Fast and Efficient Radiological Interventions via a Graphical User Interface Commanded Magnetic Resonance Compatible Robotic Device

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Abstract— **The graphical user interface for an MR compatible robotic device has the capability of displaying oblique MR slices in 2D and a 3D virtual environment along with the representation of the robotic arm in order to swiftly complete the intervention. Using the advantages of the MR modality the device saves time and effort, is safer for the medical staff and is more comfortable for the patient.**

Index Terms— **Surgical Robotics, Magnetic Resonance Imaging**

I. INTRODUCTION

Today's interventional radiology permits a wide range of operations such as biopsies, radio frequency (RF) ablations using different modalities like ultrasound, direct X–Ray and computer tomography (CT). While large scale operations, meaning the operations where deeper regions of the body has to be reached, are done using CT such as RF ablations, operations involving shallow areas, for example biopsies around the neck area, are accomplished with ultrasound. For the operations that require real time imaging, such as catheter placement, X–Ray is commonly used. With special adaptations, tailored imaging methods and compatible equipment Magnetic Resonance Imaging (MRI) is also used for catheter placement.

There are several factors which are economical, physical and practical that determine mostly the modality used in the interventional procedure. For example, any modality that involves radiation will create an exposure of the medical personal to harmful rays but is indispensable in terms of providing either real time images or resolution into the patient's region of interest (time domain and physical space resolution).

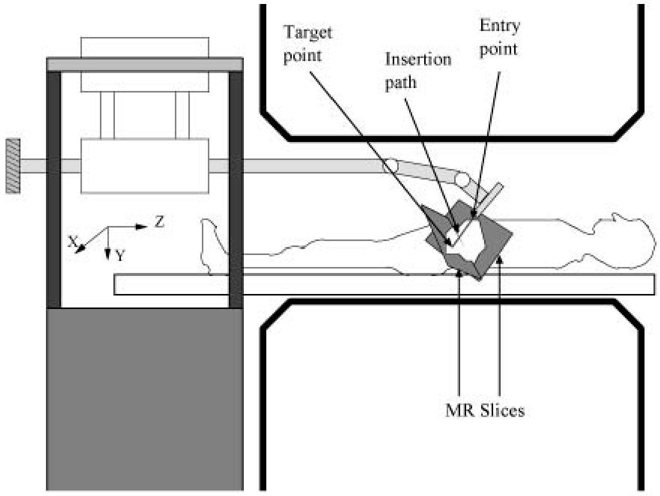

Fig. 1. The position of the patient and the robot inside the MRI scanner and the coordinate frame. The MR slices are representative of the location of the images.

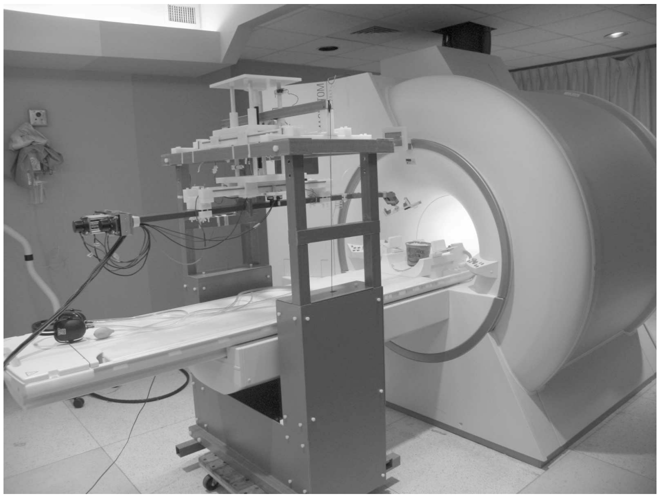

Fig. 2. The placement of the robot in front of the MR scanner

The goal of this manuscript is to present the aspects of our Magnetic Resonance (MR) guided robotic system [1] which yields to fast and efficient radiological interventions by overcoming some of the restrictions imposed by the CT modality. Magnetic resonance imaging is in use for pre and post operative surgery as well as it can be used during the surgery [2]. There are several MR compatible organ specific robotic devices that are already in existence [3]–[5]. The open MRI structure [6] is also utilized for the larger physical space it provides. There is even a specially designed

