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Robotic Applications in Neurosurgery

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1. Introduction

Recent advances in neuro-imaging and stereotactic and computer technology gave birth to minimally invasive keyhole surgery to the extent that the scale of neurosurgical procedures, demanded by patients, will soon be so small that it will not be within the capability of the most gifted and skilled neurosurgeons of today. Neurosurgical robotics is the natural progression in this field. Furthermore, the economic advantages, increased precision and improved quality in industrial applications of robotics have stimulated robotic applications in neurosurgery. These neurosurgical robots have significant manipulative advantages over neurosurgeons; neuro-robots are reliable to perform the same procedure over and over, again and again without tiresomeness, variation or boredom. They possess near absolute geometric accuracy and are impervious to biohazards and hostile environments and can work through very narrow and long surgical corridors most suited for surgery on the brain, which is an organ uniquely suited for robotic applications; it is symmetrically confined within a rigid container, the skull, and the brain can be easily damaged by even the smallest excursions of surgical instruments. Robots can also see around corners that are beyond the line of sight of the neurosurgeons during operations and in a way, robots extend the visual and manual dexterity of neurosurgeons beyond their limits.

Several ergometric studies during surgery were reported (Berguer, 1999) that have demonstrated substantial muscle fatigue occurring during procedures related to procedure duration and the angle of surgical instruments. Over the last two decades several systems were developed for use in neurosurgery; some of these neuro-robots have been used in clinical practice while others have not been near a patient because of safety and ethical concerns. Among those robots which were used included the PUMA 200 (Kwoh et al., 1985 and Drake et al., 1991), the Minerva robot from the University of Lausanne in Switzerland (Burckhart et al., 1995), the NeuroMate from Integrated Surgical Systems (Benabid et al., 1987 & 1998), the MRI compatible robot developed in Japan (Masamune et al., 1995), the Evolution 1 (Universal Robotics Systems, Schwerin, Germany), the CyberKnife (Accuracy Inc, Sunnyvale, CA), the RoboSim neurosurgery simulator (Radstzky & Radolph, 2001), the neuroArm (Louw et al., 2004), the PathFinder (Eljamel, 2006) and lastly the SpineAssist (Shoham et al., 2007). Robots were also integrated within current neurosurgical tools such as the microscope, the SurgiScope stereotactic system (Elkta AB, Stockholm, Sweden) and the MKM microscope system (Carl Zeiss Inc, Oberkochen, Germany).

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2. History of Robotics in Neurosurgery

Neurosurgical robotics had a long gestation period spanning over two decades. The main reason for this long period of development is the stringent regulation of health and safety. In contrast, industrial robots leaped into production very quickly because they can be isolated from human contact in a cage or a highly secure environment; neurosurgical robots on the other hand are designed to interact with surgeons and perform or assist the surgeon to perform complex surgical procedures on alive but anaesthetised patients. Hence, the evolution of neurosurgical robotics was slow as follows.

- **The Unimation PUMA 200** (Advances Research & Robotics, Oxford, CT):

A standard industrial robot (PUMA 200) was used to hold a stereotactic biopsy needle in a 52-year-old man on a CT scanner table, the target was identified on the CT images and the robot was used to orient a guide tube through which a needle was inserted (Kwoh et al., 1985). Localization of the target was achieved by using the Brown-Roberts-Wells (BRW) stereotactic frame localization plates and the head was secured to the CT scanner table using the stereotactic frame reference ring. It is a programmable, computer-controlled, versatile robot that was designed to perform highly accurate, delicate work, yet it was rigid enough to provide stable trajectory. It was a safe robot, designed to work with humans and its joints were equipped with spring-applied, solenoid-released brakes that automatically clamped should any mechanical or electrical defect occur. It has 6 degrees of freedom; movements are executed by DC servomotors; tracking is achieved by optical encoders and it can be used in passive or active programmable modes. It has an accuracy of 2mm and repeatability of 0.05mm. It uses the Brown-Roberts-Wells stereotactic frame for registration and CT scan for imaging. The use of the cumbersome stereotactic frame is a constraint and as such its accuracy and performance are similar to the frame, it has an advantage over the frame in those tedious calculations and manual adjustments were automatically executed by the robot. It was used as a retractor during resection of thalamic astrocytomas (Drake et al., 1991) (Figure 1).



Figure 1. The PUMA Robot (Courtesy Helge Ritter, Bielefeld University, Germany)

- **The Minerva System** (University of Lausanne, Switzerland):

The Minerva system was designed to perform within 5 degrees of freedom. It had two linear axes (vertical and lateral), two rotary axes (moving in a horizontal and vertical planes), and a linear axis (to move the tool to and from the patient's head). The robot is mounted on a horizontal carrier which moves on rails. A stereotactic frame, the Brown-Roberts-Wells (BRW) reference frame, is attached to the robot gantry and coupled to the motorized CT table by two ball-and-socket joints arranged in series. The system was used for two operations on patients in September 1993 at the CHUV Hospital in Switzerland, but the project has since been discontinued. The problems with this project were the limited degrees of freedom, the robot was unwieldy and located within the CT scanner making the environment not ideal for performing neurosurgical procedures and diagnostic imaging. It did not get rid of the cumbersome stereotactic frame and as such it did not offer performance advantage compared to the frame. It was fixed to the scanner making the procedure longer and was not cost-effective as the CT scan suite was unusable for other diagnostic scans during the procedure.

- **Evolution 1** (Universal Robotics Systems, Schwerin, Germany):

This robot was designed for both brain and spinal applications and has 6 degrees of freedom. It is a hexapod robot based on parallel actuator configuration to provide a high degree of accuracy and high payload capacity for drilling applications such, as drilling in the spinal pedicles, and more laterally was used to steer a neuroendoscope (Zimmermann et al., 2002).

- **An MRI compatible robot** (Masamune et al., 1995, Chenzie & Miller, 2001, DiMaio et al., 2006):

This robotic system was developed by Harvard Medical School in collaboration with Mechanical Engineering Laboratory, AIST, MITI (Tsukuba, Japan). It has 5 degrees of freedom and is MRI compatible. It works with intraoperative MRI system (Signa SP/1, General Electric, Milwaukee, WI) and it has non-magnetic ultrasonic motors based on parallel configuration. It consists of a three-degree-of-freedom Cartesian positioning stage and a two-degree-of-freedom orienting mechanism, and is mounted above the surgeon's head in the open MRI magnet. Two long rigid arms reach into the surgical space and form a parallel linkage for manipulating an acrylic needle holder or guide. The five motion stages are driven by ultrasonic motors (Shinsei USR-60N) attached to lead screws, and motion is measured by optical encoders with 10µm resolution (Encoder Technology, Cottonwood, AZ). A flashpoint sensor is attached to the needle holder to provide independent redundant encoding. This robot has been integrated with a software planning interface (built into the 3D Slicer), and a tracking and control system for percutaneous interventions in the prostate under MR-guidance. The surgeon interacts with the planning interface in order to specify a set of desired needle trajectories, based on anatomical structures and lesions observed in the patient's MR images. All image-space coordinates are computed and used to automatically position the needle guide, thus avoiding the limitations of the traditional fixed template guide. Once the needle holder is in position, the robot remains stationary while the surgeon manually inserts the needle through the guide and into the tissue, with real-time imaging for monitoring progress. The disadvantage of this device is its dependence on intraoperative MRI scan and MRI compatible instruments. Whilst it is beyond the reach of most centres worldwide today, it may become part of MRI technology in the future as more and more surgery is performed at the time of diagnosis.

- **The NeuroMate Robot** (Integrated Surgical Systems, Davis, California, USA):

It is commercially available and FDA approved and evolved from the work of Benabid's group in Gernoble University, France. It has 6 degrees of freedom, incorporates CT, MRI and angiographic neuroimages. It was used in conjunction with a stereotactic frame to position a cannula or probe for biopsy or targeting deep brain structures. It is a six-axis robot for neurosurgical applications. The original system was subsequently redesigned to fulfil specific stereotactic requirements and particular attention was paid to safety issues. To carry out a procedure by the NeuroMate, the robot must know where it is located relative to the patient's anatomy. This is typically done using a calibration cage, which is placed on the end-effector of the robot around the patient's head. This cage looks like an open cubic box and the four sides are each implanted with nine X-ray opaque beads, the positions of which have been precisely measured. Two X-rays are taken which show the position of these beads along with the fiducial markers of the patient's frame. In the newer versions of this robot, an ultrasonic-based registration is performed using the reference markers shown in Figure 2. This information is used to determine the transformation matrix between the robot and the patient. The defined trajectory is used to command the robot to position a mechanical guide, which is aligned with this trajectory. The robot is then fixed in this position and the physician uses this guide to introduce the surgical tool such as a drill, probe or electrode (Figure 2).



