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A General-Purpose MR-Compatible Robotic System: Implementation and Image Guidance for Performing Minimally Invasive Interventions

NIKOLAOS V. TSEKOS, EFTYCHIOS CHRISTOFOROU, and ALPAY ÖZCAN

Magnetic resonance imaging (MRI) is a versatile imaging modality and an indispensable tool in modern diagnostic medicine, with a wide range of applications in clinical and basic science research. As a result of its broad applicability and noninvasive nature, it is being developed for diagnostic and therapeutic image-guided interventions (IGIs) [1]–[4]. An impediment to this advancement, however, is the limited access to the patient, especially with the high-field cylindrical magnetic resonance (MR) scanners. To address the limited patient accessibility and facilitate real-time guidance of IGI, remotely actuated and controlled MR-compatible manipulators have been introduced. The concept of MR compatibility is discussed in the guest editorial of this special issue [29]. Several examples of MR-compatible manipulators have been developed, including a system for brain biopsies [5], two systems for breast interventions [6]–[8], one system for general use with the special “double-donut” scanners [9], [10], an endoscope positioner [11], two systems for prostate procedures [10], [12], and two general-purpose devices for use with standard cylindrical MR scanners [13], [14]. We review the development of a general-purpose robotic system at the Washington University for performing minimally invasive interventions with real-time MR guidance [14]–[17].

Our motivation for this work originates from the essential features of MRI that both compliment and improve current diagnostic and therapeutic IGIs that use X-ray fluoroscopy, computed tomography, or ultrasound. A major advantage of MRI is that it is minimally invasive, both for the patient and the medical staff. Another advantage is that MRI offers a wide range of soft-tissue contrast mechanisms (e.g., standard T1/T2 contrast, perfusion, angiography, and diffusion), which can be used to both delineate the target and characterize the effects of the intervention. MRI is also the only true three-dimensional (3-D) modality that allows oblique 3-D or multislice imaging. This property, combined with the capability of the modern MR scanners for on-the-fly adjustment of the imaging planes, offers some highly promising approaches for performing real-time IGIs.

In the following sections, we first present the criteria upon which the system was based, and an overview of its components, the design, and prototyping of the robotic manipulator are also discussed. Then, we present its control components and their general integration and logic. The human–machine interface and the practice of performing MR-guided interventions are described later. Finally, certain perspectives of this technology will be discussed.

Design Criteria and Overview of the System

The development of our system adhered to five primary design criteria. First, the robot must be compatible with the MR environment both in that its operation is not affected by the MR

scanner and that it does not deteriorate the MR images such that they are inappropriate for real-time MR-guided procedures. Second, the robot must operate safely with regard to the subject inside the confined spaces of a standard 60-cm horizontal bore magnet and the vertically limited space between the poles of an open MR scanner (with a distance of 40 cm). Third, the robotic device should be for general purpose, i.e., it is not anatomy or application specific, and is suitable for use with both cylindrical and open scanners. Fourth, the robotic device must have sufficient degrees of freedom (DoF) to maneuver a probe to set an insertion path for a defined procedure. Finally, the MRI-based operation of the device should be as simple and intuitive as possible.

Based on optimizing the above design criteria, the system evolved through several versions to its current form (Figure 1). The complete system integrates the hardware and software components necessary for an MR-guided intervention. The main hardware components are a 7-DoF robot and its associated actuators, controllers, and wiring shielded with a Faraday cage residing inside the scanner room, two control computers that reside outside the scanner room, and a manual master/slave control handle that can be used either in the scanner room or in the MR operator room. The system is interfaced to the MR scanner via a transmission control protocol/internet protocol (TCP/IP) for receiving MR images or raw MR data (unreconstructed images) and for sending commands to the MR scanner for on-the-fly control of the image acquisition parameters.

