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MRI Guided Surgical Robot

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Abstract

The advantages of surgical robots and manipulators are well recognised in the clinical and technical community. Precision, accuracy and the potential for telesurgery are the prime motivations in applying advanced robot technology in surgery. In this paper a magnetic resonance compatible surgical assist robot design and construction are described. The robot is designed to position and direct an axisymmetric tool, such as a laser pointer or a biopsy catheter. The main mechanical body is located above the head of a surgeon with two rigid arms extending to the workspace. This configuration contributed to a small occupancy in the workspace and good MR compatibility. The robot is not affected by the presence of strong magnetic fields and is able to manoeuvre during imaging without compromising the quality of images.

1 Introduction

The advantages of surgical robots and manipulators are well recognised in the clinical and technical community. Precision, accuracy, and the potential for telesurgery are the prime motivations in applying advanced robot technology in surgery [Villotte *et al*., 1992, Taylor *et al*., 1995, Sackier and Wang, 1995, Schenker *et al*., 1995]. Surgical robots require trajectory planning, which, in practice, relies upon preoperative images. If the target organ is deformable the trajectory needs to be updated according to the magnitude of the deformation. Here, image-guided surgery is a natural solution.

Magnetic resonance imaging (MRI) provides excellent soft tissue discrimination and a well-defined 3D co-ordinate reference system. An intra-operative MR scanner (Signa SP/i, GE Medical Systems, Milwaukee, WI, 0.5 Tesla) has been specifically designed to bring the power of MRI to the operating theatre. It has a pair of parallel facing donut-shaped magnets, with an air gap of 560 mm. Two surgeons can stand in the gap to access the patient. Brigham and Women's Hospital (Boston, MA), our collaborator, had recorded more than 500 cases using the intra-operative MR scanner [Schenck *et al*., 1995, Silverman *et al*., 1995, Hata *et al*., 1998, Grimson *et al*. 1999].

In this paper, we demonstrate a unique configuration of a novel MR-compatible robotic system for use in MR guided surgery. The goal of our robot assist system is to enhance the surgeon's performance by accurate mechanics and numerical control, not to eject him or her from the surgical field. Therefore, the system must coexist and co-operate with the surgeon. Minimal-invasiveness is an obvious requirement. The system is able to actively navigate a small tool, such as a catheter needle, with a "pin-point" accuracy, under intra-operative MR guidance. Intra-operative images serve as the source of trajectory revision.

The environment of intra-operative MR scanner creates two requirements for the surgical robot design, in addition to the standard issues such as safety and sterilisation.

i) **Kinematic structure (layout):** The robot must coexist with a surgeon. However, when the patient is prepared and surgeons take their place, the available space for the robot is limited, particularly around the patient.

ii) **Magnetic resonance compatibility:** To enable real-time tracking of the target position, the robot should be able to manoeuvre, even during imaging. The robot motion should not have any adverse effect on the imaging, and it should not be affected by the imaging process. This requires that the robot be made from paramagnetic materials. In addition, the robot should be MR-safe. The MR safety of the robot requires that the machine should not unpredictably move as a result of magnetic attraction and adverse electromagnetic side effects (i.e. leakage of, and heating by, eddy currents and radio frequency (RF) pulses) should not occur.

The requirement of MR compatibility created major difficulties for device developers, in particular, for mechatronic designers who build robots. Standard mechanical parts cannot be used in MR environment because they usually contain ferromagnetic components. However, experimental and theoretical studies gradually established the design criteria to build MR compatible machines. Shellock intensively studied this subject and issued a guidebook of the compatibility of many medical devices [Schellock, 1998]. Schenck defined MR compatibility and classified numerous materials [Schenck, 1996]. GE Medical Systems disclosed their guidelines for the design of MR compatible devices intended for their intra-operative scanner [GE Medical Systems, 1997]. It provides comprehensive and descriptive information about how developers should test the compatibility of their products. Hynynen developed MR guided focused ultrasound system [Hynen *et al*. 1992]. It was actuated by ultrasonic (piezoelectric) motors. Masamune developed a surgical manipulator that could reside and work in the MR environment, not during imaging, though [Masamune *et al*., 1995].

This paper illustrates the criteria to design mechatronic devices to be MR compatible, assuming their use with open configuration scanners. Possible interactions between the mechatronic devices and the MR imaging equipment are discussed. The MR compatible surgical robot is proposed and the prototype described.