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MR scanner from General Electric [7] in the shape of a double donut that will allow the robotic operations while the patient is inside the scanner. The purpose of our seven degree of freedom (DOF) device is to bring the capability of performing different kinds of interventional procedures on a range of target organs. Our idea of keeping the patient inside the scanner during the intervention in order to obtain real time images coincides with the special double donut scanner's strategy but we have decided to design the robotic device to fit to the physical space restrictions of a general closed gantry MR scanner rather than trying to reshape the MR scanner itself [8], [9]. This solution, due to high availability of closed gantry scanners (they provide better image quality than open scanners), is economically more viable than designing and building special scanners and facilitates the availability of the robotic device.

II. MRI INTERVENTIONAL PARADIGM

The general paradigm of robotic systems is to obtain information from a vision system and command the robotic manipulator to achieve the task in hand. For example, industrial robotic systems include a camera and image processing hardware and software to complete assembly tasks, to sift through defective parts etc.

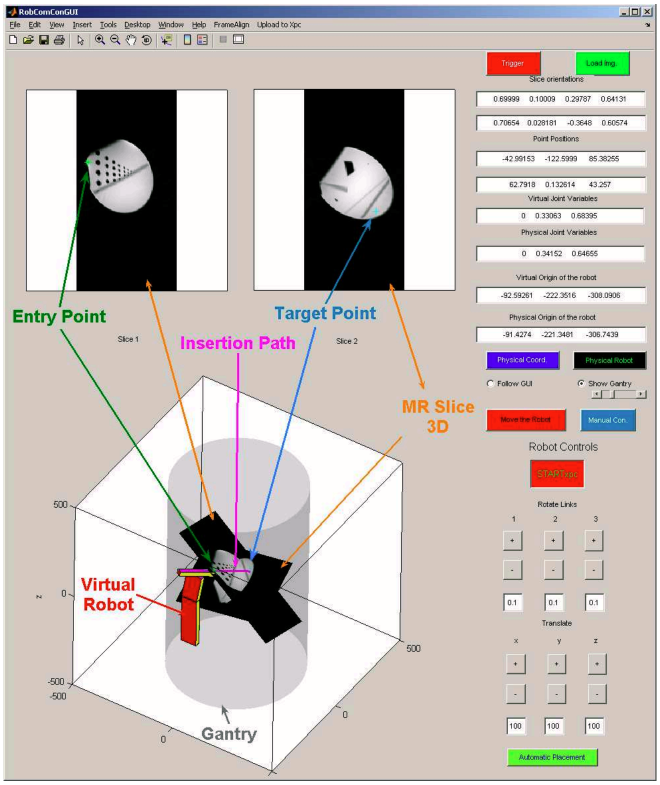
In our approach, the vision system is the MRI scanner. The scanner has the ability to obtain images of the slices oriented in any direction and centered in any location at a reasonable distance from the gantry's center. The raw data are collected after the application of a series of RF pulses and magnetic field gradients that change the strength of the main magnetic field in a location dependent manner. Afterwards, the data are discrete Fourier transformed to obtain the images.

From a technical point of view, in a clinical setup what happens after the collection and (fast) Fourier transforming of the data is the conversion of the images to Digital Imaging and Communications in Medicine (DICOM) format along with the slice and patient information in order to preserve and investigate the images using the DICOM database. The computation of the images and the maintenance of the database are the responsibility of the image reconstruction computer and the MR console (part of the MR scanner) shown in Fig. 5. The time that elapses between the collection of data, image reconstruction and database update to be able to see the images is unacceptable for real time interventional purposes. To overcome the time delay a direct connection between the operator's computer and the image reconstruction computer must be used (see Fig. 5).