The main software components include routines for manipulator-driven control of the MR scanner and safety checks to prevent collisions of the robot with the subject. All software was developed in the Simulink (The Mathworks Inc., Natick, MA)-based xPC Target real-time environment and uses two dedicated personal computers (PCs). All calculations (image reconstruction, IGI planning, preparatory processing for the safety check component) are executed on the Host PC (Dual Pentium IV Xeon 3.06-GHz system with 2-GB memory, NVI-DIA Quadro FX 3000 graphics card), which receives image data from the scanner through a 100-Mb Ethernet connection. The Host PC provides means for manual control, through a graphical user interface (GUI) or the master/slave handle. The Host PC generates and sends control instructions to the Target PC (Pentium III 450-MHz system with 512-MB RAM) via a dedicated Ethernet network card (1 Gb/s) on each side and the communication is accomplished via a TCP/IP. The Target PC runs the real-time xPC Target operating system (Mathworks), and its function is the real-time control of the manipulator and imaging planes. The Target PC uses counters (PCI-6602, National Instruments, TX) to read the optical encoder values and digital input/output cards (PCI-6503, National Instruments) to send control signals to the motors.

Design and Physical Prototyping of the Robot

The Kinematic Structure of the Robot

The limited space inside a cylindrical MR scanner was addressed by performing a series of studies to analyze the available space above the human volunteers in the supine and prone position [14], [18]. Multislice sets of transverse and sagittal MR images were collected, and the available space was extracted with edge detection processing. Subsequently, we used 3-D solid modeling (using software by SolidWorks Corporation, Concord, MA) to investigate different sizes of end effector and kinematic configurations to identify suitable approaches.

On the basis of the above space analysis studies and the design criteria for a general-purpose robot with sufficient maneuverability, we used a kinematic configuration that incorporates three orthogonal DoF (X, Y, and Z) for global positioning of an arm that carries an end effector and three rotational DoF for setting the Euler angles of access to a target [14], [15]. The end effector has an additional linear DoF (Δ) for the insertion of an interventional tool

such as biopsy needles or thermal ablaters. For higher flexibility, we selected an arrangement with two redundant DoF, θ_1 and θ_2 , along the axis of the arm and a third, θ_3 , orthogonal to it [14]. This design is compatible for operation in both the widely used cylindrical scanners and the open scanners (i.e., it is not scanner specific). In the case of cylindrical scanners, the manipulation system can be placed either at the front or at the back entrance of the gantry, depending on the requirements of a specific application. In open scanners, the system can be placed along any direction allowed by the support structure of the two poles (C-arm or all around open).

Construction Materials

For MR compatibility, the manipulator was constructed primarily of nonmagnetic and nonconductive materials such as plastic (Delrin, Teflon, and polycarbonate) and fiberglass. Certain small parts of the robot associated with the motion transmission mechanism (such as gears and support pins) were made of stainless steel, brass, or aluminum for strength. Such small parts were kept to a minimum and at least 15 cm away from the end effector, i.e., the area of operation and imaging.

Actuators

All six computer-controlled DoF are actuated with commercial ultrasonic motors (USR-60-E3, Shinsei Corporation, Tokyo, Japan), which are commonly used in many MR-compatible mechatronic assemblies, e.g., [5], [7]–[9], [11], [14]. Although the operation of those motors is not affected by magnetic fields, their conductive cases can induce severe signal artifacts to the MR images. In addition, they are bulky and thus inappropriate for direct coupling on the actuated joints. For these reasons, the motors were placed outside the scanner at the proximal end of the arm and coupled to the actuated joints with through-joint transmission lines [15]. This approach proved efficient for both the robot presented here and a robotic system we developed previously for MRI-guided interventions in the breast [7], [8]. However, one should consider the performance limitations of such transmission systems that typically suffer from friction, backlash, and elasticity [15], [18]. In this system, the linear DoF showed negligible backlash and joint flexibility due to dynamic loading [18]. The joints of the θ_1 , θ_2 , and θ_3 rotational DoF have backlashes of $\pm 2^\circ$, $\pm 1.25^\circ$, and $\pm 3^\circ$, and flexibilities of 1.2, 2.6, and $11.5^\circ/\text{Nm}$, respectively [18]. The seventh linear (Δ) DoF used for insertion is actuated manually using a cable-driven mechanism and a hand-held actuation device. Because the step of inserting a probe is preferentially performed with the operator by the side of the subject, this option provided the simplest mechanism that performed effectively in all studies [14], [17], [19].

