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Micro-Manipulator for Neurosurgical Application

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1. Introduction

Neurosurgery is a part of the surgical field that focused in taking care of the diseases related to human's central peripheral nervous system and also their central spinal cord [20]. The term surgery refers to the operation of peripheral nervous system as well as the spinal cord, brain, blood vessel connected to it, spine, spinal cord, and also nerves that control our senses and body's movement [29]. There are lots of neuro diseases, which among them were brain tumors, head trauma, stroke, thalamic astrocytomas, and spinal cord trauma. These diseases, if not thrown away, will results the patient in body disorder, health problem, and of course, death. To put an end to these disorders, appropriate treatment is mandatory. Those diseases need to be cured and removed. Surgery, or specifically neurosurgery, is one of the effective methods to treat it.

Neurosurgery comes with risks. Any operation dealing with brain or the spinal cord can cause paralysis, brain damage, infection, psychosis, or even death if a mistake happens. These operations are also likely to cause mental impairment as of any surgical procedure dealing with the brain. Therefore, it is vital for neurosurgeon to make sure that this kind of surgery is performed in an almost perfect condition to minimize any risks or poor results as the consequences from it. Traditionally, starting from scalp removing, drilling and removing the skull, handling the lump, until sewing the skull and scalp back at its original location; surgeons put their efforts with their own hands and bare eyes. Tools and equipments did improved, for example with the usage of apparatus such as top-mount microscope and magnetic resonance imaging (MRI) machine. However, they still need to manipulate the surgical tools, the closest tools to the human brain, such as the knife and biopsy needles with naked hands. As a results, it will surely introduced limits to the tools manipulation. This is where robots can do a lot better. A very precise robotic device that can perform manipulation at much smaller or micro scale, plus the capability of the surgeon himself, will produce much superior results. These robotic devices are termed surgical micro-manipulator.

This chapter presents readers with information regarding the design of a micro-manipulator purposely for neurosurgical application. It also shares beneficial facts and particulars regarding current progress about micro-manipulator research around the globe. This chapter is organized as the following: Section 2 provides details justification of designing a robotic hand in an operating room based on the constraints for a neurosurgical procedures. Section 3 will discuss design considerations for a micro-manipulator for neurosurgery. This

includes the important hardware and software elements that contributed to the build-up of a micromanipulator. Section 4 briefly shares on the design and uniqueness of one of the recent and successful micro-manipulator for neurosurgical application. Section 5 will finally conclude this article.

(a)   (b)
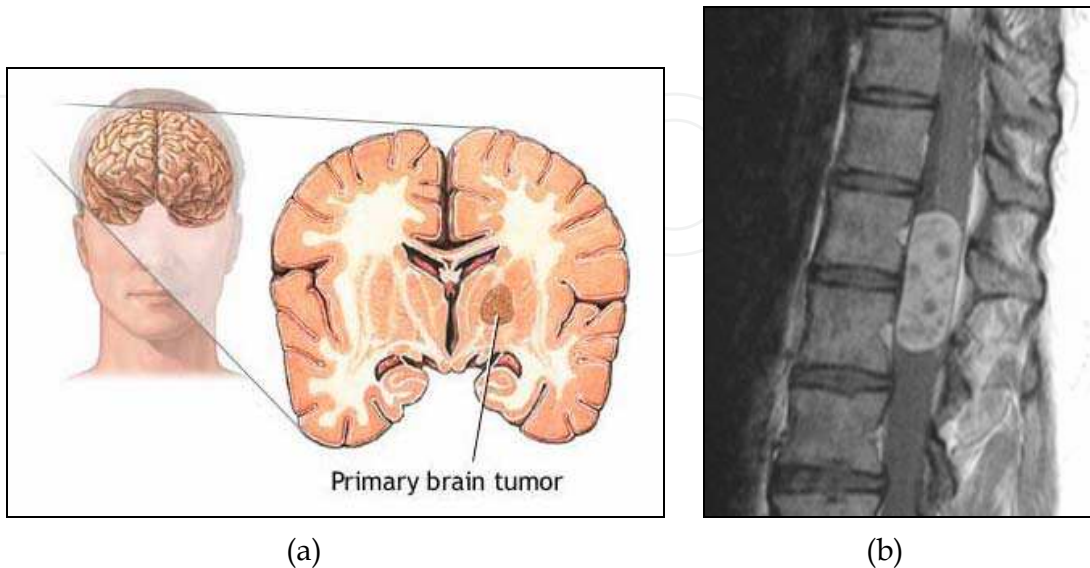
Fig. 1. (a) Graphical illustration of brain tumor. A primary brain tumor is a mass created by the growth or uncontrolled proliferation of cells in the brain. (b) Spinal tumor