The major advantage of using MR modality as the vision system is the capability to position and orient slices in any desired manner. In the CT modality the slices are inherently parallel to the gantry which forces the physician(s) to guess the insertion path. By using MR oblique slices to clearly determine the insertion path a considerable amount of time and efficiency can be gained with much less effort.

III. GENERAL SETUP AND GRAPHICAL USER INTERFACE

The basic idea is described in Fig. 1 (see also Fig. 2 to have an idea about the physical dimensions of the device with respect to a Siemens 1.5 Tesla Sonata MR scanner). The patient is placed in the scanner along with the robot and the slices of interest are imaged using the scanner. The raw data are transferred to the operator's computer (Fig. 5) including the coordinates of the slices and the fast Fourier transform is computed to obtain the images. The images are presented with the graphical user interface (GUI) in two different fashions (see Fig. 3). First, two dimensional images are shown in the windows placed on top of the GUI to decide about the entry and target point of the intervention. These windows are called slice windows. Second, there is an additional window, called 3D window, that provides a virtual presentation of the robot, of the slices displayed in their physical positions and of the gantry.



Slice orientations
0.69999 0.10009 0.29787 0.64131
0.70654 0.028181 -0.3648 0.60574
Point Positions
-42.99153 -122.5999 85.38255
62.7918 0.132614 43.257
Virtual Joint Variables
0 0.33063 0.68395
Physical Joint Variables
0 0.34152 0.64655
Virtual Origin of the robot
-92.59261 -222.3516 -308.0906
Physical Origin of the robot
-91.4274 -221.3481 -306.7439
Rotate Links: 0.1 0.1 0.1
Translate: 100 100 100

Fig. 3. The graphical user interface that commands and monitors the operations. For a close up view of the 3D portion see Fig. 4.

As shown in Fig. 3 each of the slice windows is associated with a marker. The first window displays the entry point marker and the second displays the target point marker. Using the mouse, the operator can move any of these points in order to decide about the best insertion path for the intervention. The markers are also shown in the 3D environment on their respective locations on the slices. As soon as any of the points is moved in the slice windows, the markers in 3D follow the motion of their 2D counterparts. The virtual robot in the 3D window positions itself inline with the insertion path defined by the entry and the target point.

This is accomplished by solving the inverse kinematics of the robot [10]. This mode of operation is called *automatic placement*. The virtual environment provides a comfortable framework for executing the intervention, as the calculations are finished rapidly and the graphics are updated quickly the procedure has the feeling of a movie or a video game. A warning will be issued if the length of the needle or the probe is shorter than the insertion path.

The operator is not restricted to only using the markers to actuate the manipulator. Basically, by using the buttons and/or the fields provided on the right hand side of the GUI, the operator can actuate any joint or DOF to any allowable value. This mode of operation is called *manual placement*.

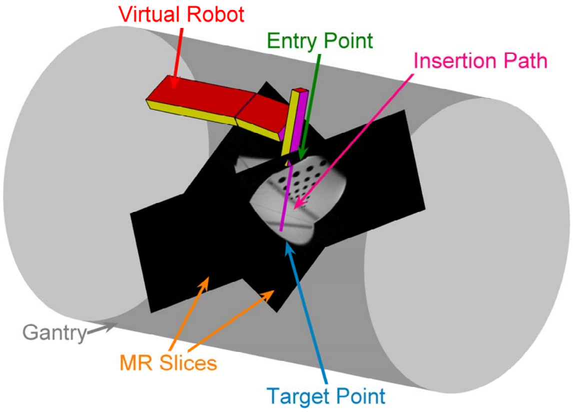
These delicate placements can be quickly achieved using the zoom features for all the images as well as changing the angle of view by rotations and tilts for the 3D window. The operator has also the option of changing gantry's transparency or not showing it at all (see Figs. 3 and 4) in order to obtain the best possible view(s). Moreover, whether the gantry is displayed or not, there exists a safety precaution in place which alerts the operator by displaying the gantry in orange if for some reason any of the extremities of the robot touch it.

