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A MR-Compatible Tele-Robotic System for MRI-Guided Intervention: System Overview and Mechanical Design

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Abstract— **In this paper, the design paradigm for a novel modular tele-robtoic system for MRI-guided neurosurgery is presented. Clinical requirements and design parameters are discussed. The overall infrastructure for MRI-guided intervention is addressed. The major focus is the application of the designed MR-compatible robotic system to MRI-guided brain biopsy. Candidate neurosurgical procedures enabled by this system include thermal ablation, radiofrequency ablation, deep brain stimulators DBS, and targeted drug delivery considering the modular structure of the slave manipulator. The mechanical design and preliminary MR-compatibility experiments are reported.**

I. Introduction

THE basic premise of Magnetic Resonance Imaging (MRI) - guided neurosurgery is that the location of a surgical instrument can be shown on an image display monitor relative to a detailed three-dimensional depiction of the head. This allows the surgeon to perform surgery while guided by the images. Image-guided procedures are substantially less invasive than traditional open surgery because the images reveal the precise location of pathologies deep to the surface that is visible to the eye, thereby permitting the surgeon to make smaller access incisions and reach the target anatomic tissues with minimum disruption to normal adjacent tissues [1]. MRI has helped increase the application of minimally invasive neurosurgery procedures to brain biopsy, thermal ablation, radiofrequency ablation, deep brain stimulators (DBS), and targeted drug delivery.

The major shortcoming in the use of conventional MRI systems for surgery is their reliance on preoperative MR images. As surgery progresses and anatomic tissue is removed or distorted, the intracranial anatomic positional relationship of the brain and surrounding structures change. This is commonly referred to as “brain shift”. Intra-operative changes due to tumor resection, brain swelling, and cerebrospinal fluid (CSF) leakage further increase brain shift [1], [2], [3]. As these processes are unavoidable in most neurosurgical procedures, they decrease the accuracy in all surgery that is based on preoperative MR images [3]. These intra-operative changes make it difficult or impossible to accurately determine the true intra-operative anatomic position of the anatomic target based on the preoperative images. Accurate localization during surgery thus requires the acquisition of intra-operative images.

Intra-operative MR images can be obtained with a variety of different MR scanner designs. These designs can generally be grouped into one of two categories: (i) “open-architecture”; and (ii) “closed-architecture”. Open systems allow the surgeon the best physical access to the patient but have degraded imaging characteristics due to their intrinsically lower magnetic field strengths and magnetic field homogeneity. Closed-bore MRI scanners produce images that have higher resolution and refresh rates than those obtained using open MRI systems [4]. Therefore, closed systems are the ones most widely used in clinics and hospitals for routine diagnostic purposes, but rarely for surgery, as accessibility to the patient is extremely limited.

The common requirement for most neurosurgical procedures is to manipulate a surgical tool relative to an anatomic target. This includes aligning, orienting, and advancing the tool to a specific anatomic target in the brain. The advantages of robotic-based neurosurgical procedures are well recognized in the clinical and technical community due to both the locating accuracy and the tele-surgery potential of the robotic systems. A neurosurgical procedure is a highly interactive process and the goal of neurosurgical robotic system is to provide the neurosurgeon with a reliable tool that augments his or her ability during the operation. Any surgical robotic system has to meet specific design considerations for its intended use such as safety, capability of being sterilized, fault-tolerancy, accuracy, stability, and dexterity. MRI-guided applications impose additional demands such as remote control, reduced size, lightweight structure, and ability to operate in the MRI bore. Primarily, there is the issue of MR- compatibility of materials and devices. Conventional robotic systems are not suitable for use inside the MRI scanner because they contain ferromagnetic materials and electrical circuits. These components cause spatial distortions and impart noise to the MR images, while conversely the magnetic field of the MRI system interferes with the electrical circuits. The strong magnetic field dictates that only non-ferromagnetic materials can be used for the mechanical parts.