The End effector

We have constructed and evaluated several versions of end effectors for carrying different tools and for being able to execute certain tasks associated with IGI. All versions have three common elements: a linear DoF for the insertion of interventional tools, actuated with the aforementioned cable-driven actuator, MRI markers for the visualization of its motion, and two-dimensional (2-D) or 3-D cross-shaped markers for the registration of the robot to the MR scanner. Figure 2(a) shows a version of the end effector designed for needle targeting applications (e.g., biopsies, thermal ablations, and localized delivery of contrast or therapeutic agents). Figures 2(b) and (c) show another end effector equipped with a remotely controlled mechanical subassembly that facilitates both the delivery of an interventional tool at a target and its release. This end effector is currently used for MR-guided radiofrequency ablation applications and certain cardiovascular applications.

All end effectors were constructed of Delrin and Teflon. Because the end effector is the part of the robot that operates directly inside the imaged volume, the use of MR inert materials is

absolutely necessary. As a result, the end effector is not visible in the MR images. To visualize the end effector, we used compartments filled with dilute solution of gadolinium (Gd)-based T1-shortening contrast agent. These markers appear hyperintense in T1-weighted MR images, which are most often used in our studies because of their high soft-tissue contrast. We have evaluated different configurations of those compartments and have attached them on the tip of the end effector or on the actuated moving holder of the interventional tool. The zoomed photograph insert in Figure 2(c) shows the markers of this particular end effector, which are two 3-mm diameter cylindrical compartments attached to the distal tip of the end effector. This very simple implementation was found highly efficient for visualizing the maneuvering and targeting of the end effector, especially with the manual control. In our work, we used passive-visualization with Gd-filled markers, when compared with active visualization with fiducial markers based on miniature RF coils, for simplicity. It should be emphasized that these markers were used only for the optical delineation of the MR-inert end effector and visualization of its maneuvering in the MR images. The temporal spatial position (localization) of the end effector was calculated from the forward kinematics using the optical encoder signals as discussed below.

Control Components and Integration

Control of the robot is based on three distinct software elements that operate in synergy (Figure 3). First, at the beginning of each study, a procedure registers the manipulator, patient, and gantry relative to the coordinate system of the MR scanner. During a study, a forward kinematics algorithm performs calculations for controlling the manipulator and updating the position and orientation of the imaging plane. The third element is a safety routine that continuously checks for potential collision with the gantry or subject. Pulse sequences and protocols were also modified appropriately to facilitate the interfacing of the scanner with the robot.

Registration

Control of the robot, MR scanner, and safety check component require registration of the robot to the same coordinate system as the MR images, which is defined by the gradient coils. For this purpose, we use a 2-D, and recently 3-D, cross-shaped MR-visible marker (made of 3% Gd-filled 3.1-mm diameter tubes), attached to a specific position on the end effector. At the beginning of a session, the end effector is advanced close to the isocenter of the scanner to minimize spatial image distortion (at the isocenter, gradient nonlinearities are minimal compared with main magnetic field inhomogeneity). First, a set of multislice scout images were acquired to localize the cross-shaped marker and then three high-resolution orthogonal slices centered on the marker were acquired from which the coordinates of the marker were determined. The panel of images in Figure 3(b) shows examples of the high-resolution images used for marker registration, underscoring the high image quality visualization of the marker. Because the manipulator is at the same default configuration (same position of the base relative to the scanner, and all DoF zeroed), this process always registers the robot accurately relative to the MR scanner. The registration procedure is performed once at the beginning of a study and in all subsequent maneuvering the forward kinematics use the initial coordinates of the end effector.