It is quite possible that the radiologist in the beginning will not be satisfied with the position and the orientation of the slices in order to accomplish the intervention. The GUI provides a trigger button that sends a signal to the scanner to start the scans. Although at this point the slice positioning must be done using the MR console, there is work in progress in collaboration with Siemens engineers to modify the slice positions and orientations from the GUI [11].

Aside the graphics, the GUI also presents at any time numerical values of the slice positions and orientations, positions of the entry and target points, numerical values of the joint variables of the physical and virtual robot as well as their origin. By pushing a GUI button the operator can also display the physical robot in the 3D window in order to have an idea about the true physical position of the device.

There are two GUI based modes of operation for the command of the robotic device. In the first one, only the virtual robot in the 3D window is actuated based on automatic or manual placement and the changes are reflected to the physical robot after the operator decides that everything is in order. The operator can use a GUI button to send the commands to the physical robot for the physical execution of the move. This mode of command is called the *planned mode* which is preferable and safe. In the second mode, the commands obtained from the GUI in the automatic or manual placement mode are immediately dispatched to the physical robot. In this mode, called the *online mode*, extreme caution must be used.

In addition, the device can be commanded by using a haptic device and/or directly controlling the motors by using electrical switches. The GUI button that puts the device into this mode does the following: it immediately disengages the feedback loop that controls the robot arm, it starts collecting the motor encoder data in order to monitor numerical values



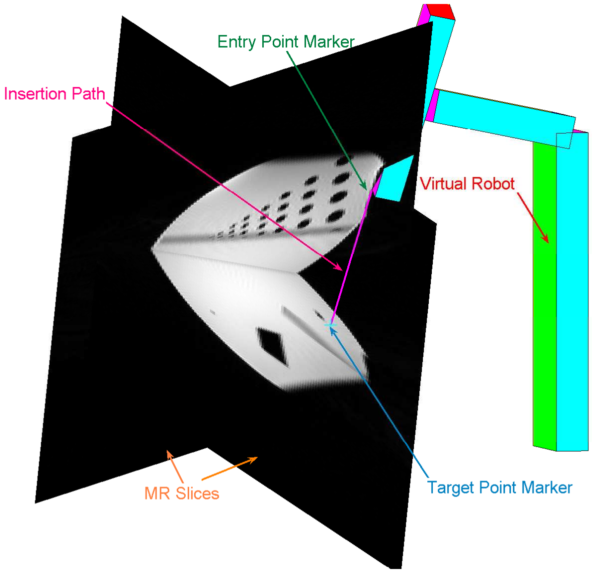


Fig. 4. Close up view of the slices and the virtual robot for different target and entry points. The operator can choose to display or not to display the gantry. The phantom is a water filled cylinder with hallow tubes inside.

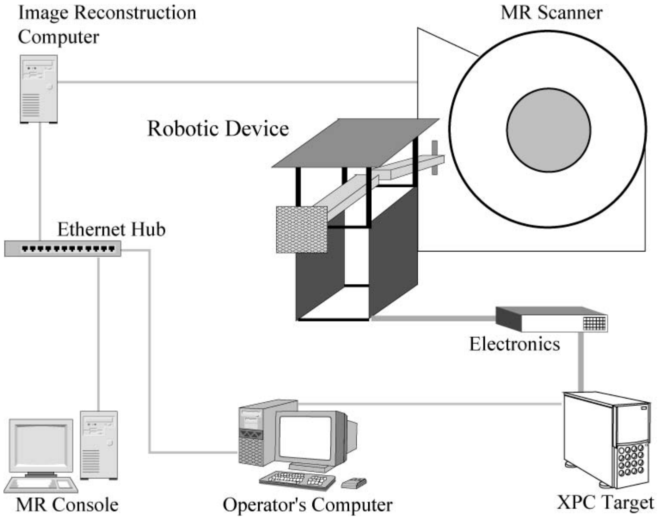


Fig. 5. The setup for the MR guided robotic operation

of the joint variables and continuously displays the physical robot on the 3D virtual environment. If desired, the virtual environment can be shown inside the scanner room so that the operator can be near the patient and can guide the intervention.