Figure 2. The NeuroMate robot during registration (courtesy TRK Varma, Liverpool)

- **The CyberKnife** (Accuray Inc, Sunnyvale, CA):

It was designed for frameless stereotactic radiosurgery and its accuracy compares well to localization errors in contemporary frame-based systems. The unique targeting capability of the CyberKnife's multi-jointed robotic arm uses a guidance system to track the location of tumours in real-time and automatically adjusts its focus to a patient's respirations to deliver high-level radiation with pinpoint accuracy. This enables access to previously unreachable tumours with faster, safer, and more comfortable treatments. The CyberKnife is an example of a robotic system delivering treatment that the surgeon cannot do (Figure 3).



Figure 3. The CyberKnife

The CyberKnife radiosurgical system is being used as a minimally invasive alternative to traditional surgery in a variety of clinical areas in neurosurgery as well as other disciplines. It offers an effective treatment option for patients who cannot undergo traditional open surgery or whose lesions are inaccessible with traditional surgical approaches. Residual tumours left after partial resection may also be treated. It has also been used as a boost to standard radiation therapy and to treat failed surgery or radiotherapy. For intracranial conditions, the CyberKnife system has been used to radiosurgically treat a variety of tumours such as residual small skull base meningiomas, small acoustic schwannomas (Sakamoto et al., 2005), small pituitary adenomas, and small metastases (Young et al., 2005) as well as other abnormalities such as small arteriovenous malformations (AVMs) and intractable pain such as in Trigeminal Neuralgia (Massaudi et al., 2005). With the Synchrony™ motion tracking system, tumours in organs moving with respiration such as the lung (Brown et al., 2005), the pancreas (Goodman & Koong, 2005), the liver and the kidney can be successfully targeted. Other tumours based in more rigid body anatomy, where minimal motion is expected, may be tracked via rigidly implanted markers including those in the spine and the prostate (Medbery et al., 2005). The CyberKnife system's range of applications is limited only by the imagination of clinicians who currently have, or will eventually have access to this technology. To date, more than 10,000 patients have benefited from the revolutionary concept of marrying robotics to image-guided radiosurgery. Scientific presentations and publications on the clinical applications of the CyberKnife are numerous – including intracranial (Young et al., 2005), spine (Gerszten et al., 2005), paediatric (Giller et al., 2005), prostate (Medbery et al., 2005), pancreas (Goodman & Koong, 2005), kidney and lung (Brown et al., 2005).

- The RoboSim Neurosurgery Simulator (Radstzky A & Radolph M, 2001):

This robotic neurosurgical simulator consists of a workstation and a robotic arm (NeuroRobot). The MRI image data-set is transferred into the system and the surgical target, its coordinates and planning trajectories are programmed. It was developed as part of the Roboscope project for minimally invasive neurosurgical procedures. Minimally invasive neurosurgery is mainly of importance for treatment of diseases in the central area of the brain, which is accessible to the surgeon only by transgression of healthy normal brain tissue, such as hydrocephalus due to cystic brain tumors and ventricular tumours.

As we enter the 21st century, real-time simulation of surgical procedures is becoming the norm in neurosurgical practice. The RoboSim is a robotic platform for surgical simulation and planning minimally invasive and complex neurosurgical procedures. Another important aspect of neurosurgery is the training of junior surgeons on how to anatomically orient them while operating within the miniaturised operating field of minimally invasive procedures. Image-guided simulation of the procedure will then allow the control of accessibility of the diseased area along the pre-planned trajectory.

- **The neuroArm** (Louw et al., 2004):

The neuroArm is an MRI-compatible, ambidextrous robot. Its dextrous components are two image-guided manipulators with end-effectors that mimic human hands and are capable of interfacing with new microsurgical tools. It has tremor filters that eliminate unwanted hand tremors seen under the microscope. It consists of a surgeon-machine interface and multiple surgical displays. The interface consists of two hand controllers which hold tools. It has 8 degrees of freedom for each arm, payload of 0.5 Kg, a force of 10 N, tip-speed of 0.5-

5mm/sec and submillimetric positional accuracy. It has optical and force sensors and can work continuously for more than 10 hours.

- **The PathFinder** (Prosurgics, UK):

The PathFinder is a neurorobotic system that is portable with a very stable base which can be wheeled in and out of the operating room. The robotic arm can rotate in a horizontal plane 90 degrees to the left or right. The base fixes to the surgical space by an attachment to the Mayfield head clamp. The proximal arm articulates with the next arm that moves in a vertical plane that articulates with the third arm which again moves in a vertical plane. The most distal arm holds the end-effector, which can rotate 360 degrees and flexes/extends by 180 degrees. The combined movements at all these joints give the PathFinder 6 degrees of freedom. The PathFinder differs from other neurosurgical robots in that it does not require X-rays, ultrasound or mechanical means to locate the surgical field; instead it depends on identifying reflectors attached to the patient's head using a camera system integrated in its head (Figure 4).



Figure 4. The PathFinder neurosurgical robotic system

The robot is driven by Windows® based task program and planning software. The planning software and PathFinder robot detect the fiducial markers automatically with a maximum accepted registration error of 1.25 mm. The tool holder is attached to the PathFinder's end-effector. The predefined path is used to command the PathFinder to align its instrument holder to the planned trajectory. Once the instrument holder is aligned to the trajectory, the

robot locks in position and instruments can then be passed to the predetermined depth such as probes, electrodes or catheters (Figure 5).



Figure 5. The instrument holder of the PathFinder

- **SmartAssist®** (Mazor Surgical Technologies, Caesarea, Israel):

This miniature robotic system was designed to overcome the need to rigidly immobilise the surgical field during robotic application. This robot achieved this by fixing the robot directly to the bony element of the surgical field. This concept was clinically used in spinal pedicle screw fixation using the SpineAssist robotic system (Shoham et al., 2007). The system consists of the miniature robot that aligns the end effectors with 6 degrees of freedom and a workstation that runs graphic user interface software and performs image manipulation, planning, registration, kinematic calculations and real-time robot control. Once the system was assembled and intraoperative registration using intraoperative fluoroscopy was performed, the plan for each pedicle screw is executed by the robot and the surgeon manually drills the pilot drill-hole and passes K-wire in the desired position. The SpineAssist is an automated pointing robot that gives the surgeon full control.

3. Pre-clinical Work

Our plan was to develop the PathFinder (Prosurgics, UK) (Figure 4) to achieve stereotactic accuracy better than the stereotactic frame with the flexibility and user-friendly features of frameless image guidance systems. Therefore we assembled two of the best available stereotactic frames around, the Cosman-Roberts-Wells (CRW) stereotactic frame (Radionics, MA, USA) (Figure 6), the Zamorano-Dujovny (ZD) stereotactic frame (Fischer-Leibinger, Freiberg, Germany) (Figure 7), and one of the best frameless stereotactic image guidance systems, Stealth Station image guidance system (Medtronic, Sofarmor Danek, Memphis, TN, USA) (Figure 8). The CRW frame localisation technique involved fixing the frame base ring to the skull, the CT localiser with its 9 rods was fixed to the frame ring and CT was obtained in an axial plane at zero angle and calculation of the target co-ordinates was obtained using frame specific software. On the other hand, the ZD frame ring was also attached to the skull

and the ZD localiser, U-version, was used and CT scan was obtained at zero angle and the coordinates were calculated using ZD frame specific software. The Stealth Station is an image guidance system using optical tracking technology to track the surgical field position, the surgical tools and the surgical microscope.