In the area of MRI guided surgery, there are currently several systems under development. The Calgary Health Region and University of Calgary are developing the world’s first image guided neurosurgical robot (NeuroArm^{TM}) in collaboration with MD Robotics. The goal

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of the NeuroArm™ project is to reduce brain invasiveness during micro-neurosurgery by the use of precise tool manipulation under MRI guidance. The robot is under design and construction stage now [5]. Nakamura et al. [6] developed and manufactured the 6 DOF manipulator using non ferromagnetic materials (aluminum) and actuated by ultrasonic motors. The structure of the manipulator was designed such that the mechanical parts operating in the surgical area could be detached and sterilized. The manipulator failed to achieve the desired requirements such as accuracy and minimum MRI image distortion. This is an ongoing project and the authors are trying to improve the manipulator design [6]. Krieger et al. [7] designed and developed a novel remotely actuated manipulator (APT-MRI) to access prostate tissue under MRI guidance. They reported preliminary in-vivo canine and first clinical trails. Tajima et al. [8] designed and built a prototype MRI-compatible manipulator for treatment and diagnosis of heart diseases. The MR-compatibility of this manipulator was evaluated by moving its arm in the field of view of an open MR scanner. No noticeable deformation but some signal-to-noise ratio (SNR) deterioration was observed. Chinzei et al. [9] designed and developed a novel MR-compatible robot used to position and direct an axisymmetric tool such as laser pointer or a biopsy catheter. The manipulator was fixed to an intra-operative MR scanner (double doughnut scanner). This manipulator is in the preclinical evaluation stage. The MR-compatibility evaluation tests were successfully accomplished. Kim et al [10] designed a new master-slave MR-compatible surgical manipulator for minimally invasive liver surgery and no clinical trail has been reported as yet. Larson et al. [11] developed a device to perform minimally invasive interventions in the breast with real time MRI guidance for the early detection and treatment of breast cancer. The device consisted of two major MR-compatible apparatus including compression plates for conditioning of the breast along a prescribed orientation and probe positioning device. The device was evaluated in terms of MR-compatibility. The results showed that the device was totally invisible in the MRI images. Moser et al. [12] designed and developed a one DOF MR-compatible master-slave robotics system using hydraulic transmission. Engineering Services Inc. (Ontario, Canada) has developed an MR compatible tele-robotic system using water hydraulic and pneumatic system [13].

Our goal is to design, fabricate, and test a novel MR compatible tel-robotic system for MRI-guided neurosurgery, in particular, the brain biopsy. This paper focuses on the overview of the entire system, design requirements, and system and component design. In addition, the results of MR compatibility tests will be presented.

I. Design Requirements

A. *Clinical Requirements and Design Parameters*

Clinical users generally express their needs and requirements based on the function of the entire system in qualitative terms. The clinical requirements expressed by surgeons are: (1) MR compatibility; (2) small size; (3) lightweight; (4) safe; (5) ability to be sterilized; (6) simple to operate; (7) reliable; and (8) accurate. A virtual prototype (3D model) of the proposed design was provided to the clinical users to help discuss the issues more effectively. The communication with clinicians remains an essential tool for collecting information and feedback related to the entire system operation.

From clinician requirements engineering design parameters were extracted as follows: (1) weight; (2) degrees of freedom; (3) payload; (4) actuation system; (5) braking system; (6) materials; (7) mechanical stiffness; (8) workspace; and (9) robot configuration.

Both clinician requirements and engineering design parameters are summarized in Table 1. Each "x" indicates the existence of a relationship between the corresponding clinician requirement and engineering parameter.

TABLE I
CLINICAL REQUIREMENTS AND DESIGN PARAMETERS

`		***Engineering requirements***								
Clinician requirements		Architecture	Materials	Workspace	Payload	DOF	Weight	Locking system	Actuator	Stiffness
	MR compatibility		x					x	x	
	Small size	x	x	x			x			x
	Lightweight		x				x	x	x	
	Safety							x		x
	Sterilization	x	x					x	x	
	Simple to operate	x				x		x	x	
	Reliability	x	x					x	x	x
	Accuracy							x	x	x
	Engineering Constrains		Compatible	Scanner	<2 Kg	<=6	<10 Kg		Compatible	Payload

B. *MR-compatible tele-robotic system at a glance*

A schematic diagram of the entire system is illustrated in Fig. 1. The system consists of three main subsystems as follows:

- Operating unit
- Manipulator power/control unit
- Surgeon-machine interface unit

As illustrated, all three subsystems communicate through image information, sensory information, control signals, and power transmission.