2. Why robotics

Fig. 2. Da Vinci® tele-surgical system.

The idea of having robots inside the operation theatre is basically to assist the neurosurgeon perform the surgery. Fatigue experienced by surgeons, post-surgery trauma on the patient and human errors are among the challenges faced during neurosurgical operation [10]. According to [6], there are studies being done that shows during a long surgical operation, there will be substantial muscle fatigue. Neurosurgical or any surgical procedure usually takes a very long time, thus will decrease the effectiveness of a surgeon. In contrast, robots will never experience fatigue because their moves are controlled by devices. Moreover, they

can be very precise and reliable because robot can filter the handshakes and keep the operation steady.

Another reason surgeons need to use such a system is that it can provide them with a minimally invasive surgery (MIS). This provides less trauma for the patient after the surgery and of course, a shorter recovery period. Moreover, human involvement is also a concern. In today's operating rooms, you'll find two or three surgeons, an anesthesiologist and several nurses, all needed for even the simplest of surgeries. Most surgeries require nearly a dozen people in the room. As with all automation, surgical robots will eventually eliminate the need for some personnel. Taking a glimpse into the future, surgery may require only one surgeon, an anesthesiologist and one or two nurses. In this nearly empty operating room, the doctor its at a computer console, either in or outside the operating room, using the surgical robot to accomplish what it once took a crowd of people to perform.

The first use of robot in a neurosurgical procedure is in 1985, according to [30]. Researches from Department of Radiology, Memorial Medical Center employed a PUMA (Programmable Universal Machine for Assembly) robot in the operating room. Even though the task of the robot at that time is only to hold and manipulate biopsy cannulae, it marked the start of a robot's manipulator cooperation inside the operation room. Since then, various researches in various aspect of neurosurgery have been explored. Those included the micromanipulators design [22], vision and imaging scheme, sensors design [16], haptic technology [9], magnetic resonance imaging (MRI) compatibility equipments, telesurgery system [15], as well as controller technique and planning.

2.1 What is a micro-manipulator?

The term manipulator in robotics means a device or equipment that allows for movement of a part through multiple joints on the mechanical device. It is also better known as robotic arm [26]. Micro-manipulator also carries the same meaning, but the term 'micro' referred it to a more specific task, which is object handling in small (micro) scale. In dealing with neurosurgical procedure, precision and accuracy plays a very important role. This situation leads to the needs of micro-manipulation, using micro-manipulator. This further explains that the level of manipulation is very small and the accuracy in need is very high. It is not
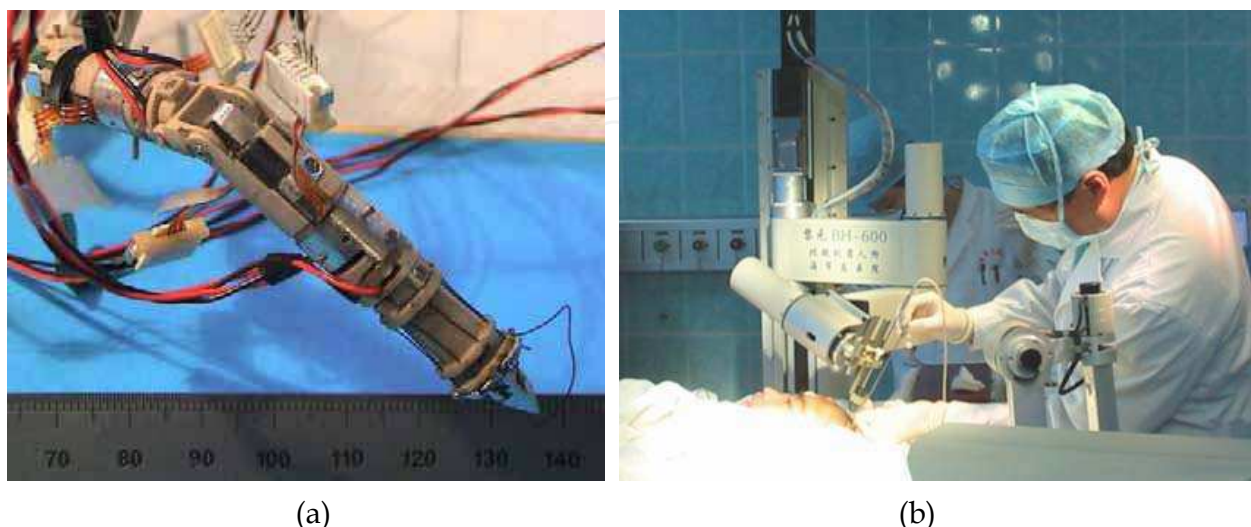