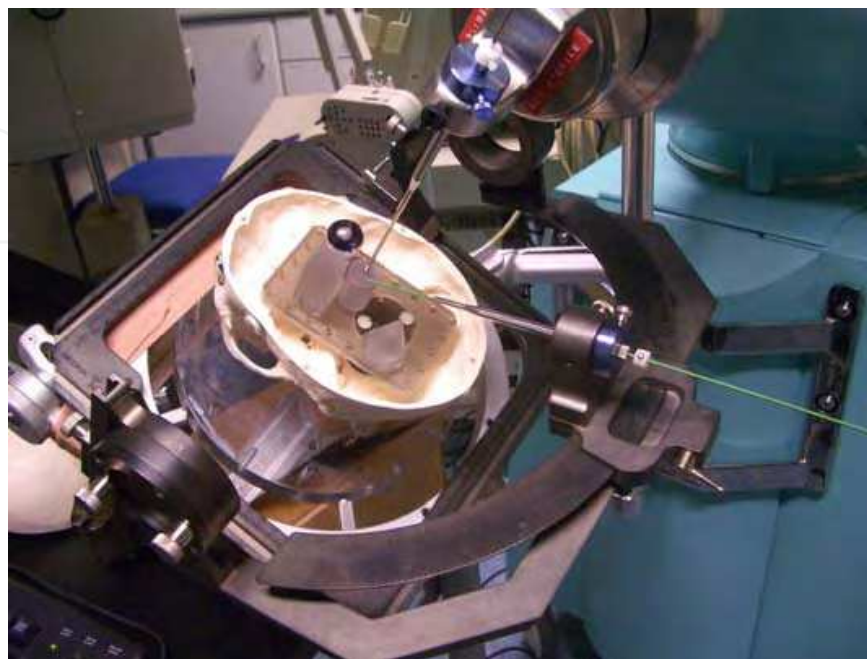


Figure 6. A photograph of the human head phantom and the CRW frame in position and the robotic system pointing to the same target from different trajectories

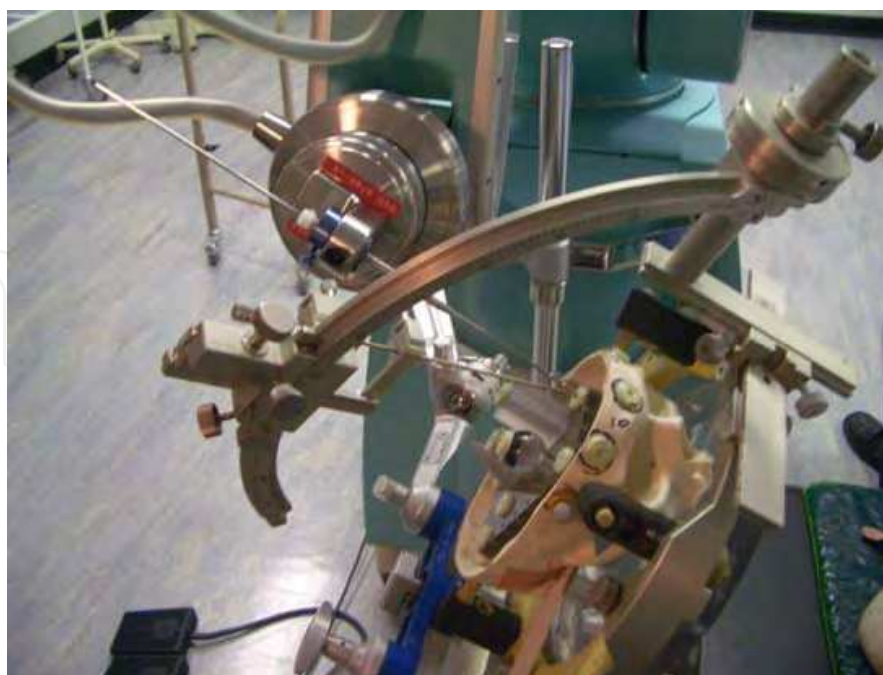


Figure 7. A photograph of the human head phantom with ZD frame in position and the robot pointing to the same target



Figure 8. A photograph of the Stealth Station and PathFinder during experiment

- **Methods:**

We performed several experiments using a replica of the human head (phantom). The surface markings of the phantom were an exact match to the human skull and the inside was fitted with easily recognisable targets at different depths from the skull vault mimicking the basal ganglia locations. The phantom was fitted with 10 surface and 9 internal targets (Figure 9 a & b).



Figure 9 a. A photograph of the human head phantom with surface targets (buttons) and robotic fiducials (reflective balls)

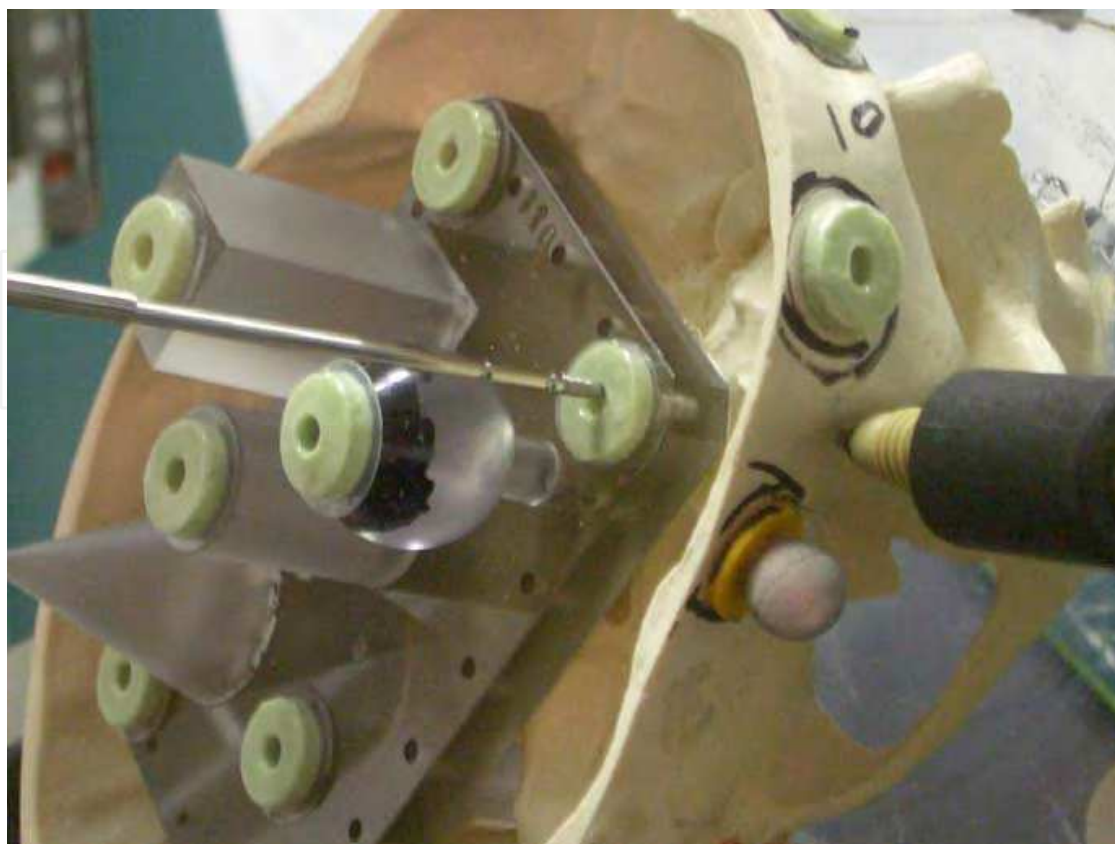


Figure 9 b. A photograph of the human head phantom with depth targets

In addition, 8 robot specific surface fiducials were fitted for robotic registration (Fig 9a). The skull was scanned using helical CT scanner at zero angle and 1 mm slice thickness twice; once with the ZD frame localiser attached and once with the CRW localiser attached. The images were transferred into Frame Link software to calculate the X, Y and Z co-ordinates of each of the 19 targets for each of the two stereotactic frames. The targets were then approached by each frame whenever possible. The same images were imported into robot specific software and the same targets were chosen in a robotic plan. The robotic planning software identified the registration markers automatically. The robot was connected to the skull through its attachment to the Mayfield head fixator. The robot performed its automatic registration by a camera embedded in its head by taking three sets of two images at different angles of the reflective robotic specific surface fiducials. We set the maximum acceptable registration error at 1.25 mm. Targeting was automated by using a foot pedal and once the instrument holder was aligned a probe was passed to manually to reach the target (Figure 6, 7, 9b). The same experiment was repeated using the Stealth Station image guidance system.