The operating unit comprises the slave manipulator, head holder, surgical table, and MRI scanner all located in the MR operating room. As shown, both the patient's head and the slave manipulator are fixed to the surgical table in order

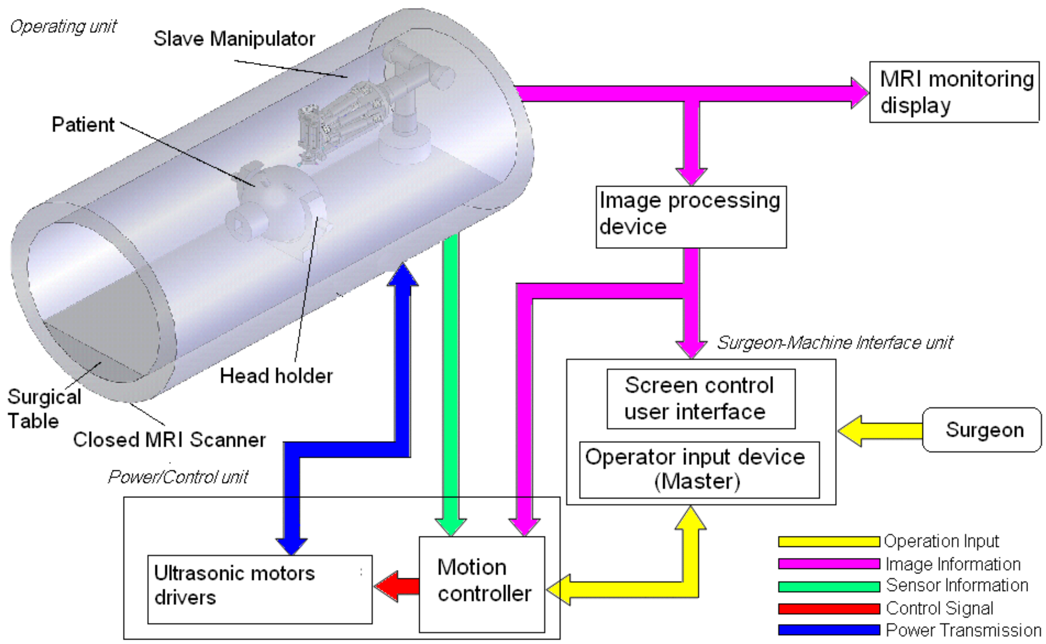

Fig 1. A schematic diagram of the entire system

to avoid any relative displacement during the operation. The patient's head need to be secured and fixed in all surgical operations to stay away from unexpected motion caused by disorderly reaction of the patient's body.

Manipulator power/control unit located in an adjacent control room provides power to the slave manipulator. It consists of power equipment and motion controller device. Depending upon the type of selected power system, it comprises of hydraulic/pneumatic valves, electrical motors, drivers, and associated controllers.

Surgeon-machine interface unit is also located in the adjacent control room. A master and a monitor interface are the major subsystems of this unit. The images of the slave and surrounding environment are projected on the monitor allowing visualization of the target and surgical tools movements. The surgeon would manipulate the position and orientation of the surgical devices via the master controller.

II. SYSTEM AND COMPONENT DESIGN

A. *Mechanical Design for the Slave Manipulator*

Fig. 2 shows a typical brain biopsy needle. It consists of two cannulas, one fitting into the other, with an opening on the side close to the tip. In addition, it has an aspiration unit. The general procedure of a brain biopsy operation is as follows: (i) the opening is closed; (ii) the needle is inserted and placed in the tissue; (iii) the notch is opened; (iv) using the aspiration unit, the tissue specimen is sucked into the needle; (v) the inner cannula is twisted by 180 degrees to cut the tissue; and (vi) the needle is pulled out with the tissue specimen that was removed.