The software component of the device including the GUI is build in Matlab (Mathworks, Natick, MA USA). All the calculations described above are executed using Matlab on the operator's computer (Dual Pentium IV Xeon 3.06GHz system with 2GB memory, NVIDIA Quadro FX 3000 graphics card). The robot is controlled by using the feedback control systems described with Simulink (Mathworks) and implemented with XPC target operating system (Mathworks). The XPC target computer (Pentium III 450MHz system with 512Mb memory) is connected to the operator's computer with a dedicated ethernet network card (1Gbit/s) on each side and the communication is accomplished via the TCP/IP protocol (Figs. 5 and 6). The XPC target computer uses quad counters (PCI-6602, National Instruments, Texas, USA) to read the encoder values from the MR compatible ultrasonic motors (USR-60-E3, Shinsei Corporation, Tokyo, Japan) and digital input/output cards (PCI-6503, National Instruments) to send control signals to the motors. The DICOM conversion process is completely bypassed by obtaining the raw data via an ethernet connection (with another 1Gbit/s dedicated network card) to the internal network of the image reconstruction computer and MR console computer (see Fig. 5). This arrangement is by no means standard and highly dependent on the MRI scanner's manufacturer.

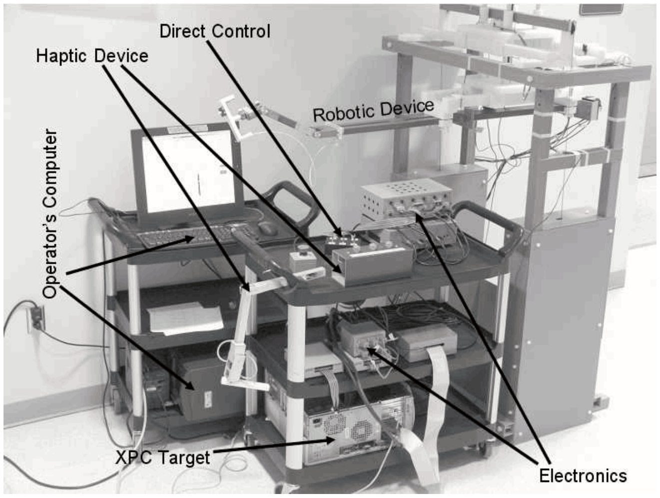


Fig. 6. Operator's Computer, XPC target computer, the electronics and the robotic device

IV. THE COMPARISON OF THE ALGORITHMS FOR THE INTERVENTIONS

In a typical CT based intervention, first the patient is sterilely prepared and brought to the operation room. The operation starts by placing the patient in the CT scanner and obtaining several slices in order to appropriately locate the area of intervention (see Fig. 7). Clearly, during imaging only core personal, if any at all, stays in the scanner room to reduce the radiation exposure. The radiologist observes the images from the CT console room.

