The case for MR-compatible robotics: a review of the state of the art

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Abstract

Background The numerous imaging capabilities of magnetic resonance imaging (MRI) coupled with its lack of ionizing radiation has made it a desirable modality for real-time guidance of interventional procedures. The combination of these abilities with the advantages granted by robotic systems to perform accurate and precise positioning of tools has driven the recent development of MR-compatible interventional and assistive devices.

Methods The challenges in this field are presented, including the selection of suitable materials, actuators and sensors in the intense magnetic fields of the MR environment.

Results Only a small number of developed systems have made it to the clinical level (only two have become commercial ventures), showing that the field has not yet reached maturity.

Conclusions A brief overview of the current state of the art is given, along with a description of the main opportunities, possibilities and challenges that the future will bring to this exciting and promising field. Copyright © 2008 John Wiley & Sons, Ltd.

Keywords MR-compatible; MR robotics; image-guided surgery; medical robotics

Introduction

The recent symbiosis between robotics and medical science (particularly imaging and intervention) has created an ideal environment to apply mechatronics to enhance the capability of the practitioner during interventional procedures. The accuracy and repeatability characteristic of robotic technologies have been successfully applied to medical interventions and a number of commercial systems are now available (1–3), of which the Acrobot (2) includes precise control of output forces. These advantages have the potential to improve all parts of the interventional process: detailed pre-operative planning can now be performed from the surgeon’s work desk using high-resolution three-dimensional (3D) images of patient-specific data (4), real-time image guidance, instrument tracking and navigation allow the procedure to be done with minimal invasiveness and real-time monitoring (5–7), and post-operative treatment and monitoring can be enhanced with the use of biological markers and specific imaging protocols (8). As a result, better surgical planning can substantially reduce surgical uncertainties, more delicate tasks can be performed in minimally invasive surgery, decreasing the demand on the dexterity of the practitioner, and hospital stay and recovery times can be greatly shortened.

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Image-guided procedures can be carried out using various imaging modalities, such as computed tomography (CT), magnetic resonance imaging (MRI) and ultrasound to visualize the target anatomy of the intervention, the surrounding tissue structures and any surgical instruments as they are moved proximal to the anatomical region of interest. These imaging modalities have been used to provide feedback to mechatronic interventional devices, especially for precise positioning tasks, such as needle insertion, biopsy interventions and catheter placement.

MRI is an imaging modality that can provide high-resolution, digitized 3D images of human tissue. It has a well-defined coordinate system and can thus produce precise, updated, spatial information of the target tissue, and any cross-section of the body can be imaged without repositioning the patient. As opposed to CT, it does not expose the patient to ionizing radiation, making it ideal for real-time image-guided interventions when combined with fast imaging sequences. Its good soft tissue contrast combined with the capability to adapt the contrast, depending on the radiological examination to be performed, gives it added versatility for pathological analysis.

These characteristics of MRI provide a powerful motivation for the development of MR-compatible manipulators, potentially combining the numerous advantages of the imaging technique with those of robotic devices. MRI can reveal the location of certain pathologies or suspicious areas within the patient, opening the door to computationally guided mechanical devices to treat only the affected area. Images can potentially be used to guide surgical instruments to the correct place and to keep track, in real time, of the navigation of the tool during the surgical procedure and the deflection of surrounding tissue, thus enhancing the capabilities of practitioners to perform many types of procedures. In addition, the severe spatial constraints of closed-bore MRI scanners, which enforce a physical separation of the practitioner from the surgical location, makes the case for MR-compatible robotics a strong one.

In this paper an introduction into the challenges imposed on the development of MR-compatible manipulators by the MR environment is presented. The current state of the art in MR-compatible mechatronics is then described, with particular emphasis on the actuators, materials and sensors employed in previously developed systems. Finally, a discussion on the current and future challenges in the use of MR-compatible systems in the surgical environment is presented.

The Challenge of the MR Environment

Although portraying numerous advantages, the MRI environment presents several challenges to the development and operation of mechatronic systems, due to the components required to obtain an image: (a) intense static magnetic fields; (b) spatial and temporal field gradients; (c) radio frequency pulses; and (d) sensitive signal detection coils, which impose a severe challenge to scientists and healthcare professionals alike in maintaining the safest MRI environment possible while maintaining good image quality.