Fig. 3 illustrates a 3D model of the slave manipulator inside the MR scanner. In addition, a 3D model of designed slave manipulator is presented in Fig. 4. As shown in Fig. 4, the biopsy needle is held and advanced by the biopsy module. The biopsy module is attached to a navigation module. The surgical arm is attached to the surgical table through a set of screws. Both the biopsy and navigation modules are held by the surgical arm.

As shown in Fig. 4, the navigation module is a six degree of freedom parallel mechanism consisting of a base plate, a moving plate, and six legs (struts). Six ultrasonic motors and six lead screws are used to provide required linear displacement for each leg. Each leg consisted of a universal joint, a spherical joint, and a prismatic joint which connects two joints together. The biopsy module provides proper mechanisms for gripping, advancing, and rotating the biopsy needle. It is fixed to the moving plate of the parallel mechanism.

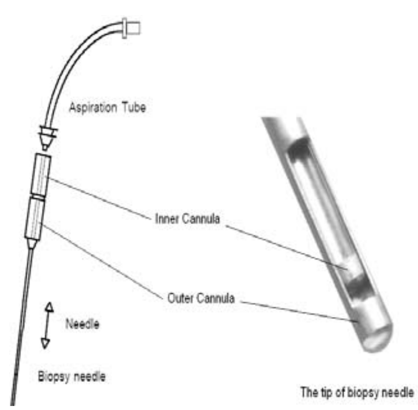

Fig. 2. A typical brain needle biopsy

A 3D model of the biopsy module is shown in Fig. 5. As shown, the biopsy module is basically a three-plate mechanism including a lower fixed plate, upper fixed plate, and a moving plate. Both lower and upper fixed plates are attached together through a connecting bar by two screws. Two guide pins are used to support the moving plate. The moving plate is moved up and down using an ultrasonic motor and a lead screw-nut mechanism. An ultrasonic motor is used to provide the rotary motion. The ultrasonic motor is attached to the moving plate through a connecting plate and moves with the moving plate. The inner cannula is rotated by 180 degrees using belt-pulley system. The needle is fixed at its position using the outer cannula clamp and the needle clamp. The former is fastened to the moving plate and the latter is attached to the lower fixed plate. Therefore, a surgeon is able to place and remove the needle very conveniently.

The advantages of using the parallel mechanism for the navigation module are as follows: (i) compact design that is an important design parameter in this project due to the limited space available inside MR scanner; (ii) light weight due to simple mechanical structure in which less material and mechanical parts are used resulting less noise on MR images and higher signal to noise ratio; (iv) high rigidity with light structure; (vi) capability of selecting an arbitrary pivot point; and (vii) high position and orientation accuracy.

The biopsy module could be attached to the navigation module in three different configurations to extend the capacity of using the system as follow:

(1) Vertical configuration (Fig. 6a)
(2) Horizontal configuration (Fig. 6b)
(3) Angled configuration (Fig. 6c)

