. A rigid link connecting the Mayfield and the instrument guiding device then ensures the constant transformation. There are computational solutions in IGS for the active robot compensation of patient motion, which presents acceptable accuracy but this is still rather limited in the compensation time delay [19]."

Robotic systems enhance accuracy, precision and steadiness [20], which are directly reflected in fewer intraoperative complications and produce a positive impact on the patient's outcome [21], [22]. It is not only the patient but also the healthcare institution that benefits from shorter patient recovery times and lower occupancy rates.

When consulted about the expectations related to the robotic system for stereotactic neurosurgery, neurosurgeons look forward to: i) a simple system of intuitive usage, ii) a cost-effective solution, iii) a small, easily mountable and movable device. Thus, apart from the main goal of positioning and manipulating surgical equipment, the most sought after assets reside in the human factors and in the integrability of the robotic system. These aspects should thus be targeted by engineers when devising a robotic platform for stereotaxy.

IV. STATE-OF-THE-ART ROBOTIC SYSTEMS

Since the first report of a robotic neurosurgical system in 1985, a wide range of neurosurgical solutions have been developed [10]. So as to keep the paper brief, we have chosen to include the most successful robotic systems or projects directed at stereotactic neurosurgery that either reached the

market or were clinically tested, with reported *in vivo* results[1] (see TABLE I). Robotic platforms for endovascular or radio-surgery were not included in this review. The listed robotic systems were divided in three categories according to user-interaction (see Nathoo et al. [23]):

- *Supervisory Controlled*, the robot motion performed during the operation is explicitly or implicitly specified by the surgeon offline. During the procedure, the robot moves autonomously under the surgeon supervision.
- *Telesurgical*, the robotic manipulator (slave) is directly controlled by the surgeon through an input device like a joystick (master), which is usually endowed with force feedback.
- *Shared Control*, surgeon and robot share the control over the surgical instrumentation. The surgeon still controls the procedure while the robot provides steady-hand manipulation or active-restrain over surgical safety areas.

The list is organised in two parts to differentiate robotic systems: those developed *specifically* for stereotactic neuro-surgery and *general* robotic systems, which are capable of performing/assisting stereotactic neurosurgery although they were not solely designed for it.

A. Specifically for Stereotactic Neurosurgery

1) SurgiScope: SurgiScope (ISIS Robotics, Saint Martin d'Hères, France) development started in 1989 and ensued from a cooperation between the University of Grenoble and the industrial company AID. It is currently available at an operating level [24], and has been produced and installed worldwide with 40 fully operating units, implemented by more than 10 surgical teams (mainly in France).

The ceiling-mounted 7 DoF robotised manipulator is based on a parallel delta mechanism (Fig. 2) and is mainly dedicated to endoscopy and biopsy procedures or neuronavigation applications [25]. SurgiScope is particularly useful in intracranial operations, when the procedure requires navigation between sensitive neural elements, visible through a restricted access [24]. Additionally, its neuronavigation function facilitates resections or targeting procedures, when the boundaries of the surgical target volume are not visually distinct [26].

SurgiScope is the basis for multiple integrable upgrade modules including: 1) image import/conversion and treatment/planning software, 2) the microscope kit, 3) a handle set to single-handedly control system motion, 4) a tool holder kit to position and hold surgical instrumentation, and 5) a head up display to exhibit customised surgical plan data in the microscope oculars.

Preoperative targeting and trajectory planning are performed in the SurgiScope workstation [27]. The patient's head is fixated to the operating bed through a Mayfield, and the registration between preoperative planning and intraoperative space is achieved with scalp fiducial markers using a handheld probe [28]. After the craniotomy, the SurgiScope robot can operate in two modes. In microscope mode, the robot acts as a platform

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[1]The Robocast and NeuRobot projects did not report clinical trials, but were involved in major European-funded programs, and were included for their contribution.

Fig. 2. ISIS Robotics SurgiScope (*Courtesy of ISIS Robotics*).

to operate a microscope. It aligns its optical axis with the predefined trajectory, and adjusts the microscope focal point to the surgical target. In biopsy mode, an arm attachment with a probe carrier is attached to the robot. The Surgiscope robot then aligns its arm to the prescribed trajectory [27]. Through the bushings of the robotically positioned stereotactic guide, the insertion needle is advanced to the planned target [29]. Lollis and Roberts [27] have reported the application accuracy of Surgiscope: the mean displacement from the catheter tip to the target is 1.6 ± 3.0mm, in the robotic placement of a central nervous system ventricular reservoir.