| (a) | (b) |

Fig. 3. (a) A micro-manipulator for surgery, deisgned by Francesco Cepolina, [4] & [7] (b)NeuroMaster, a stereotactic neurosurgery robot system by Beihang University, [13] & [18]

necessarily that the tool and manipulator must be small, but the whole system itself must be able to integrate and produce very precise micro-manipulation with a very minimal error in all the 3- axis's direction. This includes the sensors parts, vision and imaging system and also the controller technique.

2.2 Type of robotics involvement in operation theatre / operation room

According to [27], robotic involvement in surgical procedure can be divided into three categories. These categories were based on robot and surgeon interaction during the procedure.

The first category is *supervisory-controlled system*. This is where robots performed the surgery by implementing specific instructions and paths set earlier by the surgeon. Those paths were planned during planning and registration process before the operation, which integrates the images from the MRI scanning process. In this scheme, surgeon is still playing the important roles, which is planning and setting up the whole operation's path. Then, the robot will do everything that has been pre-planned, while the surgeon supervising the operation. Though, the surgeon did not directly use his hands during this procedure.

The second category, which is the *telesurgical system*, needs the surgeon to use his own hands during the process. Also known as remote surgery, this is different from the previous technique. However, it is the robotic manipulator who is doing the real operation on the patient. The surgeon, on the other hand, is manipulating the robot through some distance from a computer console. In this method, sensors including haptic feedback system are providing the surgeon with all the necessary data for the surgeon to react with. The computer console is the master, while the manipulator is called slave. The operation being done by the robotic manipulator is imitating the master controller's movement in real time. The most popular and widely used telesurgical system is the da Vinci® Surgical System manufactured by Intuitive Surgical, where more than 1000 units sold worldwide [5].

The last category is the *shared-control system*. This is where surgeon and robot works together at the same time, where a number of specifically designed tasks were done by the doctor and others by the robot. This system, compared to the previous two, has the most surgeon involvement in the operation theatre. Figure 3(b) is an example of this.

4. Discussion

The buildup of a neurosurgical type micro-manipulator usually consists of few important parts or elements, both hardwares and softwares. These elements were essential to ensure the specification and performance of the robot itself achieved the function of a micromanipulator. This description may act like a general guideline in developing the micromanipulator because some of the micro-manipulator might not have all the elements, because each of them has different specifications and design.

4.1 Modeling

Modeling is a process of using mathematical description to simulate real physical events [17]. It allows complex systems to be understood and thus their behavior can be predicted and simulated. In modeling, usually some details will be ignored or assumed, due to the shortcomings occurred in the process. Micro-manipulator is a very expensive system to build.

Thus, it needs to be modeled before it is fabricated. From the model, we can investigate much information, such as the kinematic and dynamic behavior of the model, the workspace of the model, materials to build the model, suitable actuator to achieve the design objectives and the controller technique that is most efficient to the system. There are lots of software that can be use to model a micro-manipulator system, including Robotics Toolbox® and SimMechanics from Matlab, AutoCAD, SolidWorks and Rhinoceros®.