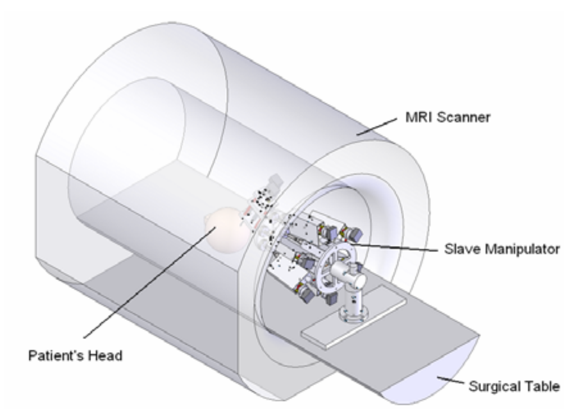

Fig. 3. The slave manipulator inside MR scanner

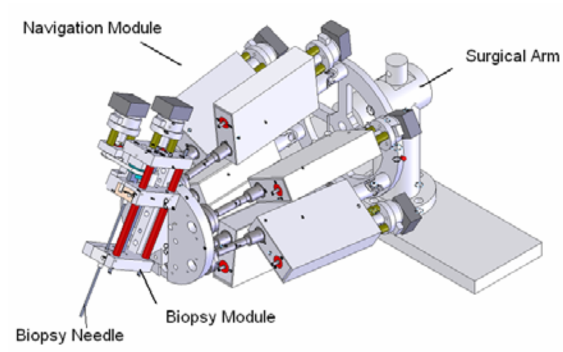

Fig. 4. 3D model of the slave manipulator

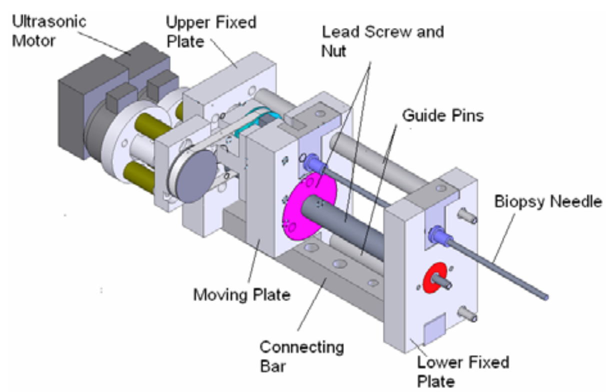

Fig. 5. The biopsy module and its main components

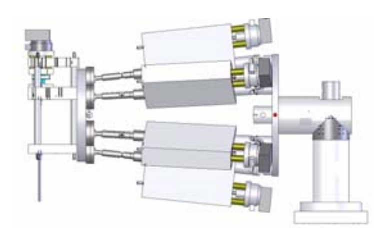

Fig. 6a. Vertical configuration of the slave manipulator

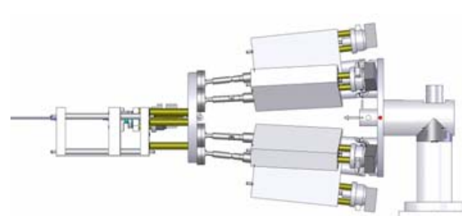

Fig. 6b. Horizontal configuration of the slave manipulator

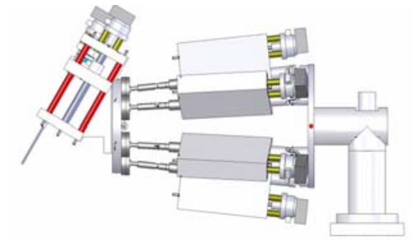

Fig. 6c. Angled configuration of the slave manipulator

Using the proposed tele-robotic system shown in Fig. 1, the brain biopsy procedure would be carried out as follows:

(1) **Preoperative imaging stage.** The patient is placed inside the MRI scanner and preoperative images are obtained.
(2) **Surgical planning stage.** Based on the pre-operative images, an entry point is determined and the incision is made by a surgeon.
(3) **Pre-alignment stage.** The slave manipulator is attached to the surgical table, and the navigation module and biopsy needle are manually located at the entry point. Although this stage doesn't require high accuracy in positioning, the slave has to be locked such that the surgical tool is positioned at the entry point. Accurate alignment with respect to target will be done in the next stage;
(4) **Real time navigation stage.** The patient is moved into the bore of MRI scanner. The navigation module is maneuvered remotely in order to align the surgical tool with the desired direction based on intra-operative images.
(5) **Intra-operative operation stage.** The operation is carried out by advancing the needle using intra-operative images as visual feedback. When the needle reaches the target, it is rotated by 180 degrees in order to cut the tissue specimen (tumor). Then the needle is pulled out completing the operation.
(6) **Final stage**. The MRI table is moved out the MRI bore. The slave manipulator and head holder are detached from the table and patient's skull respectively.