Safety Check Component

Since our early virtual prototyping studies, it was evident that we needed a safety check procedure to ensure that the robot did not collide with the subject or the gantry of the scanner. Therefore, we implemented an MR-image-based safety check software component [14], [17]. At the beginning of a session, a set of transverse slices are also acquired to extract the boundaries of the subject via an edge detection algorithm based on the Canny method

[20] and generate a 3-D mask of the subject's volume. The safety routine uses this 3-D mask and programmed gantry coordinates to define an allowable maneuvering zone for the manipulator. Figure 3(a) shows an example of the generated mask, gantry, and example trajectories of the robot. The safety component compares the solution of the forward kinematics to the allowable maneuvering zone. If the motion will result in a collision, it is rejected [Figure 3(c)].

Manipulator-Driven Control of the MR Scanner

The system implements IGI with a novel method that exploits the true 3-D capabilities of MR scanners. The method updates the scanner in real-time such that the position and orientation of the imaging locus follow the maneuvering of the end effector [17], [21]. For this manipulator-driven control, the forward kinematic algorithm calculates the position and orientation of the plane on which the needle of the end effector will reside at the end of each step. If the motion is authorized by the safety control component, then the end effector position information is sent over a TCP/IP to the MR scanner for on-the-fly adjustment of the position and orientation of the imaging plane to always image the end effector. The operator can always select a preferred plane orientation, which can be transverse, sagittal, or coronal. As discussed in more detail in [17], both computer- and operator-managed control are available.

Human–Machine Interface

The operator could interface with the robot with either a GUI or a manual master/slave device.

Graphical User Interface

Figure 4 shows the GUI interface, which is used primarily for stereotactic control of the robot. In this mode of operation, raw MR data are transferred to the Host PC (Figure 1), reconstructed by fast Fourier transform, and then presented at the three viewing windows of the GUI. The upper two windows (slice windows) present two slices (parallel or oblique to each other) selected by the user from an acquired multi-slice set. The slices are also reconstructed in 3-D and presented in the third window (virtual scene window) and, if desired, together with a virtual presentation of the robot. The slice windows have two graphical markers that can be moved with the mouse on the imaged plane, while their position on the window is translated to MR coordinates. Their markers are used for stereotactic planning [16], as discussed in more detail below. The GUI also offers the option for stepwise maneuvering of the robot using the control buttons and/or the text fields provided for each DoF. For testing purposes, the GUI also presents numerical values of the slice positions and orientations, positions of the two marker, and positions of the joint variables of the physical and virtual robots.

Master/Slave Manual Handle

The master/slave control device is used for manual freehand control and is composed of two pieces [Figures 5(a) and (b)]: an articulated handle, which resembles the geometry of the arm with joints that correspond to the three rotational DoF, and a desktop piece with three dials, which correspond to the three orthogonal DoF. The joints of the articulated device and the dials of the desktop piece are equipped with optical encoders, whose readings are converted to motion instructions and enter into the control processes shown in Figure 3. Movements of this device, which is the master manipulator, are replicated by the robot, which is the slave manipulator. The operator can visualize the maneuvering of the end effector with dynamic MRI [like the examples in Figures 5(c), (d), and 6] and adjust as necessary. The control handle presented herein is a preliminary version and lacks certain

features. It does not incorporate any active actuation mechanism, and therefore, the operator cannot sense backlash or the motion constraints imposed by the safety check component. In its current form, with freehand control, the safety check software shows a warning on the GUI when a motion is not allowable. Work is currently directed toward developing and testing a haptic manual control device that will address these issues. Manual control of the robot can also be performed with a simple GUI using the mouse pointer to activate its buttons to perform stepwise motions with user-defined steps of 0.1–5 mm for the linear DoF and 1–5° for the rotational DoF.