An intense, homogeneous static magnetic field in the order of several Teslas (T) is required to produce the magnetization of the hydrogen protons in the body. This static field decays rapidly over a very small distance (the 5 mT line in most modern scanners is only several metres away from the scanner bore), presenting an intense spatial gradient. This static field and its associated spatial gradient will produce high forces and torques on any ferromagnetic or highly paramagnetic material introduced into the scanner room, and thus these must be excluded in the interests of safety.

It is of paramount importance to ensure the homogeneity of the static field in the imaging region of interest if high quality images are to be obtained. Any device with a principle of operation based on electromagnetism will interact with the existing fields in the scanner, which can hinder the correct functioning of the device, but also distort the homogeneity of the static field. Hence an alternative technology must be found for the conventional actuators used in mechatronic systems such as DC and AC motors.

Radio frequency (RF) transmitters perform the function of exciting the magnetized protons by emitting RF pulses into the imaged region. These pulses produce currents in any conductive material found inside the scanner bore, which can result in intense heating of the element, especially if the conductive element forms a loop (even if the loop is closed through the patient), potentially producing burns. The temporal gradient fields present in the scanner for signal localization in an MR image can also produce currents in conductive materials, although the heating expected tends to be much less than in the case of the RF pulses.

The signal detected from the excited protons as they relax back to their state of equilibrium is picked up by RF receiver coils. This signal, which is in the order of µT, can easily be distorted by the presence of any electromagnetic (EM) noise produced by circuitry inside the scanner room, reducing the signal: noise ratio (SNR) of the image. Measures must be taken accordingly to shield any significant sources of EM noise.

All of these possible interactions and constraints imposed by the MR environment introduce two important concepts: those of MR safety and MR compatibility. A device is considered MR-safe if, when used in the MR environment, it does not present any additional risks to any individual, although it may affect the quality of the diagnostic information. A device is considered MR-compatible if, in addition to being MR-safe, it does not adversely affect the diagnostic quality of the image or has its normal operation affected. When defining a device to be MR-compatible or MR-safe, it is important to specify under what conditions the device was tested, as these claims are only valid under those test conditions.
number of ASTM standards (17) are available to measure the different interactions that can exist between a device and the MR environment.

MRI scanners are available with an open and closed configuration. Open scanners will allow some access to the patient, and thus are ideal for intervention with the use of compatible tools, although this comes at the expense of image quality, as field strengths in these magnets are generally under 1T. Higher field strengths are achieved with closed bore scanners, with most modern clinical scanners having 1.5T or 3T. Closed bore scanners have a cylindrical bore of around 600 mm in diameter, which accommodates both the scanner table and the patient, and the bore length will vary (1.25–2 m). These dimensions mean that access by the practitioner to the part of the patient anatomy being scanned is especially difficult, making freehand image-guided interventions much more challenging. It also means that space for a manipulator inside the bore is very limited.

MR-compatible mechatronics

The demanding constraints imposed by the MR environment require the development of technological alternatives to the conventional engineering devices used in mechatronic systems. Over the last decade, research has been focused in finding compatible actuators, materials and sensors, with the objective of producing robotic systems to assist interventions in MRI scanners.

MR-compatible materials

It is fundamental to examine the magnetic susceptibility ($\chi$) of a material, which is a quantitative measure of its tendency to interact with an applied magnetic field and to distort its value (18). A material's susceptibility is an important source of image artifacts and of the forces and torques experimented on elements inside the MRI room. Materials selected for use inside the MRI scanner room depend greatly of the location of the element, but will generally be either diamagnetic ($\chi < 0$) or slightly paramagnetic ($0 < \chi < 0.01$). For materials inside the scanner field of view, material susceptibility should be close to that of air ($\chi = 0.36 \times 10^{-3}$) (18). Materials such as nylon, PTFE, wood, copper, alumina ceramics, acetal copolymers and many other engineering plastics fall into this category, presenting almost negligible artifacts (19). Other materials that have a susceptibility slightly higher, such as aluminium, titanium and magnesium will present noticeable artifacts, but they may be acceptable in certain locations and in smaller quantities (18). In any case it is important that if any artifact appears due to the presence of a certain material, it does not cover the region of interest of the scan (5,6). Non-magnetic stainless steel has a higher susceptibility difference to that of air, but can also be acceptable at a small distance from the region of interest. Ferrous materials should be avoided in the scanner room but, if required, should be located several metres away from the scanner bore and embedded in a fixed structure to ensure they are not accelerated towards the magnet. In addition, if a selected material is processed (i.e. machined, polished, etc.), it is important to re-evaluate its MR compatibility, as some manufacturing processes can alter the magnetic properties of the element.