One common technique to model a manipulator system is to use Denavit-Hartenberg (DH) method [12]. From the DH model, either the classical or the modified version of it, we can simulate and further investigate the behavior of the micro-manipulator, both the kinematic and dynamic. Kinematics relates the motion behavior of the robot without regards to the forces that causes it, whereas dynamic considers the effect of internal and external forces or torques applied to the micro-manipulator. With the information from both the kinematic and dynamic behavior, we can have a good knowledge on how the micro-manipulator moves, which path it follows, how many micro-Newton of forces applied at the patient's head, how precise the robot is, as well as the speed of the robot movements. Those are among the vital information needed by the surgeon during his usage of the micro-manipulator during a surgery. In addition, we can always estimate the workspace of the robot. Workspace is the region where the end effector of the micro-manipulator can possibly reach, which a surgeon needs to know prior to an operation to estimate the tools arrangements and movements.

Equation 1 below represents the transformation matrices associated with modified DH method. The parameters 'α' and 'θ' represents the angular behavior of the micromanipulator's links, while the 'a' and 'd' parameters represents the prismatic aspect.

$$^{i-1}T_i = \begin{bmatrix} \cos\theta_i & -\sin\theta_i & 0 & \alpha_{i-1} \\ \sin\theta_i \times \cos\alpha_{i-1} & \cos\theta_i \times \cos\alpha_{i-1} & -\sin\alpha_{i-1} & -\sin\alpha_{i-1} \times d_i \\ \sin\theta_i \times \sin\alpha_{i-1} & \cos\theta_i \times \sin\alpha_{i-1} & \cos\alpha_{i-1} & \cos\alpha_{i-1} \times d_i \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{1}$$

Equation 2 shows the equations of motion, in general, of a micro-manipulator.

$$\tau = M(\theta)\ddot{\theta} + C(\theta,\dot{\theta})\dot{\theta} + N(\theta,\dot{\theta}) \tag{2}$$

where;
τ = torques vector
M = inertia matrix
C = Coriolis and Centrifugal matrix (these are types of internal forces)
N = gravity terms and other forces act on the joints (all external forces defines here)

4.2 Trajectory planning

Trajectory refers to time domain of the position, velocity and acceleration of a system [23]. It described the motion's behavior of the micro-manipulator in all of the 3-dimensional (3-D) axis. The trajectories were generated through interpolation or approximation of the desired path by a polynomial or any other smooth function. The function is used to approximate and provide the mathematical description of the trajectory.

There are two categories of trajectory planning techniques. They are joint space technique and Cartesian space technique. Joint space technique is suitable for point-to-point motion, where the motion planning is done at the joint level. This technique describes the time function of all the joints' variables including the speed and acceleration. Equation 3 below shows an example of a five-degree or quintic polynomial equations with its joints' variables, C_i. The position of the end effector was computed by using forward kinematics. This is just one of many smooth functions that can be used to interpolate a trajectory.

Cartesian space technique is a method that most suited with continuous path type of motion, and therefore suit neurosurgical application better than the previous technique. While joint space method focus on the joint position, Cartesian space method controls the end effector itself, with respect to the base of the robot. By using inverse kinematics, the joints variables were computed.

In general, to set a trajectory, we must define the starting and end points, as well as the mathematical function that the joints and end effector will undertake during its movement. The time taken to complete the trajectory is also important as it will affect the speed and smoothness of the manipulation. This is important in designing a micro-manipulator since we need to specify each and every point on the route of the end-effector and the joints as well. Failing to do this will let us lose control of the surgical tools.

$$\theta(t) = c_0 + c_1 t + c_2 t^2 + c_3 t^3 + c_4 t^4 + c_5 t^5 \tag{3}$$

where;

$c_0 = \theta_0$

$c_1 = \dot{\theta}_0$

$c_2 = \dfrac{\ddot{\theta}_0}{2}$

$c_3 = \dfrac{20\theta_f - 20\theta_0 - (8\dot{\theta}_f + 12\dot{\theta}_0)t_f - (3\ddot{\theta}_0 - \ddot{\theta}_f)t_f^2}{2t_f^3}$