2 Magnetic Resonance Compatibility of Mechatronic Devices

General Electric [GE Medical Systems, 1997] defines the following **MR compatibility** conditions of a foreign device:

- it is MR safe,
- its use in the MR environment does not affect imaging quality,
- it operates as designed in the MR environment.

In addition, location and timing **zones**, where MR compatibility with respect to each zone should be stated are defined. The proposed zones are as follows:

- **Zone 1 device** may remain in the image's region of interest and in contact with the patient during the surgical procedure and imaging.
- **Zone 2 device** may remain in the imaging volume and in contact with the patient during the surgical procedure and imaging, but the device is not in the region of interest.
- **Zone 3 device** is used within the imaging volume, but removed during imaging or when not in use.
- **Zone 4 device** can be used in the magnet room during the surgical procedure if it is kept a distance of more than ~1m from the magnet centre or outside the ~200Gauss line.

Various phenomena that can occur when a mechatronic device is placed adjacent to MRI scanner and is driven during imaging are listed below:

- **Effect 1: Magnetic field attracts mechanical devices.** The strong static magnetic field can attract ferrous parts in passive and active devices. This may result in unexpected behaviour. For example, standard springs often do not function as expected inside Zone 3.
- **Effect 2: Radio frequency (RF) pulse induces false signals in sensors.** High-impedance sensors can induce the RF (radio frequency) pulse depending on the distance from and directivity of the RF coil. It is not easy to eliminate such induced signals.
- **Effect 3: Foreign objects distort magnetic field.** The effect of ferromagnetic objects in Zone 1 and 2 on the homogeneity of the magnetic field is obvious. Even a paramagnetic object can have some effect if it is conductive, due to the eddy current in Zones 1 and 2. Most of standard mechatronic devices are magnetically incompatible.
- **Effect 4: Foreign objects reduce performance of RF probe.** The RF probe is a receiver antenna and is tuned to the resonance frequency. Foreign objects that are dielectric or conductive, and are adjacent to the probe, typically in Zones 1 to 2, can alter properties of the antenna.
- **Effect 5: Wiring introduces noises.** MR magnet room is an RF shield room. It cuts off electric noise from the outside and vice versa. A wire passing from outside to the magnet room can act as an antenna radiating electric noise. It can happen regardless of the distance from the scanner, significantly affecting the image quality, in particular, signal-to-noise-ratio (SNR).
- **Effect 6: Foreign resonant objects affect gain controller.** The gain controller of the signal receiver can be mistuned in the presence of a large source of resonance signal in Zone 1. This can occur when the imaging object is small in volume and a hydraulic or water driven actuator is in Zone 1.

3 Magnetic Resonance Compatible Robot

Based on our work on magnetic resonance compatibility of materials, mechanical components and motors [Chinzei *et al*., 1999] the prototype of the five-axis MRI compatible surgical manipulator (Figures 1 and 2) was constructed and installed in Brigham and Women's Hospital (Harvard Medical School, Boston, MA).

3.1 Configuration

Figure 1 shows a schematic configuration of the robot. The actuators and the end effector are spatially separated. The main body, with all actuators, is located above the surgeon's head. The end-effector is attached at the ends of two long, rigid arms. The robot has five degrees of freedom. Five degrees of freedom are sufficient to position and direct a catheter or a laser pointer because
these instruments are axisymmetric.