One of the greatest advantages of SurgiScope is the possibility to acquire and work with individual system modules, which allows surgical teams to avoid superfluous features and thus reduce system cost. SurgiMedia, a modular platform to cope with the SurgiScope multimedia part, guarantees system compatibility with any type of surgical material available, which further enhances the system's flexibility. Extended operative time, acquisition costs and lack of mobility are considered to be the main drawbacks [27].

2) NeuroMate: NeuroMate (Renishaw-mayfield; Nyon, Switzerland) was the first neurosurgical robotic device to obtain the EC brand in Europe and FDA approval in 1997 for stereotactic neurosurgical procedures (and in 1999 for frameless), thus constituting a major milestone and setting the standard [30] (Fig. 3). The NeuroMate works as an image-guided, passive assistant for holding, supporting and stabilising instrumentation controlled by the surgeon, thereby increasing surgical safety and improving surgery efficiency [31], [32]. This robotic system shows appropriate mechanical stiffness, good accuracy and convenient workspace for stereotactic key-hole neurosurgery applications. Its advantages are even more evident in surgeries or biopsies that target multiple structures [31], [33]. For a thorough explanation of a surgical workflow involving NeuroMate, refer to [34].

It includes kinematic positioning software, as well as a 5 DoF arm that achieves a technical accuracy of 0.7mm and

TABLE I
MOST SUCCESSFUL ROBOTIC SYSTEMS AND PROJECTS DIRECTED AT STEREOTACTIC NEUROSURGERY.

	Project	Phase	Category	Institution	Main features
SPECIFIC	SurgiScope	Commercial use	Supervisory Controlled	ISIS Robotics, Saint Martin d'Hères, France	Delta parallel ceiling-mounted robotic manipulator with 7 DoF, modular architecture (user chooses the modules to work with)
	NeuroMate	Commercial use	Supervisory Controlled	Renishaw-Mayfield, Nyon, Switzerland	Serial robotic manipulator with 5 DoF, low-speed profile with sensor redundancy, mobile base, integrated planning system, frame/frameless ultrasound and CT-based registration
	Pathfinder	Discontinued	Supervisory Controlled	Prosurgics Ltd., High Wycombe, United Kingdom	Serial robotic manipulator with a 6 DoF robot, mobile base, integrated planning system, frameless registration using fiducial markers
	Renaissance	Commercial use	Supervisory Controlled	Mazor Robotics Ltd., Caesarea, Israel	Hexapod parallel robotic manipulator with 6 DoF, small and portable, directly mounted on the skull, integrated planning system, frameless and markerless, low-cost
	Robocast	Project terminated	Supervisory Controlled, Telesurgical	NearLab, Politecnico di Milano, Milan, Italy	Serial, parallel and linear multi-robotic tele-operated system with $6+6+1$ DoF, mobile base and integrated planning system
	Rosa	Commercial use	Supervisory Controlled, Shared Control	MedTech SAS, Montpellier, France	Serial robotic manipulator with 6 DoF, low-speed profile, mobile base, integrated planning system, frameless registration, shared control manoeuvrability
GENERAL	MKM	Discontinued	Supervisory Controlled, Telesurgical	Carl Zeiss, Oberkochen, Germany	Operating microscope mounted on a 6 DoF serial robotic manipulator for microscope navigation and tool guidance in biopsy applications
	NeuRobot	Project ended	Supervisory Controlled	Imperial College of Science, Technology and Medicine, London, United Kingdom	4 DoF rigid platform to hold and manipulate an endoscope around a pivot point, dynamical workspace constraint, frame reliant
	Evolution 1	Discontinued	Telesurgical	Universal Robot Systems, Schwerin, Germany	4 DoF hexapod robot with tele-operated parallel actuator, mobile base, integrated planning system, for brain and spine applications
	neuroArm / SYMBIS	Experimental setup	Telesurgical	IMRIS, Winnipeg, Canada	Two 7 DoF tele-operated manipulators with an extra DoF due to the tool actuation mechanism, integrated with MRI technology for intraoperative instrumentation tracking

Fig. 3. Renishaw-Mayfield NeuroMate.

a precision of 0.15mm, guaranteeing payload stability up to 5kg [35], [36]. The neurosurgeon may choose to purchase the basic NeuroMate platform and acquire additional modules for frame-based, frameless and other functionalities on demand. Alternatively, the Neuromate system may be integrated in a custom workflow, coping with existing solutions [33], [37], [38]. Its design enables the use of conventional stereotactic localiser frames or an exclusive frameless method that resorts to an ultrasound system to register the robot's position in relation to the patient's skull [36]. Developed for neurosurgery, the NeuroMate presents unique features that distinguish it from industrial robots, such as low speed, sensor redundancy and safety devices [31], [32].