B. Robot Control

Referring to the schematic diagram of the entire system shown in Fig. 1, the surgeon could adjust the orientation of the surgical tool based on intra-operative visual MR images through the master. The inverse kinematics of the parallel mechanism is used to obtain the desired length of each strut assosiated the desired position and orientation of the needle biopsy. Six MR-compatible ultrasonic motor are equipped with six fiber optic encoder to feed back the actual length of each strut. A controller generates a control signal that drives a corresponding ultrasonic motor. Comparing desired length and measured length, the controller provides a control signal that drives an ultrasonic motor in each servo control loop. Therefore, there are six servo control loops in total. In addition, two ultrasonic motors are used to provide required advancement and rotation of the biopsy needle in the biopsy module.

The position and orientation of the slave manipulator coordinate system with respect to the MR scanner coordinate system will be achieved through the registration of the robot inside MR scanner using fiducials tracking system. Ultrasonic motor drivers, amplifier, controller, and master are located in the fringe area or control room to avoid any possible distortion on MR images. The position and orientation of the biopsy needle with respect to the target are identified using MR images in order to accomplish required task in real time navigation stage as mentioned before.

III. Results

MR compatibility is a necessary condition for this system. Series of MR compatibility tests have been conducted to evaluate the MR compatibility of the ulterasonic motor USR60-E3N (Shinsei Kogyo Corp., Tokyo, Japan) inside a MR scanner (GE, Signa 1.5T). The imaging object was a watermelon placed at the center of the bore and used to compare the images obtained under different test conditions. In addition, the effect of various MR compatible materials was tested by placing a manifold during experiment. To evaluate the noise, Signal to Noise Ratio (SNR) was calculated as the follow:

$$SNR = MV / STDV \qquad (1)$$

MV is the mean value of 5.4 cm^2 measured at homogenous area on the image and STDV is the standard deviation of the same area on the background. The results are shown in Fig. 7 and summarized in Table II. The following is the test condition for each experiment:

Test 1. The watermelon was placed in the center of the scanner.

Test 2. The motor was placed inside the scanner at 30 cm away from the center. Motor was unplugged.

Test 3. An aluminum structure was placed inside the scanner at 20 cm away from the center.

Test 4. The aluminum structure and motor were placed inside the scanner at 30 cm away from the center. Motor was unplugged.

Test 5. The aluminum structure and motor were placed inside the scanner. Motor was plugged at 25% load.

Test 6. The aluminum structure and motor were placed inside the scanner. Motor was plugged at 75% load.

As shown, actuation of the motor slightly deteriorates the image. Image shift and significant degradation of SNR were not observed.

TABLE II
MR COMPATIBILITY TEST RESULTS

Test	Mean value	Standard deviation	SNR
1	297.4	2.4	124
2	247.3	4.1	60
3	248.7	3.8	65
4	237.8	4.2	59
5	237.8	3.9	61
6	240.3	4	60

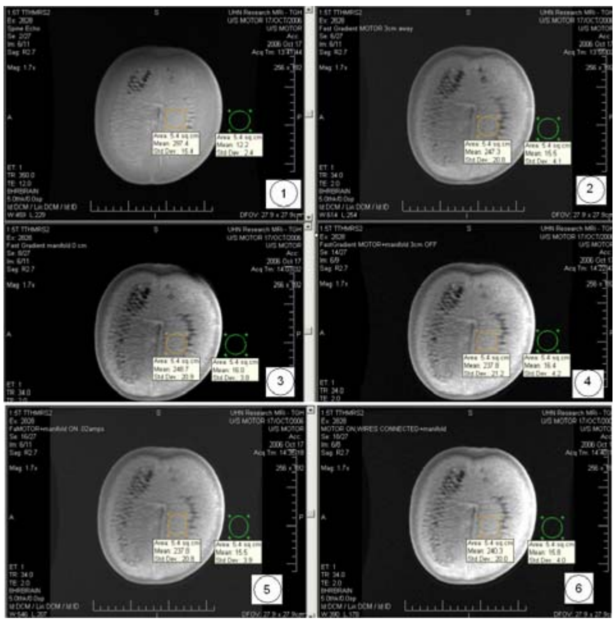

Fig. 7. MR-compatibility tests

IV. CONCLUSION AND FUTURE WORK

We have designed an MR-compatible tele-robotic system that can be used for orientation and advancement of a biopsy needle on the brain biopsy procedure. The robot has been designed such that it will perform desired tasks inside MR scanner GE Signa 1.5T. Considering the modular design implemented in the design of the mechanical structure of the slave manipulator, the proposed robotic system will be used for brain biopsy and its application will be extended to other neurosurgical procedures with similar kinematic task including thermal ablation, radiofrequency ablation, deep brain stimulators, and targeted drug delivery.