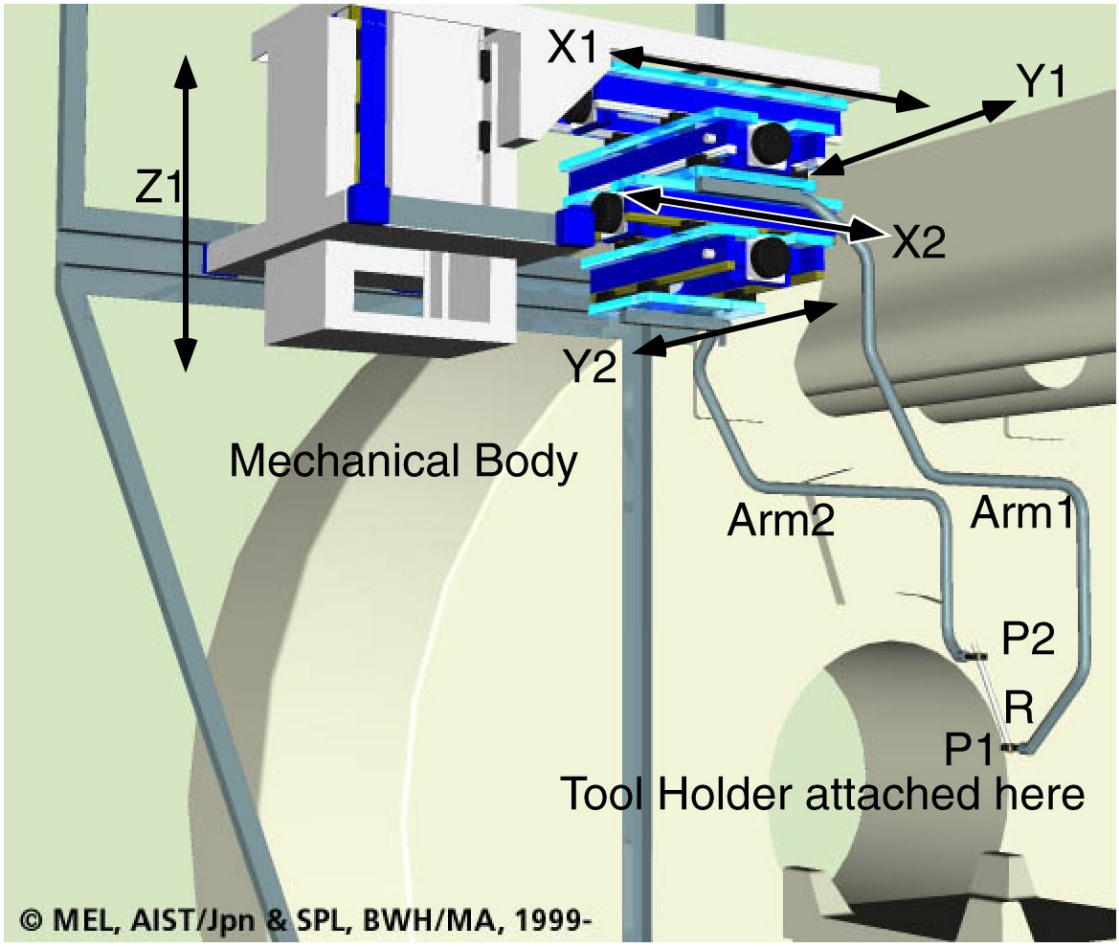


Figure 1. Robot axes layout. X1, Y1, Z1, X2 and Y2 are actuated.

3.2 MR Compatibility Design and Its Evaluation

The five degree-of-freedom main body is composed of five linear motion tables. Each table unit has a ball screw and a pair of linear guides. These are made of either stainless steel (YHD50) or beryllium-copper. As shown in [Chinzei *et al*., 1999] both materials have low magnetic susceptibility and a hard surface that can be used as a point-touch mechanism. The ball screws and linear guides made from YHD50 were manufactured by NSK Ltd. (Tokyo, Japan), and those made from beryllium-copper were manufactured by Koyo Seiko Co., Ltd. (Osaka, Japan.) The ball-screw is supported by a pair of ball bearings made from silicon nitride (Si3N4) ceramics.