MR-Guided Interventions

Stereotactic Control

The stereotactic controlled IGI use the GUI described above and entails three steps [16]. First, the operator defines a path of insertion, based on preoperative MR images. Second, if this path is allowed by the safety control checks, the system maneuvers the robot and aligns the end effector to this path. Third, the operator inserts the interventional tool by manual actuation of the translational DoF (Δ). For the definition of the path of insertion, the operator adjusts with the mouse the two graphical markers provided on the two slice windows. Specifically, the first slice window is used for setting the entry point and the second slice window for setting the target point. During this task, the 3-D window is continuously updated by refreshing the position of the markers, the insertion path that connects them and the virtual robot. Setting the insertion path is straightforward. This 3-D virtual environment provides a comfortable visualization framework for executing the intervention: as the calculations are finished rapidly and the graphics are updated quickly, visualization of the procedure has the feeling of a movie.

Freehand/Manual Control

This mode allows the operator to maneuver the end effector above the area of interest while scanning the anatomy. A phantom study demonstrating this method is shown in Figure 6. In this study, dynamic imaging was performed with a True Fast Imaging with Steady Precession (TrueFISP) sequence (with TR/TE/a = 4.3 ms/2.15 ms/308; slice thickness = 8 mm; acquisition matrix = 128×256 ; field of view (FOV) = $260 \times 260 \text{ mm}^2$; pixel size = $1.5 \times 1.5 \text{ mm}^2$). The two bright lines are Gd-filled markers attached on each side of a biopsy needle. The operator is provided a forward-looking view of the anatomy and moves the manipulator by either control commands issued through the GUI or the master/slave control handle. The graphical interface shows the end effector centered relative to the field of view with the anatomy or phantom moving relative to it. After the needle is properly aligned with the insertion path, the insertion DoF is activated. The advancement of the needle is monitored with dynamic MRI to confirm its placement. This method has been used successfully in MR-guided access to the spinal canal in the lumbar area on pig cadavers (Figure 7) [19].

The freehand man-in-the-loop direct control of the interventional tool, combined with on-the-fly manipulator-driven update of the imaging plane, provides simple and intuitive image guidance comparable to that which is currently used with ultrasound-guided interventions. The operator can easily scout the subject, identify a target, and set the insertion path. This capability may also provide the means for compensation of needle bending, a major source of error [12], [22]–[24], because the operator can use dynamic imaging and direct maneuvering to appropriately react and correct the bending. The feature of having the tool always at the same position and orientation relative to the FOV provides a straightforward way of directing the tool, while a simple software routine can place a line of sight on any

frame without additional image processing. In these studies, the system demonstrated an accuracy of ± 1.6 mm and in-plane path orientation of $\pm 2.5^\circ$ relative to the line of sight [17].

Looking into the Future

Performance of IGI with MR-compatible manipulators is an emerging and exciting area that requires expertise from a wide range of engineering, basic science, and clinical fields. The introduction and development of such systems has been prompted primarily by the wide range of soft-tissue contrasts available to guide diagnostic (i.e., biopsies) and therapeutic interventions and to address the limited patient accessibility of MRI, especially with the high-field cylindrical MR scanners. The contrast ability of MRI allows IGI procedures to be performed with excellent visualization not only of the target tissue but also of the neighboring tissues and along the trajectory of the interventional tool. This is potentially a great advantage because the trajectory of the tool may need to be adjusted to avoid passing through other organs where injury can be inflicted, such as blood vessels, isolated nerves or nerve plexuses, and solid organs [25]–[27]. In addition, in the case of procedures in which an injection is to be made in a certain area of the body, the spread of the injected liquid could also be visualized [4], [13], [28]. MRI technology also offers excellent oblique 3-D or multislice visualizations and no radiation exposure for the patient or physician. Therefore, even though MR-compatible interventional systems are not yet proven, it is worthwhile pursuing further development in this area, as the potential benefits can be substantial.