$c_4 = \dfrac{30\theta_0 - 30\theta_f + (14\dot{\theta}_f + 16\dot{\theta}_0)t_f - (3\ddot{\theta}_0 - 2\ddot{\theta}_f)t_f^2}{2t_f^4}$

$c_5 = \dfrac{12\theta_f - 12\theta_0 - (6\dot{\theta}_f + 6\dot{\theta}_0)t_f - (\ddot{\theta}_0 - \ddot{\theta}_f)t_f^2}{2t_f^5}$

4.3 Actuator

This is an equipment that allows a robot to move by conversion of different energy types such as electrical or mechanical processes [26]. This includes human muscles, propellers, and hydraulic cylinders. Actuators are very important because it's the main mechanism to make the robot being in specified motion. For micro-manipulator, type of actuator that is widely used is the electrically controlled motors. Electrical motors are favored because it is much more precise and accurate in terms of their generated motion, as compared to the hydraulic and pneumatic-actuated motor.

Accuracy to the highest level is very important for a micro-manipulator design. Thus, the selection of a suitable actuator is very important. In [1], Adha Cahyadi et al use piezo

electric actuator in their micro-manipulator design. With the special capability of piezo material, it can produce a very fine displacement, down till micrometers. This shows the importance of selecting the right actuator. It really depends on the micro-manipulator design. Moreover, suitable controller implementation technique can also contribute well to manage the output of an actuator.

4.4 Sensors

Sensors are very important devices that allow the analog world to communicate with the digital environment. By definition, it converts physical signals such as heat, light, sound, rotary motion, and force into electrical signal [24]. The resulting electrical signal will be send to the controller and the required calculation or assigned resulting action will be taken. A precise rotary encoder for example, can provide the system with the exact location of each joints and the end effector. Then by using various types of control method, their locations can be corrected if it does slightly differ from the desired one.

In micro-manipulator design, there are many types sensor that is very useful to be incorporated with. Among them is vision or imaging sensor and force or haptic devices. Imaging is a key element for a robotic neurosurgery. It can be used during the registration process before the surgery to organize the surgery through coordinate relationship between the robot frame and the patient head's frame [13]. In addition, MRI images can also help the surgeon. Using images from the MRI and special software, the patient head can be redraw in the computer, and allows the surgeon to use it for a rehearsal before the real surgery [8]. From the MRI images as well, the location of the tumor can be captured and locked for operation. This can act as a simulation tool for the surgeon, as well as it can help the surgeon during the registration process.

On the other hand, the term haptic is referring to the tactile or sense of touch information that is required during a surgery [11]. By using the tele-operated surgery system, this kind of information is not there with the surgeon. Thus, haptic or force feedback sensor must be put at the slave robot so that the surgeon who is manipulating the master robot can have better control and awareness of the operation undertaken. Excessive force applied on the head of a patient might well damage important tissues or nerves.

4.5 End-effector

It is a device or tool specifically designed and attached to the last link of the robot or to the robot wrist [25]. It enables the robot to perform its intended tasks, for example cutting the skull or taking samples inside a body. The end-effector is loosely comparable to a human's hand. Its size is depending on the tasks assigned and also the working area. For a MIS operation, the end effector must be small enough to get to the body through the specified path or hole created.

4.6 Controller design

Control technique or controller is a tools used to cause the micro-manipulator perform the desired motions and actions, for example to executes planned trajectories. There are two class of manipulator control, namely the linear control and the nonlinear control. If a system can be defined using linear differential equations, than a linear control method is used. Otherwise, nonlinear control will come into action. There are various types of control method or technique. Among them were closed loop and open loop, classical, adaptive and intelligent control technique.

4.7 Size and materials

The micro-manipulator's type of materials used, its shape and size depends on the purpose and intended usage. The size and shape can be as shown in Figure 3(a) or as big as the DaVinci® system. It goes back to the user or surgeon, and the use of the system. The most important aspect is that it can works as it was intended to be, in a neurosurgical procedure. Moreover, the material is also very important. Let say it is going to be used inside an MRI machine, thus it must be made from MRI compatible type of materials.