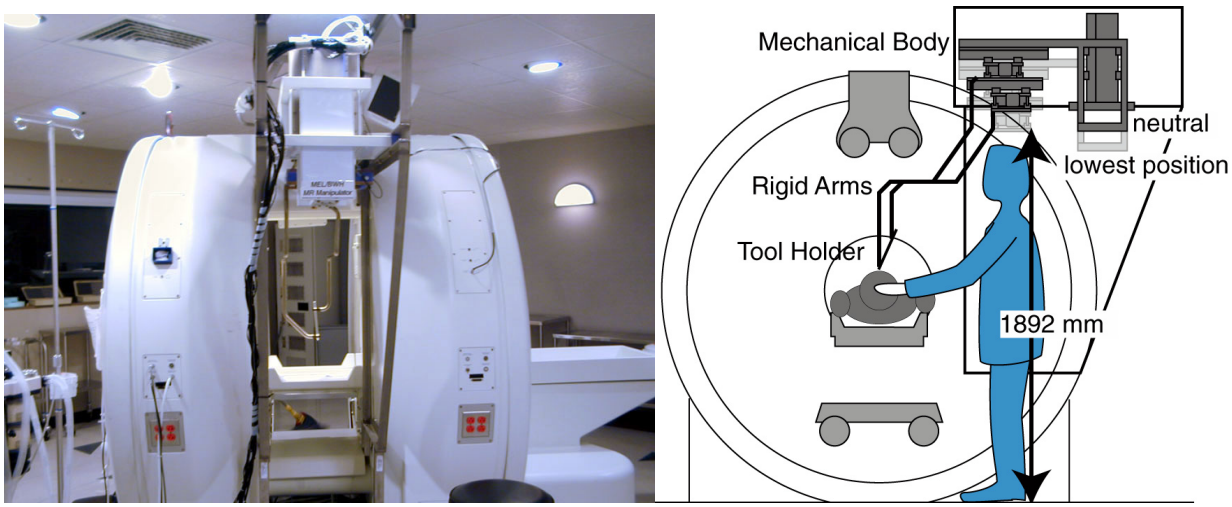
Non-magnetic (piezoelectric) ultrasonic motors, USR60-S3N, (Shinsei Kogyo Corp., Tokyo, Japan) directly drive ball screws. Motor's maximum rotational torque is 0.5 Nm, and its holding torque is more than 0.7 Nm. A mechanical clutch was inserted between the motor and the ball screw to allow for manual motion.

All parts of the robot were made from paramagnetic materials. The rigid arms, the frame structure of the vertical axis, and the attachment of the robot to the scanner were made from a titanium alloy. For frames of the horizontal axes polycarbonate resin was used. Only titanium alloy or brass screws and bolts were used. A laser pointer, with minor modifications for MR compatibility, was attached. The arms can be divided into three pieces. The end pieces can fit in a typical autoclave tray, whose internal dimensions are approximately 450 x 80 x 200 mm. The robot was equipped with linear optical encoders and optical limit detectors. We employed fibre optics to guide the signals to the optic sensors outside the magnet room. This technique was shown to be effective.

Co-operation between the robot control, MRI, and 3D position tracking was implemented using the object distribution server-client model [Schorr *et al*., 2000] consisting of three modules: (i) a robot hardware module; (ii) a Modular Robot Control (MRC) developed at Johns Hopkins University; and (iii) Slicer3D modules (Image processing/surgical planning) [Gering *et al*., 1999].

The presence and motion of the robot may distort or shift the image by decreasing the homogeneity of the magnetic field. These may also affect the image signal-to-noise-ratio (SNR). To test that, a series of experiments was conducted. The images of a spherical phantom containing $CuSO_4$ solution were obtained while the robot manoeuvred inside the scanner. The robot repeated a simple Y2 axis motion, which was the most adjacent axis to the imaging region. The control data were obtained by the same phantom without the robot.

The inhomogeneity of the magnetic field and the SNR were evaluated. The magnetic field inhomogeneity values



a) b)

Figure 2. Constructed robot attached to the intra-operative MR scanner (a) and the profile of the workspace (b). The moving part does not obstruct the workspace of the surgeon.

are listed in Table 1. When the robot was in motion the inhomogeneity value of 0.53 was observed. This was better than that of a clinically used stereotactic frame or of the human body itself. Therefore, the robot effect on the homogeneity of the magnetic field was negligible.

Table 1. Observed inhomogeneity values. The smaller the value the greater the homogeneity.

	Inhomogeneity (ppm)
Spherical phantom, without robot (baseline)	0.45
Spherical phantom, with moving robot	0.53
Spherical phantom, with an 'MR compatible' Mayfield stereotactic frame	0.9
Human volunteer	ca. 1.4

The observed signal-to-noise ratio (SNR) loss was 1.6% to 1.8%. As an SNR loss up to 10% is acceptable, the observed SNR was in the negligible range. Figure 3 shows an image of the spherical phantom with, and without the robot.

These results indicated that the presence and the motion of the robot did not affect imaging. Also, we did not observe any unintended behaviour of the robot system that could be attributed to operation during imaging. The robot itself was not affected by the imaging process. We conclude that the robot proposed is MR compatible.