- **Steps of the procedure:**

- **Fiducials and markers:**

Before neuro-imaging, PathFinder specific fiducials are fixed to the surface of the surgical field. These fiducials are impregnated with radio-opaque material so that they can be easily seen on CT and picked up by the planning software. They are also coated with reflective material so that the robotic camera can easily pick them up (Figure 9a). It is important that these fiducials are placed at a reasonable distance from each other (5 cm) and placed in a non-symmetrical fashion to make it easy for the registration process. They should also be

spread around the surgical volume. These fiducials can be fixed to the skin using double sided adhesive tape or alternatively a registration plate can be rigidly attached to the skull (Figure 10).

- Image acquisition:

The registration process is heavily dependant on CT images; these should be acquired at zero angle in an axial plane at 1-3 mm slice thickness. MRI scan should also be obtained in an axial plane at zero angle with no spacing. Although the best sequence is volumetric MPRage, T1 or T2 axial sequences could also be used.

- Preoperative planning:

The surgeon imports the image data-sets into the planning software. The software automatically builds sagittal, coronal and 3D reconstructions of the primary axial images. The CT data-set is used to recognise the fiducials and either the CT or MRI images could be used to plan the target and entry points of the trajectory. The CT and MRI data-sets are merged to provide the final plan. The surgeon can then rehearse the plan and get a visual feedback before the surgery and can change the planned trajectories to avoid any critical structures (Figures 12 & 13).

- Robot set up:

The PathFinder robot is positioned either at right angle (opposite to the surgical side) or at an acute angle parallel to the patient. This position provides the maximum degrees of freedom for the robot and the surgeon and keeps the robot out of the way when it is not in use. The robot is attached to the head via a rigid fixing arm attaching to the Mayfield head clamp. The robot is connected to the computer and switched on. Once it is ready to receive commands from the workstation, the robot task controller software is executed.

- Quality assurance:

The first quality check in the PathFinder is the robot self-test to establish that the workstation and the robot communicate to each other. The system then asks the surgeon to load the surgical plan. The second quality check is confirmation that the surgical plan loaded is in fact that the one was intended by the surgeon. The final quality check deals with the accuracy of the system starting with the registration accuracy and then the application accuracy on the surface.

- Registration:

The robot performs registration on command from the workstation and a foot-pedal press. The registration is achieved by taking and analysing three sets of photographic images of the fiducials. The maximum registration error is 1.25 mm. The system displays a registration error at the end of the registration process. The most common reasons of registration failure are: bright light in the room, some of the fiducials were invisible, fiducial images were superimposed on each other or fiducials were covered by hair. The system displays an image of the fiducials during each registration steps and paying attention to these images often make it easier to resolve any failed registration. If the registration process fails, it can be repeated after paying attention to the cause of failure.

- Plan execution:

Once the registration process is complete, executable surgical trajectories are displayed and can be tested by the surgeon. The tool length can be changed and the entry point can also be fine tuned from within the task controller. The surgeon then prepares the surgical field and drapes the robot and the patient. The surgeon manually performs the entry burr hole or

craniotomy, then aligns the robot for the planned trajectories and manually advances the surgical tool to the target.

• **Results:**

When the robotic system was compared to the golden standard of stereotaxy, the stereotactic frame, the robot was successful in approaching 17 out of 19 targets (89.5%). To reach the remaining two it was necessary to change the position of the robot in relation to the phantom axis, without the need for re-scanning or re-planning. On the other hand, both the CRW & ZD frames failed to reach points above certain depth due to the fact that the frame ring in both frames was positioned at a low level in the phantom, primarily to avoid distorting the artificial skull by the frame-ring fixation mechanism. Each frame however, was able to reach 4 targets out of 19 (21.1%). When the targets were possible, the robot, the CRW and the ZD systems were very accurate (0.5 mm in the Robot and 0.98 mm in the Frames) (Table 1).

| Device | Robot System | | CRW frame | | ZD Frame | |
|----------------|--------------|------|-----------|------|----------|------|
| | No. | % | No. | % | No. | % |
| Superficial | 8/10 | 80 | 0/10 | 0 | 0/10 | 0 |
| Deep targets | 9/9 | 100 | 4/9 | 44.4 | 4/9 | 44.4 |
| Overall result | 17/19 | 89.5 | 4/19 | 21.1 | 4/17 | 21.1 |
| Accuracy in mm | 0.5 | | 0.98 | | 0.98 | |

Table 1. Comparison of the PathFinder neurosurgical robotic system and the CRW and ZD stereotactic frames using CT scan and a Phantom human head

The clear advantages of the robotic system over the frames in these experiments were avoidance of cumbersome frame ring, ability to target multiple areas in the same plan, avoidance of manual adjustments of the coordinates, coverage of all the surgical field with no limitations imposed by frame ring fixation primary position and flexibility to change the plan without the need for rescanning, as well as changing the position of the robot in relation to the phantom head without the need for rescanning or replanning.

When the robotic system was compared to frameless stereotactic system, the Stealth Station, the robotic system outperformed the Stealth Station in accuracy, precision and repeatability (Table 2). The accuracy remained the same irrespective of the target location, while the frameless image guidance system accuracy was good near the surface of the phantom but deteriorated as the target moved backwards and deeper (Table 2).

| The system | Robotic system | Frameless image guidance |
|------------------|----------------|--------------------------|
| Accuracy | 0.44 mm | 1.96 mm |
| Surface accuracy | 0.44 mm | 1 mm |
| Deep anterior | 0.44 mm | 1-2 mm |
| Deep middle | 0.44 mm | 2-3 mm |
| Deep posterior | 0.44 mm | 3-4.4 mm |

Table 2. Comparison of the PathFinder neurosurgical robotic system and the Stealth Station image guidance system using CT scan and a Phantom human head

From these experiments, we found that the robotic system provided the accuracy, precision and repeatability of the stereotactic frame and the flexibility of the frameless system.

While these experiments demonstrated that the robotic system outperformed both existing stereotactic systems in use, there is still the possibility that the robot will not perform in the clinical setting because skin markers do move during and after scanning. Therefore, we designed a registration plate that can be fixed to the patient's skull via three microscrews. The plate can then be removed and reapplied at will, allowing scanning and planning to be divorced from the registration and the operation in time and place. (Figure 10)



Figure 10. A photograph of the relocatable registration plate

We have encountered several problems during development. Bright fluorescence operating room lights may interfere with the registration process, therefore theatre lights are not switched on till after registration. Power failure during a procedure can lead to loss of registration, therefore a rechargeable battery was fitted which can keep the Robot and workstation going, and finally the axis of the patient in relation to the robot is important as the best position was to place the robot at an angle of 20-30 degrees.

4. Clinical Applications

The human brain is uniquely suited for robotics applications because it is contained in a rigid structure, the skull, and the slightest intrusion of surgical tools can produce

devastating, irreversible and potentially fatal complications. The robotic system is useful in the following ways:

- **Planning:**

The robotic systems of today come with robust image processing and planning software, which can segment CT and MRI images, merge these imaging modalities and display the output in axial, coronal, sagittal, 3D and probe eye views. The surgeon can gain significant insight in the pathology under consideration, enhancing his/her understanding of the anatomical relationships of the lesion to the surrounding brain and external landmarks allowing planning trajectories that avoid critical structures taking the shortest and safest route. Furthermore, the planning software allows surgeons to rehearse their surgical trajectories modifying them if felt necessary before embarking on the procedure. It provides an excellent teaching tool for trainees and residents (Figure 11).