Li et al. [31] have reported the NeuroMate's *in vitro* application accuracy using the frame-based (0.86 ± 0.32mm) and frameless (1.95 ± 0.44mm) approach. It was concluded that there is no statistically significant difference in accuracy between the frame-based traditional approach and NeuroMate's frame-based application. Other studies [36], [39] have validated and demonstrated the reliability of the frameless method against frame-based surgery. Cardinale et al. [37] have reported the *in vivo* localisation error of the NeuroMate frame-based approach in 91 SEEG procedures as being 0.86 ± 0.54mm at the entry point and 2.04 ± 1.31mm at the target point. Recently, von Langsdorff et al. [40] studied the application accuracy (better than 1mm) of the NeuroMate frame-based approach *in vivo* for DBS electrode implantations.

The negative aspects pointed out reside in the bulk robot structure and the cost of the system's acquisition. According to neurosurgeons, one desired upgrade would be to endow NeuroMate with drilling capabilities [37].

3) Pathfinder: The Pathfinder system (Prosurgics Ltd., High Wycombe, United Kingdom) (Fig. 4) is a robot built for neurosurgical procedures. It constitutes response to instrumen-

tation miniaturisation and to the demand for greater accuracy which, as stated by Eljamel [41], will soon transcend even the most skilled surgeon capabilities. A 6 DoF robotic arm is installed on a mobile and stable platform, which can be easily moved around the operating room and firmly fixed to the Mayfied during surgery. One of Pathfinder trademarks lies in the fiducial markers (reflectors) attached to the patient's scalp or skull, and their continuous tracking using an embedded vision system to register the robot to the intraoperative space [42]. These markers consist of a black titanium sphere, coated in a reflective material, which is easily visible in CT scans and by the camera system [41], [43].

Fig. 4. Prosurgics Pathfinder.

An initial CT exam is used to pinpoint the marker positions in relation to the surgical volume, while the MRI dataset is required to segment the target brain structures. The CT and MRI datasets are then matched to overlay the targets and fiducial markers' locations. The Pathfinder planning software allows the neurosurgeon to view, edit and mark medical images of the patient, and to plan the probe's trajectory [44]. The Pathfinder can fixate itself to the Mayfield, opposite the surgical side or at an acute angle parallel to the patient. By doing so, the robot can operate with some flexibility without interfering or obstructing the neurosurgeon's workspace [41].

Pathfinder frameless registration allows for target acquisition with millimetric accuracy [44]. Furthermore, the robot can be repositioned in the operating room without the need to rescan or replan [45]. External fiducial markers allow the robotic system to constantly track its position in relation to the patient, thus solving one of the greatest issues regarding preoperative image guided robots, and relieving the need for intraoperative online image scans [41], [42]. The most commonly reported problems with the Pathfinder system are: possible skin movements between preoperative and intraoperative scans, and registration failures caused by the misidentification of markers due to abnormal lighting conditions [41].

Upon contacting the Pathfinder manufacturers, we were informed that this project terminated at the beginning of 2009 due to lack of substantial funding and certification issues, and that Prosurgics was later acquired by FreeHand 2010 Ltd.

4) Renaissance: The Renaissance robotic system (Mazor Robotics Ltd., Caesarea, Israel), originally developed for spine pedicle screw insertion by Prof. Shoham, was adapted for minimally invasive neurosurgeries [46]–[48]. The system is composed of the MARS robot and controller, a custom robot base, a targeting guide and a registration jig. It is also accompanied by an "off-the-shelf" 3D laser scanner and a standard PC [49]. The system comprises 4 software modules: i) preoperative planning; ii) surface scan processing; iii) 3-way registration and iv) intraoperative execution. The system fits in the category of Supervisory Controlled, and mainly serves the purpose of tool guiding and drill assistance.

MARS is a small portable 6 DoF parallel robot ($5\times 8\times 8$cm and a weight of 250g) with a motion accuracy of 0.1mm and a resolution of 0.02mm (Fig. 5). The robot can be directly mounted on the patient's skull through the custom robot base, or mounted on a Mayfield. It is endowed with a lock mechanism, which is activated upon aligning the guide with the predefined entry point/target axis. The robot remains locked and rigid throughout the guiding and drilling phase, and is able to withstand lateral forces of up to 10kg and actuation forces up to 1kg.