To date, design and analysis of the entire system have been completed. Material selection and the controller architecture and its component have been finalized. A physical prototype of the slave manipulator is in the process of being constructed. MR compatibility tests have been conducted. Current and future work includes the development of the slave manipulator and performance of series of experimental tests inside the MR scanner using the first physical prototype.

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REFERENCES

[1] R. D. Howe, and Y. Matsuoka, "Robotics for Surgery", Annual Review of Biomedical Engineering, Vol. 1, pp. 211 – 240, 1999

[2] J. Kettenbach, D. F. Kacher, S.K. Koskinen, S. Silverman, A. Nabavi, D. Geringt, C. Tempany, R. B. Schwartz, R.Kikinis, P. K. Black,, and F.A. Jolesz, "Interventional and Intra-operative Magnetic Resonance Imaging", *Annual Review Biomedical Engineering*, Vol. 2 , pp. 661-90, 2000

[3] Nabavi et al, "Neurosurgical procedure in 0.5 Tesla, open-configuration intraoperative MRI: planning, visualization, and navigation", *Automedia*, Vol.00, pp.1-35, 2001

[4] D. F. Kacher et al, "Design and implementation of surgical instruments, devices, and receiver coils for intra-operative MRI-guided neurosurgical and neuro ablative procedures", *Automedica*, Vol. 00, pp. 1-45, 2001

[5] D. F. Louv, T. Fielding, P. McBeth, D. Gregoris, P. Newhook, and G. R. Sutherland, "Surgical Robotics, "A Review and Neurosurgical Prototype Development", *Neurosurgery*, Volume 54, No. 3, pp.525-535, 2004

[6] R. Nakamura, K. Masamune, Y. Nishikawa, E. Koboayashi, I. Sakuma,T. Dohi, H. Iseki, K. Takakura, "Development of a sterilizable MRI-compatible manipulator for stereotactic neurosurgery", *Proc. Of Computer Assisted Radiology and Surgery* (CARS' 99), Paris, 1999

[7] A. Krieger, R. Susil, C. Menard, J. Coleman, G. Fichtinger, E. Atalar, and L. Whitcomb , "Design of a Novel MRI Compatible Manipulator for Image Guided Prostate Intervention", *IEEE Trans. On Biomedical Engineering*, Vol. 52, No. 2, pp. 306-313, 2005

[8] F. Tajima, K. Kishi, K. Nishizawa, K. Kan, Y. Nemoto, H. Takeda et al, "Development of MR Compatible Surgical Manipulator toward a Unified Support System for Diagnosis and Treatment of Heart Disease", *Proc .of MICCA O2*, pp. 83-90, 2002

[9] K. Chinzei, and K. Miller , "MR Guided Surgical Robot", *Proc. 2001 Australian Conference on Robotics and Automation*, Sydney, 2001

[10] D. Kim, and T. Dohi, "A New, Compact MR-Compatible Surgical Manipulator for Minimally Invasive Liver Surgery", *Proc of MICCA 2oo2*, pp. 99-106, 2002

[11] B. Larson, N. Tsekos, and A. g. Erdman, "A Robotic Device for Minimally Invasive Breast Intervention with Real-Time MRI Guidance", *Proc. Of the Third IEEE Symposium on Bioinformatics and Bioengineering*, 2003

[12] R. Moser, R. Gassert, E. Burdet, L. Sache, H. Woodtli, J. Erni, W. Maeder, and H. Bleuler, "An MR compatible Robot Technology", Proc. Of the 2003 IEEE, International Conference on Robotics & Automation, 2003

[13] Engineering Services Inc., http://www.esit.com, *Internal report*, 2003