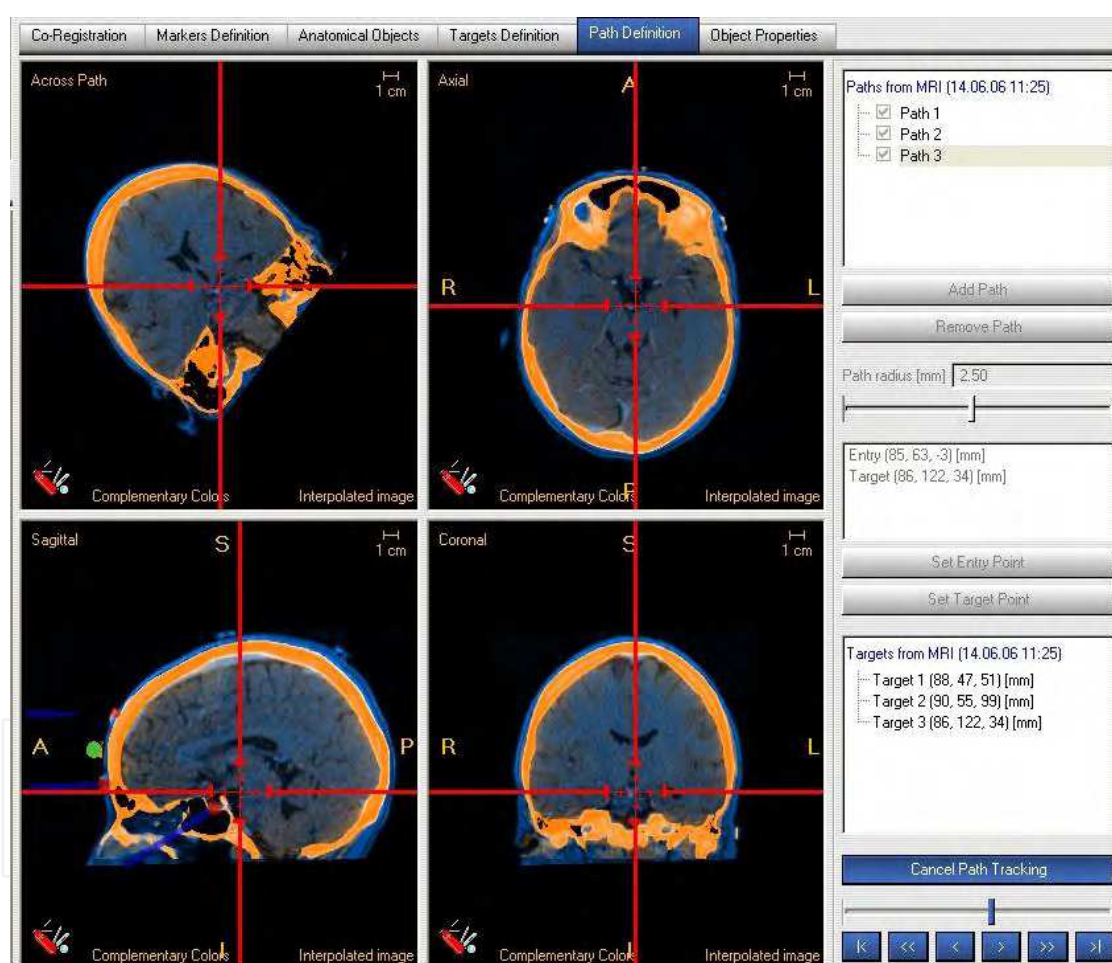


Figure 11. A robotic platform for planning, planning and rehearsing trajectory is very simple

- **Assist in performing stereotactic procedures:**

The advantages of using a robotic system to assist in performing almost all stereotactic procedures are automation of target coordinates, transformation to the tip of the robotic instrument in a moment without the tedious calculations of the X, Y & Z coordinates, transforming and adjusting these coordinates to the aiming arc of the stereotactic frame and the flexibility to perform multiple targeting, multiple trajectories and multiple plans without

the tedious and time-consuming steps of fixing the frame reference ring to the patient’s head, rescanning, recalculating and readjusting the aiming frame-arc. It was clear that robotic systems would be faster, more automated, more flexible, more reliable, and more accurate. The neurosurgical robots can be used in the following applications.

- Intracranial tumours:

Intracranial tumours are suitable applications for robotics in neurosurgery because they often require stereotactic biopsy which can be performed elegantly by the robotic system. The advantage for using the robot in this area is the ability to perform accurately multiple biopsies to obtain the exact pathological classification of the tumour rather than getting a piece of necrotic centre. The robotic system could be used to plan and insert interstitial radiotherapy, victor therapy or photodynamic therapy. Furthermore, the robotic system would be an ideal tool to plan and execute the plan to excise a tumour by placing a fence around the tumour margins before opening the skull (Figure 12).

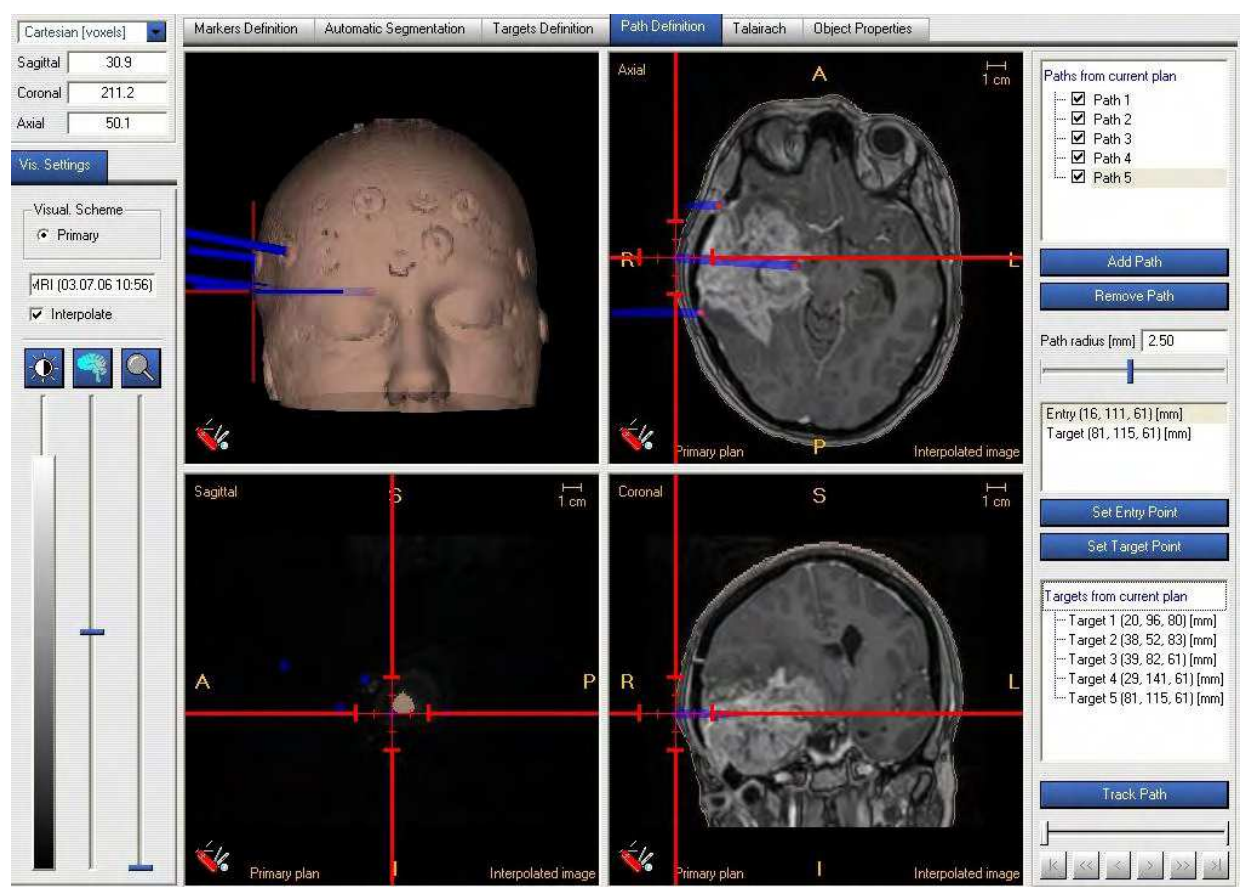


Figure 12. A fencing robotic plan for Glioblastoma multiforme

- Intracranial abscess:

The management of intracranial abscess is drainage, which can be performed using freehand needle aspiration or more appropriately using a stereotactic aspiration. The tendency in common practice is to use freehand aspiration because to put a stereotactic frame is often thought to be cumbersome. However, a flexible robotic system would be an ideal precise way to aspirate such abscess to obtain the micro-organism and drain the pus as the main therapeutic procedure.

- Deep brain stimulation:
Deep brain stimulation is widely used in practice to treat advanced Parkinson’s disease, Benign Essential tremor, rubral tremor of Multiple Sclerosis, dystonia, obsessive compulsive disorders and treatment refractory depression. These procedures require the accuracy of the stereotactic frame and neurophysiological monitoring using micro-electrode recordings or macrostimulation and measurement of impedance. The robotic system would be an ideal planning and execution system for performing these procedures precisely. It would be used for the anatomical planning to target the subthalamic nucleus in Parkinson’s disease, the Globus pallidus internal in dystonia, the ventral intermediate nucleus of the thalamus for tremor control, the anterior capsule in obsessive compulsive disorders or the cingulum in treatment refractory depression (Figure 13).