Another factor to consider is the conductivity of the material, as the presence of pulsed RF and gradient fields may produce eddy currents and heating (18), as well as possible artifacts. This can be an issue when using non-magnetic metals to ensure the rigidity of a mechanical structure, and preference should be given to dielectrics.

To evaluate the artifact produced by a specific material, the ASTM standard (17) sets a specific set of test conditions in which to evaluate the produced artifact, which is measured under the worse set of conditions. Figure 1 shows the artifacts produced by a sample of acrylic, Macor ceramic and brass, using the aforementioned protocol. Depending on the size of the artifact, the minimum distance from which the materials must be located from the region of interest can be obtained.

Figure 1. Artifact produced by a cylindrical sample (Φ 10 x 50 mm) of (a) acrylic, (b) Macor® and (c) brass, suspended in a liquid with a nylon netting. The first two materials show a negligible artifact, where the signal void corresponds to the area occupied by the material. Brass shows the largest artifact and, if used, must be located at least at 90 mm away from the imaged region of interest.
MR-compatible actuation

Choosing a particular actuation method and the location of the actuator for use in a MR-compatible manipulator is of paramount importance and will affect the entire design of the system. Three main strategies have been observed in the literature: (a) generating motion using traditional EM actuators located outside the scanner room; (b) having a piezoceramic actuator inside the scanner room but located at a distance from the scanner isocentre to ensure MR compatibility; and (c) placing the actuator inside or close to the scanner isocentre.

The first strategy involves placing an actuator outside the scanner room and thus eliminating the restrictions imposed by the MR environment, allowing the use of regular electromagnetic actuators. Motion is then transmitted into the scanner room through a waveguide via mechanical transmissions, such as cables or belts, with the materials of the transmission having to comply with compatibility criteria. Actuation was successfully demonstrated using this technique (21), although it often meant using a fixed support structure for the transmission mechanism. In Gassert et al.’s system (20), motion and force were produced using two DC motors in the control room, which drove a pair of master cylinders. Transmission to the scanner room was done using a hydrostatic infrastructure in flexible tubes to a slave manipulator just outside the scanner bore, as indicated in Figure 2. Stiffness was ensured for relatively long lengths of tubing, although a fluid at high pressure is required, which can arouse certain concerns in the case of a malfunction or leak.

The second strategy is the most frequently reported in the MR literature. Ultrasonic motors produce movement based on resonant vibrations of non-magnetic piezoceramic materials, and thus do not require electromagnetic fields to operate, making them potentially MR-compatible. Commercial ultrasonic motors have been made available in versions which do not include ferrous materials in their casings (22–24), and their use is reported in many systems (4,5,14). One drawback is the need for electrical circuitry to produce the high voltages needed to control these motors, which, unless suitably shielded and filtered, can distort the MR images by drastically reducing the SNR. To ensure that the reduction in SNR is limited to an acceptable level, these motors are located at a distance of around 0.5–1 m from the scanner isocentre (25), and rotation and translation is transmitted to the workspace inside the scanner by means of shafts, cables, kinematic links and other mechanical means (26,27), as shown in Figure 3. While avoiding interference in the images, these transmissions inevitably introduce a degree of compliance and backlash into the system.

Similarly, a master–slave actuation mechanism was developed (28) which produces motion of a master by an ultrasonic motor, which is transferred to a slave via a hydrostatic transmission in a similar way to that in (29). By having the actuator inside the scanner room, a reduction in the length of the hoses can be obtained, which increases the energy transmission (29).

The third strategy involves introducing the actuation method directly inside the bore of the scanner. Masamune et al. (31) located the USR-30 ultrasonic motors by the joints of the robotic system they developed for neurosurgery inside a closed-bore 1.5 T scanner. This resulted in severe image degradation when imaging was performed simultaneous to motor actuation, and real-time image guidance was thus discarded. We used a different model of piezoceramic motor (5,23) and, by placing the electronics in a shielded enclosure (which acts as a Faraday cage) and filtering the control lines, were able to introduce the motors inside the scanner isocentre, as shown in Figure 4a, with only a small reduction in SNR.