Fig. 5. Renaissance MARS robot (*Courtesy of Mazor Robotics, Inc.*).

The surgical procedure using the Renaissance system follows the premises of IGS. Initially, a markerless and frameless CT/MRI scan of the patient is undertaken, where the surgeon defines entry and target points, and the type of robot mounting selected (custom base or Mayfield) [50]. The registration between preoperative planning and the intraoperative space is achieved through the surface matching of the CT/MRI and laser scan cloud of points [51], [52]. The transformation between MARS robot base and the intraoperative space is computed based on a surface cloud of points containing both the registration jig (high relief wide-angle tetrahedron shape) and the patient's forehead or ear. The MARS robot now replaces the registration jig, and automatically positions its guide along the planned insertion trajectory. On surgeon demand, it automatically changes its guide position to a new trajectory [50].

The Renaissance system surface registration error was reported to be close to 1mm, while the target registration error was approximately that of 1.7mm [50]–[52]. Recently, a target registration error of 0.65mm was reported by Joskowicz et al. [53] in a phantom study.

As a frameless and markerless system, Renaissance overcomes the morbidity and head immobilisation requirements associated with stereotactic frames; it further eliminates the line-of-sight and tracking requirements of navigation systems and still provides a rigid platform for mechanical guidance without the bulk and costs associated to large robots. The system's cost was initially aimed to be under 100k USD, unlike other robotic solutions which range from 300k to 500k USD [50], [52]. A recent article in an investment research platform revealed the listed system price to be 849k USD and the disposables 1.5k USD [54].

5) Robocast: The Robocast – an acronym of Robot and Sensor integration for Computer Assisted Surgery and Therapy project (FP7 ICT-2007-215190) – aimed to create a modular system to integrate image guided navigation and robotic devices for keyhole surgery (Fig. 6). The project developers envisaged a human-robot interface with context-intuitive communication, embedded haptic feedback, a multiple robot chain with kinematic redundancy, an autonomous trajectory planner and a high level controller [55], [56].

Fig. 6. Robocast robot (*Courtesy of De Momi, E. and Ferrigno, G. - Robocast Project*).

The Robocast system consists of an optical and electromagnetic tracking system, ultrasound and three robotic actuators with haptic devices. The first robot, or *gross positioner*, is the Pathfinder robot with 6 DoF. There is another called *fine positioner*, which is the MARS (Renaissance) parallel robot with 6 DoF to further improve accuracy. The third is a linear piezo actuator to ensure the linear insertion of electrodes or biopsy probes. The optical tracking system is used to *register* the intraoperative environment according to the preoperative plan. A single DoF haptic feedback actuator is used to control probe depth [57].

The software platform can be divided into six subsystems: preoperative planning, human computer interface, sensor manager, high level controller, haptic controller and safety check [58]. After the neurosurgeon has selected the target and entry area, the preoperative planning software autonomously calculates the lower risk optimal entry point and trajectory [38], [56]. Human Computer Interface allows the surgeon to interact with the navigation system, while the sensor manager assembles data from the ultrasound and tracking system and inputs this to the system control centre. The high level controller manages information from the preoperative planning and sensor manager subsystems, and iteratively calculates the gross positioner and fine positioner kinematics [59]. The haptic controller interfaces the linear actuator robot with the haptic device, transmitting a force-feedback reaction to the surgeon so that the probe will be moved. Finally, the safety check module runs regular state verifications for each subsystem; in the case of failure, it stops the probe movement [60].

The technical accuracy of the iterative targeting approach based on continuous optical feedback was evaluated *in vitro*, in optimal and noise induced conditions. The largest reported translation median error was 0.6mm and 0.4mm for the entry and target points, respectively. While the largest rotation median error was 6.5×10^{-3}rad [59]. The accuracy reported fits the requirements for clinical applications.

The Robocast project ended in 2011 and has been continued by the Active project - acronym for Active Constraints Technologies for Ill-defined or Volatile Environments (FP7-ICT-2009-6-270460) [61], [62], which proposes an integrated redundant robotic platform. This relies on two autonomous cooperating robotic manipulators for neurosurgery, which form a light and agile system with 20 DoF.

6) Rosa: The Rosa robotic system (MedTech SAS, Montpellier, France) is the latest generation of neurosurgical computer controlled robots for stereotactic surgery (Fig. 7). The Rosa system comprises a mechatronic part consisting of a 6 DoF serial robotic manipulator and a control software part for neurosurgery planning, registration and guidance [63].