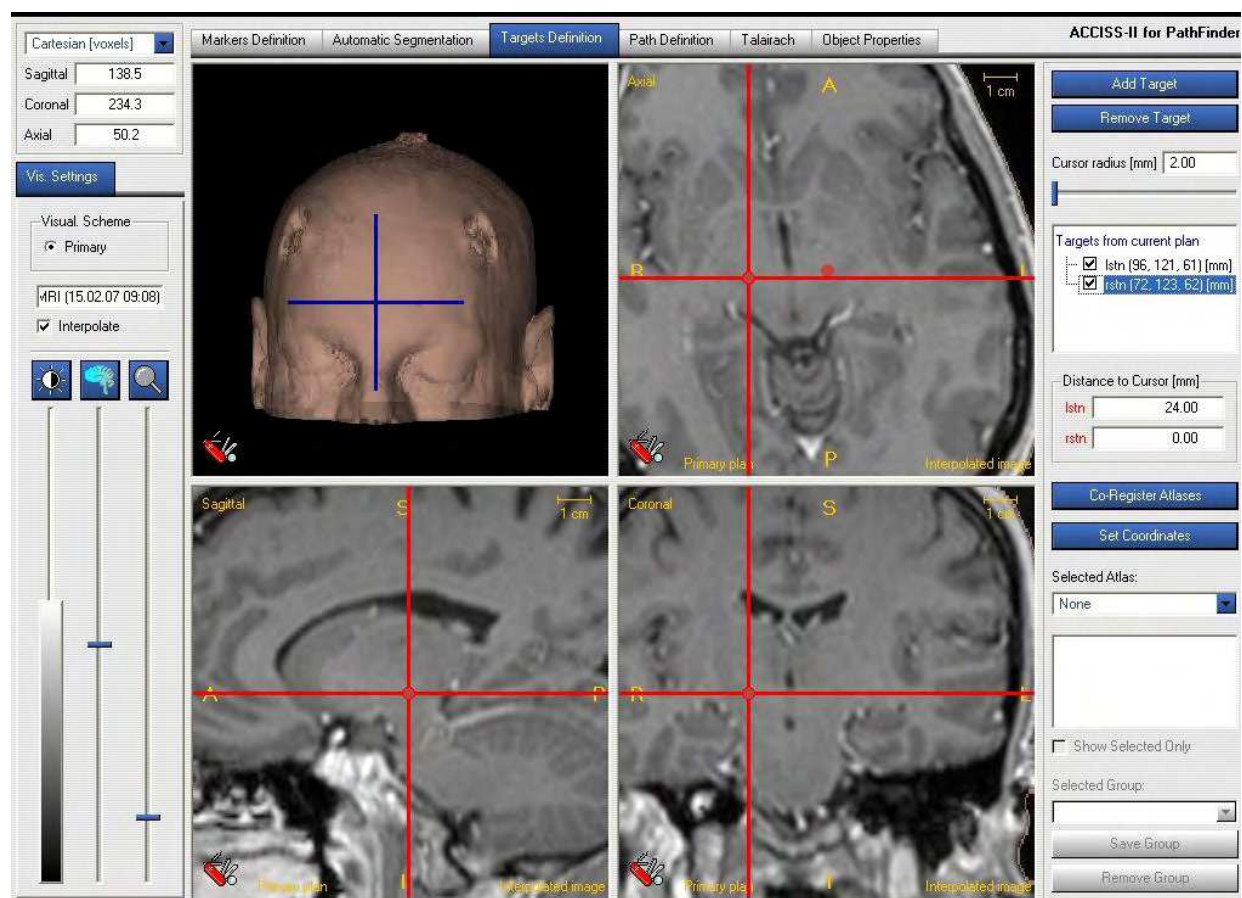


Figure 13. A robotic plan for DBS placement or lesion generation in the left subthalamic nucleus

- Intracranial lesion generation:
Intracranial lesions are less commonly used nowadays in neurosurgery as the neurostimulation technology provides the same clinical efficacy of lesions with a lesser risk. However, lesions in one side of the pallidum, thalamus, internal capsule or the cingulum still have a place in the management of functional disorders of the brain. Their precise planning and execution requires the accuracy of the stereotactic frame and the flexibility of

image guidance. Precise accuracy and flexibility are the characteristics of the robotic system and therefore it would be an ideal system to execute these lesions (Figure 12).

- **Epilepsy surgery:**

Temporal lobe surgery is a cost-effective treatment for drug resistant temporal lobe epilepsy (Alarcon et al., 2006 and Kelemen et al., 2006). Its success is dependant on pre and intra-operative localisation of the epileptogenic focus and the surgery is facilitated by early identification of the temporal horn. To locate precisely the temporal horn and the epilepsy focus we explored the use of a neurosurgical robot. We found that the robotic system was very useful in inserting depth electrodes precisely to localise the seizure focus and was very helpful to identify the temporal horn early on, shortening the procedure (Figure 14) (Eljamel, 2006).

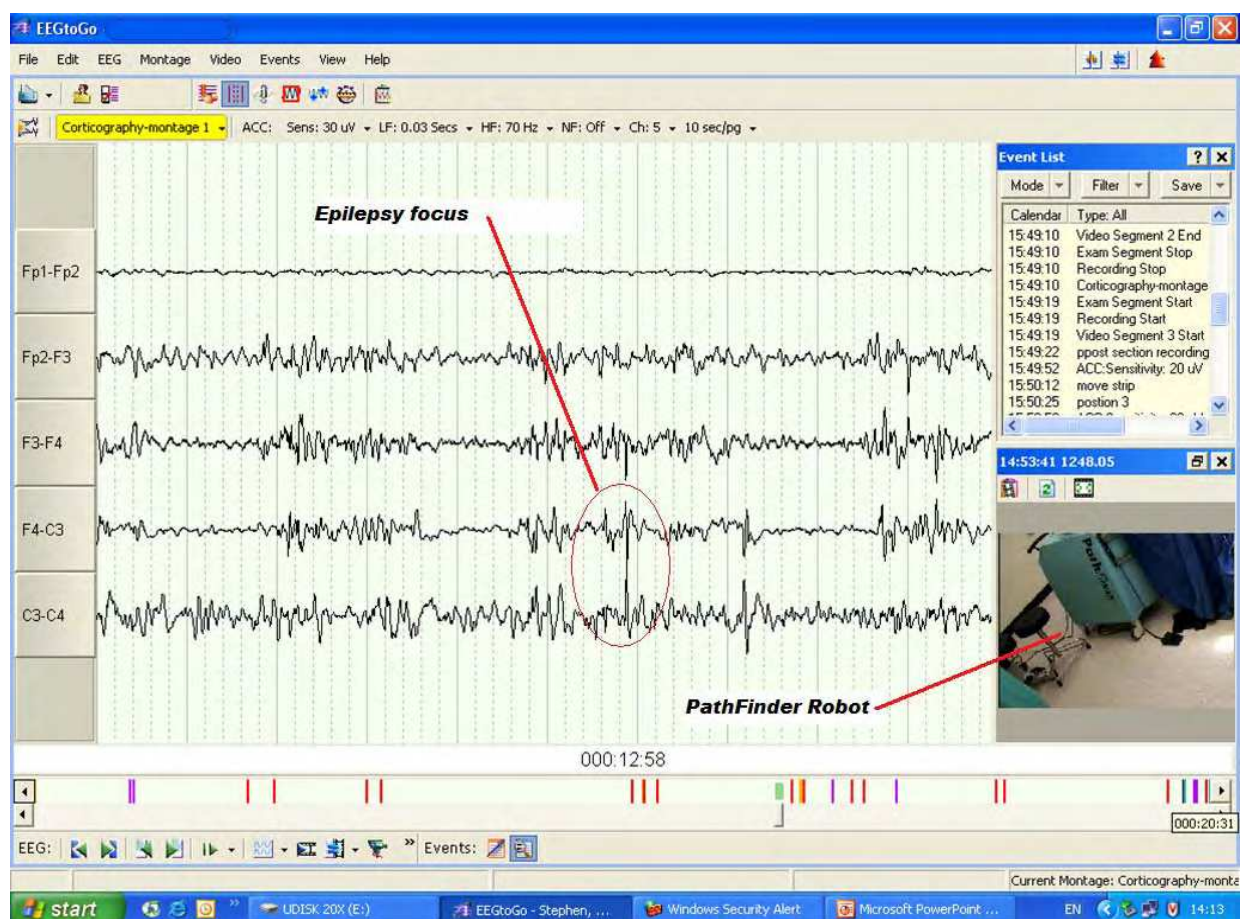


Figure 14. Intraoperative corticography for epilepsy focus localisation, notice the PathFinder in the right bottom corner where it was used to insert depth electrodes and insert a catheter in the temporal horn of the lateral ventricle during medial temporal lobectomy for temporal lobe refractory epilepsy

- **Intracranial vascular lesions:**

Intracranial arteriovenous malformation (AVM) and intracerebral haematomas can be treated using the robotic system. The system could be used to localise the AVM and planning of the surgery, while in spontaneous haematoma the robot could be used to aspirate the blood clot precisely.