Another aspect we believe to be of paramount importance is the effective integration of imaging modality with the operation and control of the manipulator. In our work, we have implemented methods for stereotactic and freehand guidance of a procedure, with the maneuvering constraint by continuous safety checks to avoid collisions. Our preliminary studies indicate that both methods are suitable and may have different applications. Stereotactic approaches can take advantage of the fact that MRI offers unparallel 3-D and multislice capabilities and a wide range of contrast mechanisms. However, sometimes too much information may not serve in favor of guiding a procedure because it may increase the workload and distract the operator. Depending on the physician and the procedure, freehand may be far more intuitive because it resembles the performance of a procedure with the gold standard ultrasound imaging. In pilot studies, the manipulator-driven on-the-fly control of the MR scanner proved an efficient way for guiding the maneuvering of the manipulator, by offering “forward-looking” capabilities and at-will scouting of the target [17], [19], [21]. Together with the development of the mechatronic technology, it is important to focus research on fast imaging protocols, image processing, and displays that simplify the workload of the operator. Previous studies have illustrated that MRI with different contrast can be segmented and overlaid to define pathways and avoid sensitive structures (such as vessels) and healthy tissue [1]–[4]. Always the end user being the primary determinant of a design, an additional aspect that needs careful evaluation is the human–machine interface.

Although the contrast ability, 3-D visualization, and noninvasive nature of MRI are clinically relevant, other factors will affect the clinical merit of this technology. The first is whether MRI-guided and robot-assisted procedures indeed offer substantial benefits to patient management compared with current interventional practices and whether they can facilitate new procedures not possible with the available modalities. Identification of clinically viable applications for MR-compatible interventional robotic systems has already started with clinical studies in the breast [23], [24], spine [13], and prostate [22]. Only extensive multicenter trials can assess this. The second is cost-effectiveness. In an era of managed health care and limited financial resources, high-cost and high-technology systems will be highly scrutinized. The financial aspect encompasses different levels: acquisition of a robotic system, training of personnel, maintenance and upgrade of the devices, operation

and, especially, mechanisms of reimbursement. When looking into the cost-effectiveness of MR-compatible systems, one cannot ignore the fact that MRI is among the most expensive imaging modalities to acquire and operate. As a result, the cost of the personnel and time the scanner room is occupied, including setting up the system and performing the procedure, must be considered.

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Biographies

Nikolaos V. Tsekos received his B.S. degree in Physics from the National and Kapodistrian University of Athens in Greece, his M.Sc. degree in Physiology and Biophysics from the University of Illinois in Urbana Champaign and his Ph.D. from the University of Minnesota in Minneapolis. His research interests are in the areas of cardiovascular and interventional MRI and in particular are focused on the development of dynamic MRI and MR-compatible robotic manipulators. His work has been funded by the NIH, the Whitaker Foundation, the American Heart Association and the RSNA. Currently he is an assistant professor of Radiology and Biomedical Engineering at the Washington University in St. Louis.

Eftychios Christoforou received his Ph.D. in Mechanical Engineering from the University of Canterbury, New Zealand (2000). He also holds a diploma in Mechanical Engineering from the National Technical University of Athens, Greece (1994), and a postgraduate diploma in Management from the Mediterranean Institute of Management, Cyprus (1996). He has industrial experience in the design of mechatronic systems and also in the fields of process dynamics and control. He currently works as an adjunct professor at the Department of Electrical and Systems Engineering and as a researcher at the Department of Radiology of Washington University in St. Louis, MO. His research interests are in the areas of robotics, dynamics and control of flexible structures, nonlinear and adaptive control, system identification, image-guided robotic interventions, and biomechanics.