Fig. 7. Medtech Rosa (*Courtesy of Medtech Surgical*).

The planning software (Rosana, MedTech) allows for the merging of different and complementary imaging techniques when studying the best surgical approach. The patient initially undergoes an MRI exam (with or without contrast, various supported sequences) to visualise the target anatomical structures, and to plan the optimal guiding trajectory [64], [65]. This plan is then registered to a CT scan, performed near

the time of surgery, and which serves as the reference due to its homogeneous geometric accuracy. An intraoperative Flat-Panel CT can be integrated in the surgery workflow to compensate for brain shift or robot registration errors [66], [67].

After uploading the plan to the Rosa system, the robot is firmly fixed to the skull clamp. The surgery team may choose to register the robot to the intraoperative scene in a frame-based (Leksell frame) or frameless approach. The frameless method is carried out using fiducial markers attached to the scalp/skull, or via the Rosa patented automatic surface scan. The latter combines robot motion and laser telemetry to provide a non-invasive registration [68], [69].

The robot is draped after a satisfactory registration and, upon the surgeon's command, automatically moves to the planned guiding trajectory. It remains in a locked state while the entry point is marked and prepared. Scalp incision and skull drilling is performed with a cordless power drill [64]. The neurosurgeon may choose to insert the probes or electrodes manually through the adapted reducers held by the arm, or may use the haptic robot interface to lower the instruments [67]. This shared-control feature allows for intuitive interaction and control by the neurosurgeon with tremorless and motion restriction advantages.

Lefranc et al. [68] presents a study comparing different modalities of image and robot registration with a phantom and in actual procedures. The Rosa system achieves an accuracy below 1mm for frame-based and fiducial registration, and a 1.22mm accuracy for frameless surface registration, both with CT as well as reference imaging[2].

The greatest asset of the Rosa system, when compared to the other solutions, is its flexibility. It is easily integrated in the institution workflow and is reported to be well accepted [67]. No other robotic system offers so many options regarding robot registration. The Rosa system provides consistent and accurate instrument guidance, while keeping surgery times comparable to conventional methodologies [64], [66], [67]. With regard to its negative aspects, users point to the robot's learning curve and bulk dimensions, which limit the neurosurgeon's workspace.

B. General and capable of Stereotactic Neurosurgery

1) MKM: The MKM system (Carl Zeiss, Oberkochen, Germany) stands for "Multicoordinate Manipulator", and consists of three components: 1) an operating microscope mounted on 2) a 6 DoF motor-driven robotic arm, and 3) a computer workstation [70]. Its initial goal was to serve as a frameless stereotactic navigation system, by joining the concepts of intraoperative microscopy and neuronavigation in minimally invasive IGS [71].

The surgical procedure is planned and based on preoperative image scans, which are then registered to the intraoperative scene using scalp or bone fiducials. Inside the operating room, the neurosurgeon visualises the neuroimaging plan, superimposed onto the microscope optical field, and showing the entry point, target point, lesion contours and other structure markings [70], [72]. Several advantages arise from this fusion: the potential to outline and minimise the size and shape of skin incision, craniotomy and corticotomy; the capacity to decide between different surgical approaches and the possibility of performing more aggressive resections with a lower risk of damaging surrounding structures [71].

Willems et al. [73] extended the applicability of the MKM system by introducing an instrument holder for frameless stereotactic procedures to be mounted on the microscope. This instrument holder, also developed by Carl Zeiss, consisted of an extension arm which rigidly fixed to the microscope with a large channel for tool guidance. Plastic reducers are fitted to the channel to constrain different instrumentation, for probe guidance or bone drilling [73]. The MKM software was equipped with a "tool mode" module, which sets the instrument holder so as to align it with the surgery planned trajectories, rather than the optical axis [74]. Additionally, instead of tele-manipulating the microscope with a spherical sensor joystick, the microscope holder automatically moves to the predefined position (manual repositioning possible). During instrument insertion, however, the system movements are disabled for safety reasons [73].

In vitro and *in vivo* studies were performed with the mounted instrument holder to assess the MKM system's accuracy. Willems et al. [73] reported a slightly lower application accuracy with the robot when compared to the BRW frame; yet, there was a comparable target localisation error. Willems et al. [74] reported an average biopsy localisation error of 3.3mm and 4.5mm, depending on the registration method used (bone screws or scalp adhesive fiducials). While this is acceptable for brain biopsy procedures, further accuracy is required for functional neurosurgery.