- Hydrocephalus and intracranial cysts:

The robotics system is ideally suited for draining intracranial cysts. A colloid cyst which lies within the third ventricle and can cause hydrocephalus can be drained using the robot. Pineal body cysts and other cysts of the third ventricle can also be drained this way. Craniopharyngioma is another tumour that can present with large cysts and other tumour cysts (Figure 15) and can also be drained using the robotic system. The robot can also be used to place shunt tubing into any of the aforementioned cystic lesions or hydrocephalus. These intracystic catheters can then be connected to a valve to shunt the fluid away to a suitable absorption cavity such as the peritoneum in hydrocephalus or the catheter can be connected to a subcutaneous reservoir for future aspirations or instillation of therapeutic agents in the case of tumour cysts.

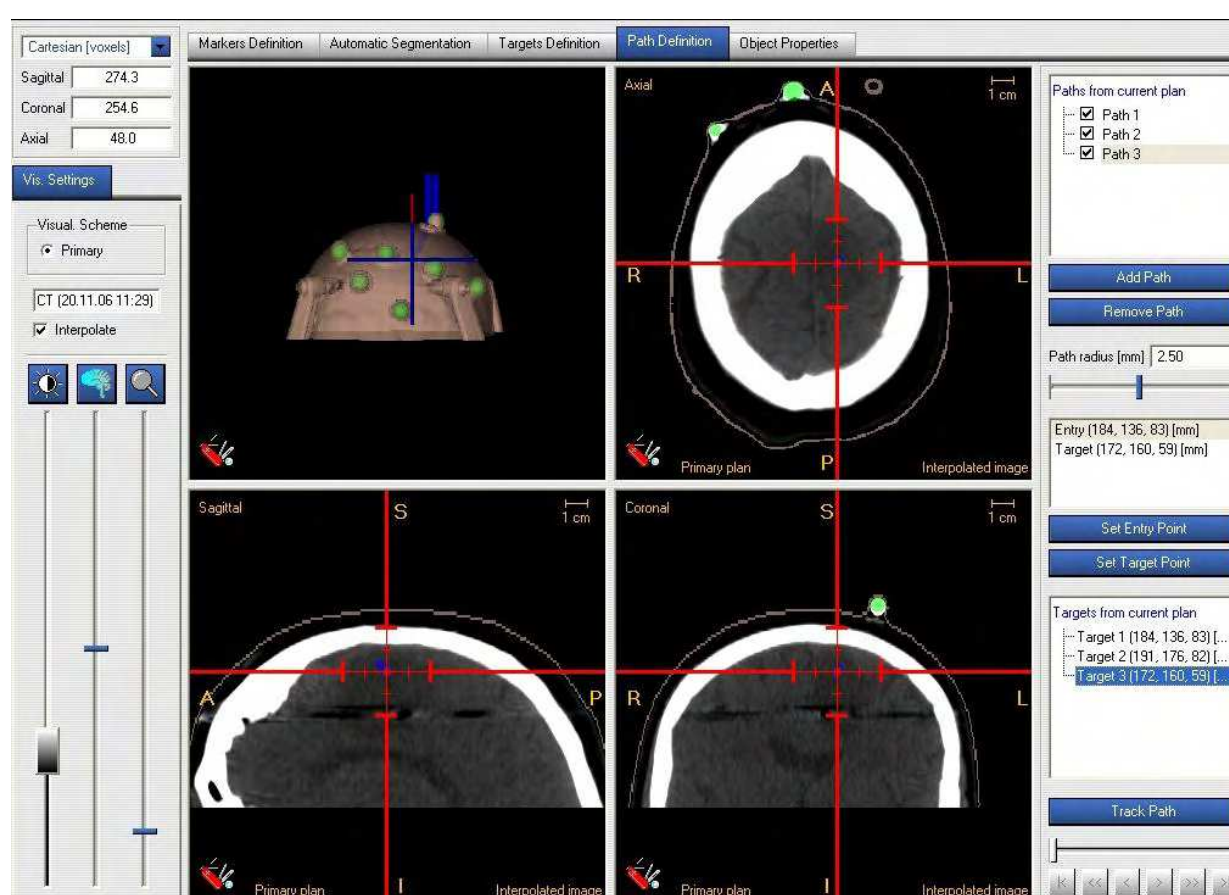


Figure 15. A robotic plan for drainage and biopsy of left frontal lobe cyst

- Head trauma:

In head trauma, the lateral ventricles are often very small and cannot be drained effectively using freehand methods, a robotic system will be an ideal tool to insert very precisely an external ventricular drain when required to drain cerebrospinal fluid (CSF) and control the raised intracranial pressure in these critical patients.

- Pituitary lesions:

Pituitary lesions, including simple cysts, pituitary abscess and Rathke cleft cysts, can be drained using the robot via the trans-nasal – transsphenoidal route (Figure 16). Furthermore pituitary ablation using chemicals, such as alcohol, can be performed.

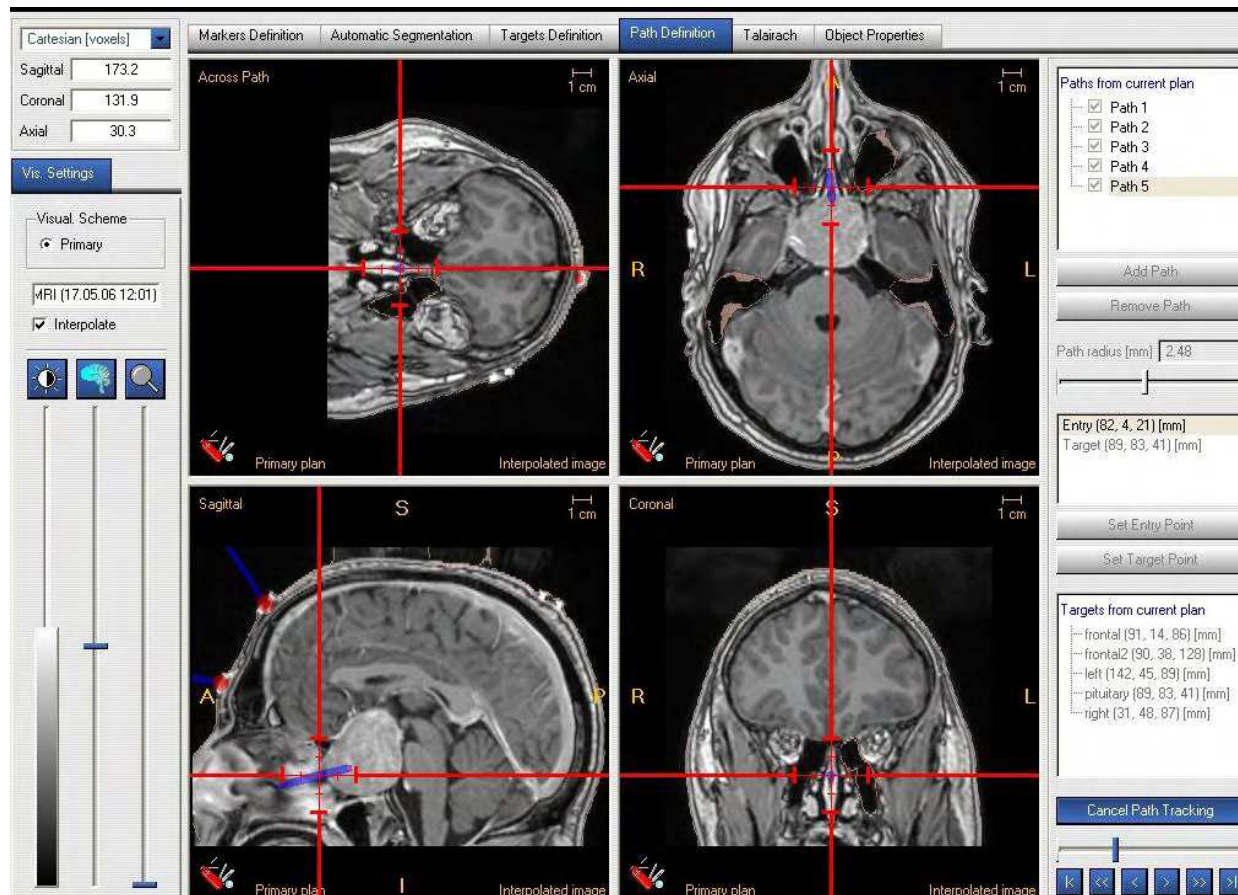


Figure 16. A robotic plan for reaching a pituitary lesion through the transnasal-transsphenoidal route for either aspirating a pituitary abscess, pituitary cyst, Rathke cleft cyst or injecting a chemical to ablate the pituitary gland