Pneumatics constitutes another promising actuation method for use inside the scanner bore. MR suites generally include pressurized air supplies and pneumatic cylinders can be made to be MR-compatible. In Hempel et al.’s system (32,33), specially developed plastic...
pneumatic cylinders were used for positioning of a needle, which allow slow and continuous movement of the piston. Traditionally, pneumatic cylinders are designed to move between two limit positions, presenting difficulties to achieving accurate position control for intermediate locations, due to the compressibility of the air, and they present limited bandwidth and motion delays (4). Alternative methods of using pneumatics to achieve higher position accuracy have been reported recently. In Tajima et al.'s system (27), when the limit of the pneumatic cylinder is reached by the piston, a sprocket wheel is moved in single increments, making the movement precise and easy to control. Stoianovici et al. (34) designed and developed a pneumatic stepper motor which provides an angular step of 3.33° and torques of several hundred Nmm. These motors have been used to actuate a prostate intervention device called MR-Bot (25), which is shown in Figure 4b. We also designed an air motor (36), which uses a jet of pressured air to impulse a turbine rotor at high speeds. Once the rotor is heavily geared down, it can produce torques of up to 0.6 Nm with air at only 1.3 bar pressure. Control of the air flow to the motor requires the use of valves, which, if solenoid-based, need to be located outside the scanner room, increasing the length of the air hoses. Piezovalves are also a possibility and can be placed inside the scanner room, considerably decreasing hose length (37).

MR-compatible position and force sensors

An important part of robotic assists for intervention is their capability of providing precise position and force control of the end effector. This task requires the provision of specific sensors that can feed back certain measures to the control algorithm, and these sensors need to be compatible with the MR environment.

A common solution for position sensing in robotics is to use optical encoders, although conventional models tend to include ferrous materials and thus need to be
adapted for use inside the scanner room. Additionally they often use electric pulses to encode position, and this can introduce noise into the image, degrading the SNR. A number of systems have dealt with the problem by sending the optical signals directly outside the scanner room via fibre-optic cables, consequently using circuitry to convert these signals into electrical pulses (34,38). In (5) we used surface-mounted optical encoders inside the bore (see Figure 5a), which only have small amounts of non-compatible materials, resulting in an acceptably small image artifact of 20 mm diameter. To avoid electrical interference with the scanner, cables were shielded and filtered accordingly.

Potentiometers can be used for position detection, although they must be made of non-magnetic materials to assure compatibility, and thus are generally acceptable for use outside the scanner bore, where compatibility criteria can be relaxed.

Force sensing allows the possibility of introducing force control algorithms and haptic interfaces into the MR environment, which is particularly important given that the physical separation imposed by closed bore scanners results in the loss of the sense of touch experienced by practitioners during regular interventional procedures. A number of custom-made sensors have been developed, making use of photo sensors for force measurement and adapting optical fibres for data transmission (4). Tada et al. (39) proposed a two-axis optical force sensor which uses a segmented quadrant photosensor to detect light from a source. The source is moved when a force is applied in two possible directions, which changes the electrical signal coming from each of the segments on the photosensor. In this way it can measure forces of 0–6 N, with displacement accuracy of 1%.

Chapius et al. (40) proposed the use of an optical sensor to detect the displacement of a flexible hinge spring with light-intensity measurement. A light beam is reflected on a mirror in a flexible polymer probe and transmitted via an optical fibre to outside the scanner room. This concept of force measurement allows a compact design with only two fibres per DOF required and can be applied in torque measurement, as indicated in Figure 5b.

In Tse et al.’s system (41) haptic feedback was incorporated and tissue stiffness measured by using a commercial piezoresistive force sensor (42). The small sensor produces a localized artifact measuring 42 mm (41). It can measure forces of up to 15 N and has been successfully implemented into a one DOF test rig and used for tissue stiffness measurements.

**Current and Future Challenges in the Field of MR Robotics**

The body of literature describing the development of MR-compatible manipulators for intervention has increased considerably in recent years. Systems have been developed for use in a wide variety of applications in intervention, e.g. catheter placement (43), biopsy (5), brachytherapy (25), neurosurgery and surgical assist devices (38), with two examples presented in Figure 6. There is also an increase in reported clinical trials for the systems that are developed (32), and even some systems which have made their way into the commercial playing field (33,44). Although these are promising signs which in some way foretell the introduction of MR-compatible devices into the clinical environment, in actuality the field is still in its infancy and will have to face some important challenges if these systems are to become a common feature in most MR suites in hospitals.