5. Case study: NeuroArm

NeuroArm is a research project that was organized by the University of Calgary and MacDonald Dettwiler Associates (MDA). It was aimed to develop a MR-compatible micro-manipulator system for neurosurgical operation. This surgical robot system provides an immersive robotic system with full complement of planning and assistive software. Besides being a MR-compatible, this system is also incorporated with powerful image-guided system and haptic devices in its architecture ([2], [6] & [8]).

The system consists of three main parts. They are the robot itself, the workstation, and its cabinet for control system. The robot has with two arms with a moveable platform. Each arm has 8 degree of freedom (dof). The size of the arm is small and can operate in a 68cm working area inside the MRI scanner. The end-effector of the robot can fit various surgical tools required by the surgical procedure, such as forceps, needle drivers, suction, microscissor, and dissector. It is using the master-slave concept, means it incorporated the telesurgical system. The type of actuator used on the surgical side is a piezoceramic motors. This is primarily used to ensure safe functioning of the robot at the operative site and to avoid image distortion.
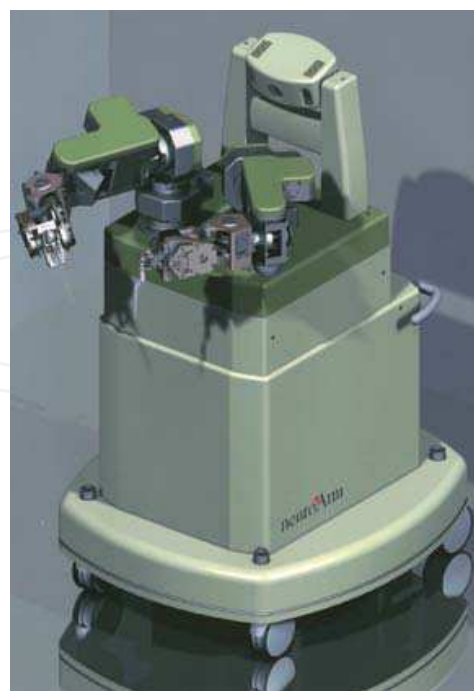
(a)   (b)

Fig. 4. (a) NeuroArm workstation. (b) NeuroArm surgical robot.

The master and the surgeon workstation are placed in a room adjacent to the operation room, while the slave or the robot itself was put inside the operation room. The master and slave are bit different in design, where the master was only a 6-dof controller with 3-dof positional force feedback. The workstation also consists of high-resolution binoculars where the surgeon can have direct access to the surgical binoculars, haptic hand-controllers, microphone to communicate with the operation room's personnel, and four monitors that display the information needed to know by the surgeon of the surgery that is going on. The master manipulator, as shown in Figure 6 has high-fidelity haptic capability, so the surgeon that is using the master controller will know the force currently being exerted to the patient at real time. In addition, tremor filter was installed in the system, to improve accuracy and precision as well as the stamina of the surgeon. This also enhances the surgical ability of the robot. The force exerted during operation can be limited. And for security purpose, if the robot fails itself, intrinsic braking system will automatically freeze the robot. Besides, the robot's actuators are functioning at low torque and low force in order to reduce any risks of injury. It can also move on a slow pace as 1mm/s, and can go up to 200mm/s, depending on the needs.

TABLE 1. NeuroArm mechanical specifications	
Parameters	**Specification**
Degrees of freedom	8 (including tool actuation) for each arm; 16 total
Payload	0.5 kg
Force (static)	10 N
Tool tip speed	Surgery: 0.5–50 mm/s
	Tool change: 200 mm/s
Positional accuracy	
Payload <100 g	± 1 mm absolute
	100 μm resolution
Payload >100 g	± 2 mm absolute
	1 mm resolution
Optical force sensors	Sensitivity: 0.02–5 N
	Dynamic range: 450:1
Continuous operation time	>10 h

TABLE 2. NeuroArm workstation specifications[a]	
Parameters	**Specification**
Hand controller	6-DOF position sensing
	3-DOF translational force feedback using direct current motors
	Workspace (tool tip) $x \times y \times z$ (ellipsoid) 40 × 25 × 50 cm
	Pitch, ± 130 degrees; yaw, ± 150 degrees; roll, ± 168 degrees
Microscope	Counterbalanced microscope equipped with motorized tilt and high-quality optics
	Beam splitter with two high-resolution JVC cameras
	High-definition 1080i format
Visual display	Binoculars using miniature display technology
	XGA resolution
Voice communication	Simultaneous talk/listen voice communication
	Wireless digital headset

[a] DOF, degrees of freedom; XGA, extended graphics array.