- Spinal surgery:

There are potential spinal applications in spinal surgery to perform needle aspiration/biopsy of spinal pathology or to align trajectories for pedicle screw fixation, lateral mass plating or C1/2 fixation. The principles are the same as intracranial surgery with the exception that each vertebral level had to be registered in turn or the robotic system needed to be integrated with fluoroscopy, which can be easily achieved. An example of such robotic application is the SpineAssist® (Shoham et al., 2007).

- Cranial and body radiotherapy:

The CyberKnife is an excellent example of cranial and body radiotherapy application of robotics, allowing a high tumour irradiation dose with minimal normal tissue exposure to the harmful radiation as discussed earlier in this chapter. Furthermore, the robotic system could be used to insert radioisotope implants or intraoperative radiosurgery machines such as the Photoelectrone radiosurgery system 400 (Figure 17 and 18). The advantage of robotic systems in this modality of therapy is the precision, the speed at which therapy can be delivered and the ability of the system to deliver therapy remotely in a radiation shielded environment without the risk of radiation to the surgeon or other staff looking after the patient.



Figure 17. Intraoperative Photoelectron radiotherapy system (PRS400) which can fit nicely in the Pathfinder robot. The robot could perform a stereotactic biopsy followed by radiosurgery

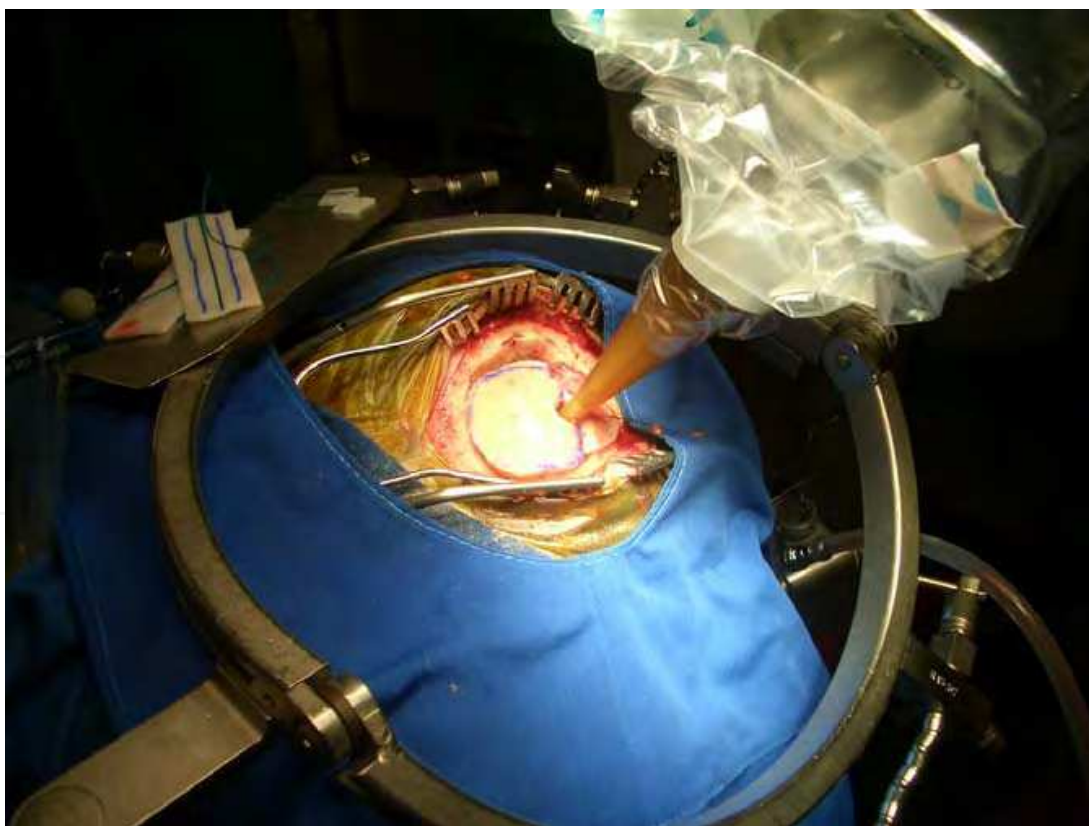


Figure 19. Intraoperative radiotherapy of a malignant brain tumour using the Photoelectron radiotherapy system (PRS400)

- Futuristic therapies:

The robotic system is an ideal tool to implant micro-catheters in deep structures of the brain to deliver missing or deficient neurotransmitters or growth factors such as glial derived neurotrophic factor (GDNF) to promote neuro-regeneration (Gill et al., 2003). It would be also an ideal delivery system for neurotransplantation (Ourednik & Ourednik, 2004) and victor and gene therapy (Alavi & Eck, 2001). Although these modalities of therapy are still in their infancy at present, it is only a matter of time before they will be used on a large scale to treat neuro-degenerative diseases such as Parkinson's disease and Alzheimer's disease.

5. The Future of Robotics in Neurosurgery

The future of robotics in neurosurgery is bright and it is not going to be long before each neurosurgical operating room, each neuro CT scanner and each neuro MRI scanner will be integrated with a robotic system. This inevitable progression is natural as we move along the path from image-guided minimally invasive surgery to a technology driven nano surgery. The scale of neurosurgical procedures in the future is going to be so small that neurosurgeons will not be able to deliver them without the assistance of robotics. The amount of collateral damage acceptable by patients in the future is going to be none that current technology and human performance would not be able to guarantee without the use of robotics. Patients in the future will be asking a different question from what present patients are asking: it is not going to be "who is the surgeon?" but who is the surgeon's assistant?

Robotics in the future will incorporate new technology that will make it possible for these systems to analyse tissue composition by combining imaging, biochemical and biological markers of these tissues to deliver specific treatment and repair any abnormal tissue damage. One example of such futuristic application which can be integrated in robotics is the NASA smart probe project which utilises neural network and fuzzy logic algorithms to integrate data from multiple sensors in real-time for tissue identification (Andrews et al., 2006).

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The first generation of surgical robots are already being installed in a number of operating rooms around the world. Robotics is being introduced to medicine because it allows for unprecedented control and precision of surgical instruments in minimally invasive procedures. So far, robots have been used to position an endoscope, perform gallbladder surgery and correct gastroesophageal reflux and heartburn. The ultimate goal of the robotic surgery field is to design a robot that can be used to perform closed-chest, beating-heart surgery. The use of robotics in surgery will expand over the next decades without any doubt. Minimally Invasive Surgery (MIS) is a revolutionary approach in surgery. In MIS, the operation is performed with instruments and viewing equipment inserted into the body through small incisions created by the surgeon, in contrast to open surgery with large incisions. This minimizes surgical trauma and damage to healthy tissue, resulting in shorter patient recovery time. The aim of this book is to provide an overview of the state-of-art, to present new ideas, original results and practical experiences in this expanding area. Nevertheless, many chapters in the book concern advanced research on this growing area. The book provides critical analysis of clinical trials, assessment of the benefits and risks of the application of these technologies. This book is certainly a small sample of the research activity on Medical Robotics going on around the globe as you read it, but it surely covers a good deal of what has been done in the field recently, and as such it works as a valuable source for researchers interested in the involved subjects, whether they are currently “medical roboticists” or not.

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