Alpaz Özcan received the graduate degrees in electrical and electronics engineering and mathematics with honors, from Boğaziçi University, Istanbul, Turkey, the M.Sc. degree in electrical engineering with honors from Imperial College London, London, UK, and the M.S. and doctoral degrees in systems science and mathematics from Washington University, St. Louis, MO. At Washington University, he worked as a research assistant and a systems administrator while pursuing his doctoral degree. He is currently a research assistant professor at the Biomedical Magnetic Resonance Laboratory, Mallinckrodt Institute of Radiology, Washington University. His research interests include magnetic resonance imaging, robotics, nonlinear systems, optimal control, power systems, image processing, computational techniques, probability, and stochastic analysis.

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Fig. 1. Overview of the architecture of the interventional system. The photographs depict: (a) the Host PC with its two monitors at the MR operator room. Components and lines shaded in light gray are shielded (Faraday cage and connections to and from the manipulator and the Target PC), (b) the robot in place in front the gantry of an cylindrical 1.5 Tesla MR scanner, (c) the master/slave handle for manual control of the robot, and (d) the power supply, motion controllers and wiring boxes that reside inside the Faraday cages. Dashed lines represent video connections (one passes through the filter plate to a projector for viewing the MR console output inside the scanner room).

Fig. 2.

(a) One of the implemented end effectors loaded with an MR-compatible needle on the insertion mechanism. The θ_2 , θ_3 , and Δ DoF are identified with the gray arrows. (b) and (c) An end effector that has a remotely actuated mechanism for releasing an interventional tool after it was placed at the target. (b) The end effector has inserted an introducer sheath through the openings of a radiofrequency coil. (c) The sheath has been released and the end effector rotated (actuation of θ_3). The white arrows in the zoomed insert photograph point to the two Gd-filled tubular markers used for the visualization of the end effector in the MR images [as shown in Figures 5(c), (d), and 6].

Fig. 3.

Block flowchart showing the flow of information and processes in the control software. The input parameters are shaded in gray. The operator enters the Control Command through the GUI (Figure 4) or with the master/slave handle (Figure 5). Initially, the software extracts from multislice MR images the Allowable Space inside the MR scanner (a) for use by the Collision and Safety Check routine. Subsequently, the robot is registered relative to the MR scanner by measuring the coordinates of a 2-D or a 3-D cross-shaped MR visible marker from MR images (b). (b) The transverse and sagittal images centered on a 2-D cross-shaped marker (white circle; also pointed by the white notched arrow in the zoomed images). The forward kinematics are then solved to determine the coordinates of the requested final position, which are then tested for compliance with the safety and collision avoidance routine. If they are within the allowable space the motion is executed otherwise the motion is rejected. The operation (c) shows the commanded (solid line) and the executed (dashed line) motion; when a motion is not allowed, the safety routine prevents its execution.

Fig. 4.
The graphical user interface used for stereotactic performance of IGI with this system.

Fig. 5.

(a) and (b) Two frames depicting the motion of the master/slave handle with the robot following the instructed motions. (c) A photograph of the screen projected with a projector (Figure 1) inside the MR scanner room when the operator resides by the patient couch. The insert (d) shows a zoomed view of the real-time reconstruction window of the scanner console with the oval line delineating the MR-visible markers on the end effector.

Fig. 6.

Selected frames from a target acquisition study using the manipulator-driven control of the MR scanner. The end effector is visible with the MR markers attached on the moving component of the end effector (for visualization of the Δ DoF). Note how the end effector remains at the center of the FOV during maneuvering. (a)–(c) Motion of the robot along the z axis of the scanner (scouting to identify the target, pointed with the white cross, and the insertion path identified with the white triangle), (d)–(f) translation of the robot along the x axis of the scanner (to the left when looking toward the gantry), (g)–(i) rotation of the θ_3 DoF, and (j)–(l) insertion of the needle to the aimed target.

Fig. 7. Results from an MR-guided intervention in the spine of a pig cadaver with the robotic device inside a cylindrical 1.5-T MR scanner. Selected slices show (a) an oblique sagittal view of the pig's abdomen and (b) an oblique transverse slice. The white box in (a) indicates the position of the slice shown in (b), and the box in (b) the position of the slice shown in (a).