First, it is important that systems are to be developed from a real interventional need. Their application must show an obvious improvement in the procedure or allow the performance of procedures which previously could not be done. Now that there is a growing range of technical solutions for MR-compatible mechatronics, systems should be developed as a result of a hospital
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Figure 6. Two examples of recently developed MR-compatible manipulators: (a) an in-bore device to assist percutaneous interventions (2); (b) a system for MR-guided neurosurgery (25)

‘pull’, i.e. stemming from a real need, rather than from a technological ‘push’. In this way the benefits that the system can supply will outweigh their extra cost and complexity.

Another important challenge is to become time- and thus cost-effective. That means that procedures must be performed in a significantly short amount of time, as the MR suite is already a very scarce and costly resource. Systems should also have a relatively short learning curve, so that training can be reduced to a period affordable by the already busy radiologists and practitioners. This requires systems to be almost ‘plug and play’, not requiring the presence of technical expertise in the operating room supervising and monitoring the system in case of failure.

Multi-application systems have already started to make a presence in the literature. These systems are designed to be able to perform not just one type of intervention, but rather a range of related procedures. Tsekos et al.’s system (45) is designed for general-purpose MR-guided procedures; Innomotion can do a variety of radiological interventions (33); and (14) is a robot assist for inserting axisymmetric tools such as needles and biopsies. This generally means that a large number of degrees of freedom need to be incorporated into the device, and hence the systems are more complex and larger in size. The clinical environment will best decide whether a preference is made towards the use of a single system for multiple procedures, which will require more training and higher acquisition costs, or several smaller systems or intelligent tools, each designed specifically for use in a particular procedure.

The presence of numerous scanner types, models, field strengths and manufacturers presents an additional difficulty when designing systems for use inside these scanners. Bore dimensions differ, scanning protocols have different names and MR compatibility must be reassessed at higher field strengths. Software and hardware platforms change between makes and collaboration with the scanner manufacturers is required if interfacing to the scanner is necessary. In order to make systems useable across several machines, it is important to either provide systems which do not need to interface directly into the scanner software, i.e. making the systems as scanner independent as possible, or to offer some other solution that is easily transferable from one platform to the next.

Progress is also required on the human–machine interface, where information generated from the scanner needs to be integrated with the system control and motion of the manipulator in an intuitive, well presented and effective manner, while not greatly increasing the workload of the practitioner. In addition, safety measures in both hardware and software need to be implemented to assure the safety of the staff, patients and equipment (i.e. redundant sensing, emergency stop routines, etc.). Sterility issues must also be considered in design and system implementation.

It is also important to note that an MRI scanner is not only an imaging tool and additional information is abundantly available. MR elastography (which can measure tissue stiffness), perfusion and diffusion MRI, spectroscopy, etc., can all offer relevant information which can be integrated into the system and used to improve intervention and diagnosis.

The current trend in new cylindrical MRI scanners is to increase the diameter of the scanner bore while reducing its length (the Siemens Magnetom Espree has a bore diameter of 70 cm and a bore length of 125 cm) which will relieve some of the severe spatial constraints of traditional scanners and may allow free-hand intervention, where the practitioner uses a screen mounted on the outside of the bore and uses the real-time images to guide a needle or other tool into a desired region in the anatomy (46). Manipulators may have more of a function to help guide the freehand intervention, and passive assists or templates might be just as useful as complex actuated devices. This will shift the research focus towards navigation and computer-assisted intervention.

Conclusions

Given the numerous advantages that MRI can offer as an imaging technique, but also as a tool capable of
providing extensive information about specific regions of anatomy, there is a clear motivation for the development of technology that can enhance the capabilities of the practitioner inside the MR environment. The current state of the art provides numerous solutions to overcome the demanding constraints imposed by the MR environment. A good selection of engineering components are available in compatible materials, certain actuators can now be incorporated into the scanner isocentre, and fibre-optics can isolate the electrical circuits of both position and force sensors, so that all electrical circuits can be located outside the scanner room. MR-compatible mechatronics can now provide the technological base for the development of manipulators able to perform interventions inside the scanner bore. Although the field is still at a relatively early stage of development, the growing number of publications, research groups, clinical trials and even commercial systems show a bright future ahead. Before MR-compatible mechatronic systems become regular devices in hospital MR suites, a number of challenges still need to be addressed by the MR robotics community, which will require tighter links between research groups, hospitals and scanner manufacturers.

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