The MKM system presents a rapid, flexible and reliable alternative to stereotactic frames in biopsy brain surgeries and stereotactic neurosurgery guidance [73]. On the other hand, its high costs of acquisition, bulky structure and lack of mobility, constitute some of its negative features [67], [74].

2) NeuRobot: NeuRobot[3] stemmed from the European Community funded project ROBOSCOPE to provide a joint solution for common problems in Neurosurgery. The project involved a robotic arm (NeuRobot) and a simulator image-guided system, ROBO-SIM. Focusing on the robot platform, the NeuRobot is described by Auer et al. [78] as "an active manipulator with inbuilt robotic capabilities" that includes: active constraint mechanisms of the manipulator motions based on mapped permitted regions, a precise pattern control and the capacity to automatically track moving features (Fig. 8).

The robotic manipulator has no more than 4 DoF to manipulate instrumentation around a pivot point – the burr hole entry point in stereotaxy. These 4 DoF control the probe orientation around the Yaw, Pitch, *Endoscope* rotation and the

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[2]Surface registration with MRI scans are error prone due to image-related distortions, leading to significantly lower overall accuracy.

[3]Do not confuse this with another system called the NeuRobot [75], [76], which is a telecontroled micromanipulator system with a master-slave control hierarchy to perform minimally invasive procedures using an endoscope and three robotic arms. There is also another system, also called NeuroBot, which is used in skull-based surgeries [77].
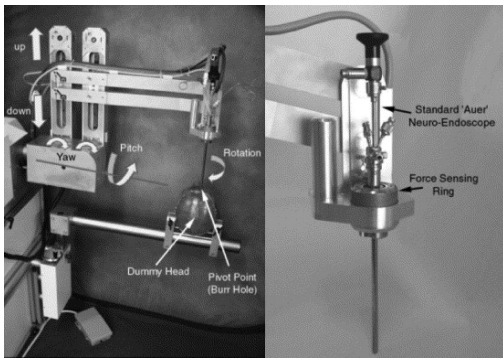
Fig. 8. NeuRobot (*Courtesy of Prof. Brian Davies, at Imperial College of London*).

position along an *Endoscope* depth DoF, which implies that the NeuRobot cannot reach the pivot point on its own and must, therefore, be previously positioned. This is one of the system's disadvantages since, if more than one trajectory is required, the robot needs to be repositioned and readjusted to the surgery table [79].

The manipulator includes a control mechanism developed from a flight-simulator experience by Fokker control systems b. v., and enhances precise motion and force-control using low force inputs [78]. Special attention was paid to safety issues. The system thus includes: a dead man's switch and a workspace which is physically constrained in a safe operating volume based on MRI segmented data. An ultrasound imaging system is used to track tissue deformation during the procedure, and the probe position is dynamically compensated in real-time. The NeuRobot was able to operate autonomously, yet it raised concerns about "who is in-charge" of the surgery [79].

Despite its advantages, the system is still dependent on a stereotactic frame to *register* the robot with the surgery reference [79]. The robot was initially projected to hold and manipulate a neuroendoscope but, as stated by the authors, it could in principle be used to handle other stereotactic instrumentation. One remarkable advantage of the NeuRobot system is the integrated ROBO-SIM software, which enables the same manipulator to be used in real or simulated interventions to train and help neurosurgeons to become acquainted with the system [78].

3) Evolution 1: The Evolution 1 robotic system (Universal Robot Systems, Schwerin, Germany) was especially designed for neurosurgical and endoscopic applications for micro scale brain and spine procedures. Unlike the previous examples, Evolution 1 is a 4 DoF hexapod with a parallel actuator, which combines high accuracy with great payload capacity. Its 6 mechanical parallel axes work as a spherical joint to move a platform with a slider mechanism that holds the endoscope. The parallel actuator approach enhances motion precision achieving an absolute positioning accuracy of $20\mu m$ and a motion resolution of $10\mu m$, even under loads of up to $500N$ [80], [81].

Evolution 1 is able to compute the movement of all axes in less than 120μsec. It comprises a universal adapter enabling it to incorporate different types of surgical instrumentation like endoscopes and high speed drills. Due to the rather reduced working range, however, it must be pre-positioned in the desired orientation, approximately 5cm above the entry point. Its user-interface is a touch screen and a master joystick device to control end-effector motion and speed [80], [81].

Following IGS methodology, end-effector instrumentation follows a trajectory set preoperatively and based on MRI scans and planning software (VectorVision, BrainLab). Intraoperatively, the patient's face is scanned for surface recognition by using infrared technology or laser surface scanning. Later, this information is matched with the preoperative MRI to ensure that the robot knows its position in relation to the surgery reference frame [81].