Fig. 5. Specifications and accuracy of NeuroArm

This system has has a simulation software that allows the surgeon to do a simulation operation before actually going for the real surgery. During the simulation, he can calculate the safe region for the robot's arm to operate. The virtual boundaries were also being able to define before the surgery. This can prevent injuries to the neural area surrounding the operation area.

Among the uniqueness of this NeuroArm is that it can fit into an MRI magnet bore. This means that the material used in building this robot is not affected by the effect of the magnet bore. Its upper arm is made of titanium and its lower arm is made from polyetheretherketone (PEEK) materials. In addition it ensures that the image generated by

the MRI is not significantly affected by the surgical tools. Even though some of the procedure is still being done by the surgeon himself, like burr holes and cranial exposure, NeuroArm has started creating its milestones in neurosurgery. With tested accuracy of 30micron, it is so great that in will surely enhance surgical capability. In addition to that, NeuroArm has successfully performed a neurosurgical operation in May 2008. The operation is to remove a tumor from a 21-year old's women brain in United States of America.
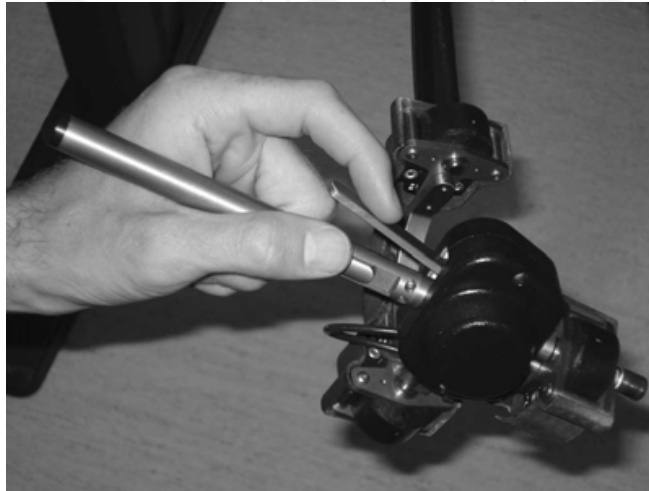
Fig. 6. Master manipulator of NeuroArm, that has the haptic interface

6. Conclusion

Researches on various aspects of neurosurgical operation were still going on. The purpose is to improve the existing system and also human lives. While surgical robots offer some advantages over the human hand, we are still a long way from the day when autonomous robots will operate on people without human interaction. With advances in our technology, it is not an impossible thing to be done. However, besides the excitement in this research field, the safety of the patient inside the operation theatre must be the highest priority.

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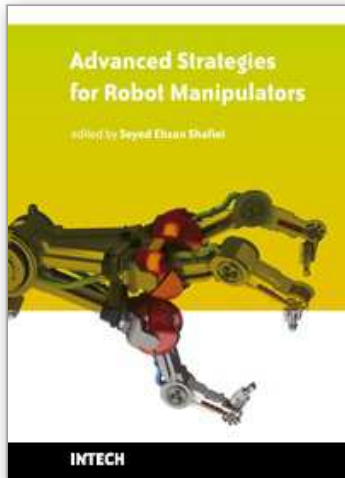
Advanced Strategies for Robot Manipulators

Edited by S. Ehsan Shafiei

Amongst the robotic systems, robot manipulators have proven themselves to be of increasing importance and are widely adopted to substitute for human in repetitive and/or hazardous tasks. Modern manipulators are designed complicatedly and need to do more precise, crucial and critical tasks. So, the simple traditional control methods cannot be efficient, and advanced control strategies with considering special constraints are needed to establish. In spite of the fact that groundbreaking researches have been carried out in this realm until now, there are still many novel aspects which have to be explored.

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