3.3 Possible Applications

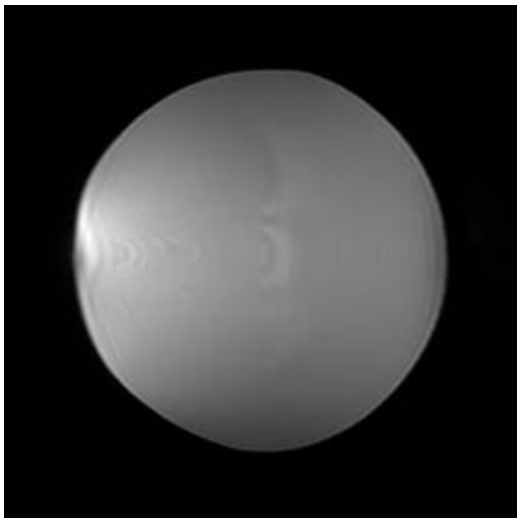
Intended first application of the presented robotic system is needle navigation in the brachytherapy of prostate cancer. This is a minimally invasive outpatient radiotherapy that delivers an internalised radioactive source to the tumour. A number of small iodine-125 radiation seeds are placed using catheters, under the guidance of MRI [D'Amico, 1998]. This procedure implants 50 to 120 seeds by 12 to 20 catheter insertions, according to a preoperative seeding plan. The seeding was previously performed using ultrasound or CT guidance. These methods could not adjust for any prostate motion, and could not delineate normal or abnormal structures in three dimensions. MR guidance offers greater spatial resolution and soft tissue discrimination.

Currently, a human operator manually inserts the catheter, so that the shadow of the catheter follows the planned trajectory on the display. It is a difficult task, requiring high level of skill. At the same time it presents itself as a good application for the robot.

4 Conclusions

The definition of MR compatibility was reviewed and the criteria to design mechatronic devices to be MR compatible were proposed. A surgical robot was designed and the prototype constructed. The robot showed excellent Magnetic Resonance compatibility. Its motion did not have any adverse effect on the imaging and the robot itself was not affected by the imaging process.

Modern medicine has rich sources of information regarding the state of health of a patient. High quality three-dimensional images (e.g. MRI) transfer the real world (patient) into the virtual world. Computer models for virtual manipulation in surgical planning have already been developed. In contrast, the transfer from the virtual to the real world (i.e. the operating theatre) has been mostly limited to visual assistance. Here, the flow of online information is unidirectional and incomplete. Surgical robots will provide the means of physical assistance and create a bi-directional flow of online information. The impact of the combination of the intra-operative MRI, and the MR compatible robot, will be even greater, because it will bring the possibility of near real-time processing of the virtual and real worlds in a bi-directional manner.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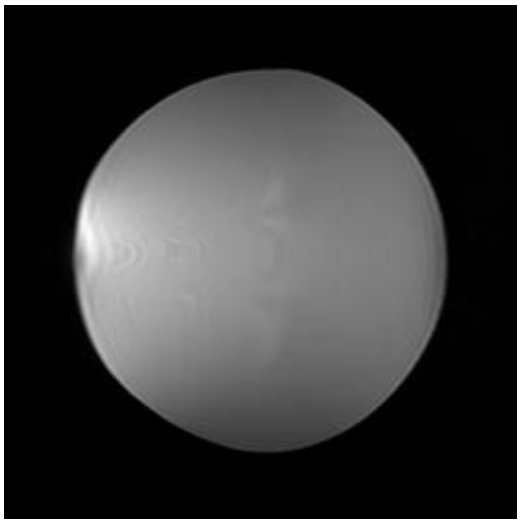
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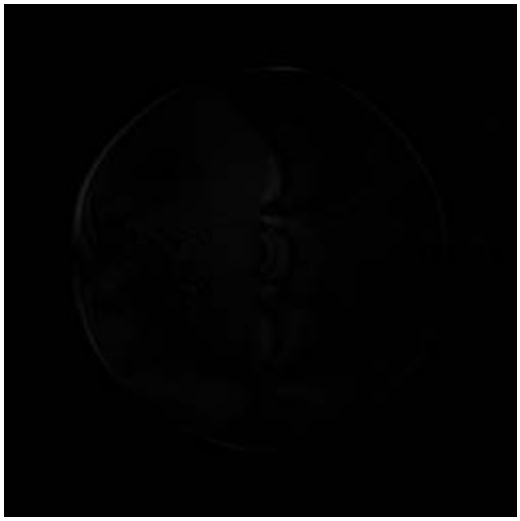
c)

Figure 3.
Images of the spherical phantom when the robot was not installed (a) and when one axis of the robot was in motion (b). The subtraction of these images showed no shift (c).

Acknowledgements

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