The main advantages of Evolution 1 are: high precision and steady positioning/manipulation of endoscope, smooth and slow execution of movement within critical anatomical areas while handling surgical equipment. This system can be potentially adapted to assist stereotactic surgeries. However, a high payload capacity is superfluous since the weight factor is not an important aspect for the instrumentation and tasks at hand. Consequently, a parallel actuator is not always the best choice as it is typically large, thus restraining the neurosurgeon's workspace, and possesses a relatively limited reach/flexibility.

4) neuroArm / SYMBIS: The award-winning system, neuroArm, was developed by Dr. Garnette Sutherland from the University of Calgary in association with engineers from Macdonald Dettwiler and Associates (MDA). It was introduced in 2002, and was recently acquired and renamed SYMBIS (IMRIS, Winnipeg, Canada). The project's main goal is to take advantage of the MR-environment and haptic feedback technology, adding 3D image reconstruction and high-end hand-controller design. It claims the title of being the first image-guided, MR-compatible surgical robot, capable of microsurgery and stereotaxy. It consists of two 7+1 DoF manipulators, which are semi-actively actuated in a master-slave control type and moved by hand control at a remote workstation. The human-robot interface filters undesired hand tremors and can scale the movement of the controls in relation to end-effectors [82], [83].
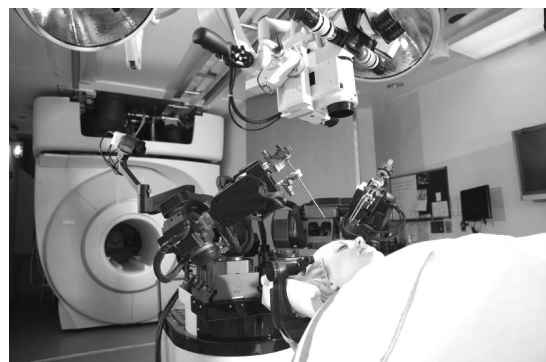

Fig. 9. University of Calgary neuroArm (*Courtesy of neuroArm Project, at University of Calgary*).

The neuroArm is built for neurosurgery precision tasks, so that each arm has a limited payload of $0.5kg$, a force output of $10N$, a tip speed that ranges from 0.5 to $5mm/sec$ and sub-millimetric accuracy. Patient safety was paramount concern throughout the development of the robotic system, and features such as active workspace constraints were added in case the robot leaves the safe operating zone. These policies granted neuroArm the approval of the Canadian Standards Association in 2007, as well as that of Institutional Ethics and Investigational Testing by the University of Calgary and Health Canada in 2008 (Fig. 9).

This robotic system is capable of microsurgery and stereotaxy, which has granted it a place among the *general* robotic platforms [84]. Despite increasing surgery time, its precision, steadiness and compatibility with planning software have resulted in reduced trauma and blood loss [82]. The end-effector positioning can be verified by overlaying 2D and 3D MRI preoperative and intraoperative information, respectively. After positioning, a Z-Lock feature is used to restrict the tool motion along the defined longitudinal trajectory.

The main advantage of the neuroArm system also constitutes a drawback in some types of stereotactic neurosurgery, due to the need for an MRI scanning machine during the entire surgery with the associated maintenance and acquisition costs. Furthermore, the robotic system costs are also considerably higher since the robotic manipulator is manufactured exclusively with non-ferromagnetic materials (primarily titanium and polyetheretherketone) [83].

V. CURRENT PERSPECTIVES AND FUTURE DIRECTIONS

If one is to compare the most successful robotic systems/projects for stereotactic procedures, one will find several similarities. All the systems follow a very standard and similar surgical protocol related to the IGS paradigm. The main differences are chiefly related to technical aspects.

Starting with the robot structure itself, most systems rely on serial instead of parallel actuators. Parallel robots excel at precision associated with larger payload requirements; even so, a larger payload capacity will seldom be a requirement in stereotactic procedures. Additionally, parallel actuators have very limited access to the surgical target and typically occupy more space next to the patient. Serial manipulators, on the other hand, present greater flexibility and compactness, while still providing a larger workspace, i. e., easier access to surgical targets and trajectories. It is important to note the Renaissance system's unorthodox solution, which takes advantage of the sturdiness of parallel actuators to miniaturise and create a portable robot. Although its narrow workspace prevents its use in SEEG applications, it is used in DBS and biopsy surgeries.

The number of the manipulators' DoF is application-dependent, but this tends to vary between 4 and 7, except for the *Robocast* project's robot, which follows a multi-robotic 13 DoF approach (for enhanced precision). The number of manipulation DoF affect not only the workspace but the robot's dexterity and flexibility, thus conditioning surgical

planning. Fewer DoF and a more reduced workspace means less flexibility, which directly influences how the robot should be placed in order to reach the planned trajectories, often implying obstructions to the medical team's workspace and vision of the surgical field. Although more DoF and high dexterity is generally an advantage regarding collision avoidance problems, a larger number of joints – particularly in serial manipulators – means more sources of errors that accumulate along the robotic chain.

Most of the robotic systems and projects for stereotactic neurosurgery enable a frameless approach and are gradually becoming detached from the dependency on stereotactic frames. While frameless is one of the flags of robotic systems, the accuracy and repeatability of frameless systems is still surpassed by frame-based systems [37], [68]. Specially in the case of functional neurosurgery in deep-seated targets, frame-based is still the preferred solution. This is because the frameless approach maximises accuracy and precision at the entry point rather than at the target point, as in the arc-centred approach [85], [86]. Improving efficiency and developing new frameless registration/fixation methods constitutes a timely endeavour and a research opportunity.

The robotic systems listed converge in other aspects, such as their portability and embedded imaging and planning technology. The lack of mobility in systems like Surgiscope and MKM is seen as a disadvantage. The fact that they are easy to transport and quick/easy to set up is certainly a premise for future robotic system developers. Additionally, the system's modularity and possibility of choosing from different surgical approaches depending on the clinical case, greatly improves the system's acceptance.

Safety is of paramount concern and should be addressed from the early stages of the system's development [87]. It is the most cited reason underlying a medical team's apprehension in the face of robotic technology [88]. To achieve clinical clearance, a robotic system must at no single point of failure lead to a loss of control and injury to the patient. Critical safety systems like these are typically endowed with redundant position encoders and mechanical limits for speed and exerted forces. Any sensory mismatch or consistency failure should cause the robot to *freeze* or go limp, while assuring a safe retract mechanism to resume the surgery in a traditional fashion [89], [90]. Regarding sterilisation, the system parts which are in direct contact with the patient must be either disposable or robust enough to withstand autoclaving or other sterilisation methods. Non-sterilised components need to be covered in sterile drapes or pre-sterilised bags [87]. Lastly, the neurosurgeon can also constitute a source of errors, and must thus be carefully trained with the robotic system, and with the new procedure workflow involving the robot. Surgeons need to be instructed as to the capabilities and limitations of the system, and become acquainted with the execution of the new surgical plan to check for any potential changes/problems [90].

The most referred drawbacks of surgical robots are the high acquisition costs for hospitals and academic institutions [13]. One can argue that the passive behaviour expected of a robot assisting stereotactic surgery in manipulation and placement tasks is somewhat similar to industrial tasks. An

obvious choice would be to import industrial technology to the operating room. However, according to Davies [91], for an industrial manipulator to comply with healthcare safety regulations, it should undergo several modifications which will further increase the robot's costs. In any case, the major obstacles for the development of new surgical robotic systems can be attributed to: long and costly developments with little return; insurmountable barriers of regulatory approvals or legal battles for intellectual property [92].

For new robotic platforms to achieve significant clinical acceptance, they should present unambiguous advantages over conventional approaches [12], [90]. The trend of technological progress is currently oriented towards: the miniaturisation and development of cost-effective robotic systems without jeopardising performance; and the upgrading of human-machine interfaces possessing enhanced haptic feedback and a seamless integration with several imaging modalities in a surgically relevant and yet intuitive manner [13], [93].

VI. CONCLUSION

The disclosure of surgical robots has already contributed significantly to an improved neurosurgical practice through increased precision, stability and the possibility to integrate state-of-the-art technology. The robotic solutions which are currently available for stereotactic surgeries can easily enhance the surgeons' performance with regard to standard surgery, and are becoming easier and more intuitive to use as this technology evolves. However, unfamiliarity with robot technology and the costs of the few commercially available solutions can discourage its use.

Narrowing the gap between physicians and engineers and promoting an active cooperation between both groups will constitute a key factor if one is to improve robots for neurosurgery and encourage their use. Improvements in the quality of healthcare will ultimately surpass the inherent costs of robotic surgery systems, through fewer intraoperative lesions, as well as shorter recovery and hospitalisation periods.

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