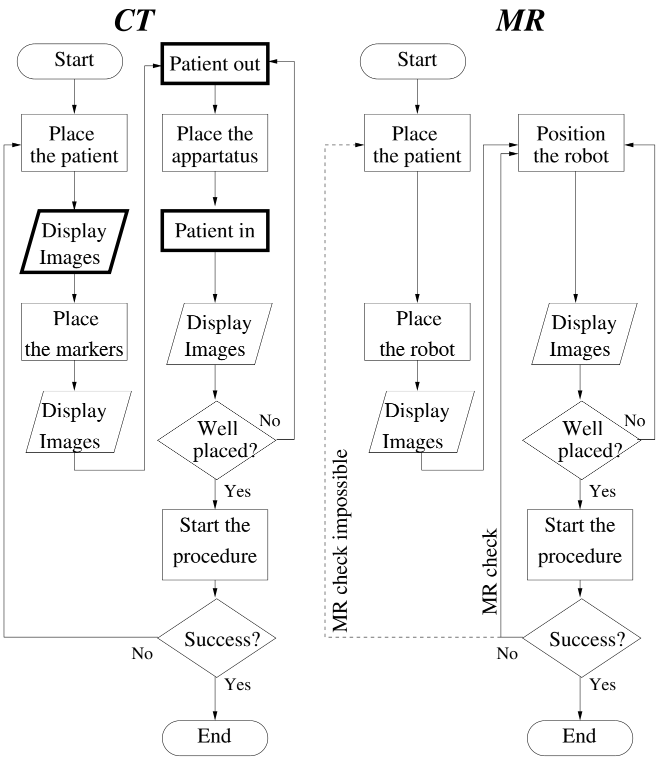


Fig. 7. Comparison of the algorithms for CT and MR. The extra steps in CT take longer time to accommodate.

At the end of the first imaging round the radiologist walks back to the patient in the CT room and places fiducial markers by using the visual information on the computer monitors in the room and moving the patient table accordingly. At the second round the same procedure is repeated in order to decide about the insertion path. Once the decision is made the patient is taken out using the table. Although the gantry of a CT scanner is shorter than the gantry of an MR scanner, there may not be enough room to comfortably place the needle by hand. Moreover, the needle advancement must be done in stages to make sure that non–target organs are not hit. To accomplish these goals, after the initial needle insertion, the patient is moved in the scanner, the medical staff walks out of the room, images are taken to see the needle's placement. This loop is repeated (see Fig. 7) until it is decided that the probe had reached safely the right target. It is also possible to use fluoroscopy to place the needle in real time without having to have to leave the room and come back. Once the placement is acceptable the patient table is moved out and the operation starts. At the end there is usually a test to assess the success of the operation. For example, in the case of RF ablation, a probe is inserted to the intervention area to measure the temperature of the surrounding tissue (if it is above a certain value, this indicates that the tissue is successfully ablated). If the operation does not yield to satisfactory results the steps are executed again until success as described in the CT part of Fig. 7.

By comparing the interventional algorithms for CT and MR in Fig. 7 it can be quickly seen that a tremendous amount of time and effort is saved with MR by keeping the radiologist in one room and the patient in the scanner all the time. Confidence levels are boosted by having the visual information quickly during the procedure. In CT, slices in different locations can only be obtained by displacing the patient table whereas in MR, as long as the imaging area is close to the center of the magnet, there is no need to displace the table. Plus, having access to oblique slices in MR increases the choices of efficient insertion paths and eliminates the possibility of hitting non–target organs. As different paths can be visualized and the probe resides on the robotic arm inside the scanner near the intended target area, the patient does not need to be taken in and out in order to complete the procedure safely. The radiologist has the option to stay in the room and command the whole operation near the patient without being exposed to high levels of radiation. This is an advantage over CT fluoroscopy where severe detrimental radiation effects can occur particularly to the hands of the physician in time. However, inevitably, there will be high levels of sound (the level depends on the pulse sequence) produced by the MR scanner during the imaging process.

Basically, from the patient's point of view, the intervention will be completed in a shorter amount of time without radiation exposure and with almost no displacement of the patient. This is definitely preferable over a lengthy operation. From the point of the medical staff, radiation exposure that forces them to walk in and out of the scanner room is eliminated. In this manner, in addition to avoiding the harmful effects of radiation, their time and energy is saved as well.

Moreover, MR techniques such as perfusion, diffusion imaging methods can be used to determine the success of the operation in a detailed manner thanks to the possibility of changing the contrast properties of MRI [12] by using different pulse sequences. This makes it possible to assess the success of the operation in a multidimensional manner. If this is achievable the patient can be kept in the scanner until success (see *MR check* path in Fig. 7). Otherwise the patient must be taken out of the scanner to complete the test (dashed line in Fig. 7) as it is done by default with the CT modality.

V. CONCLUSION AND FUTURE DIRECTIONS

Using the medical imaging modalities as vision systems for medical robotics is not new. There are several systems developed for different imaging modalities [13] with their merits and disadvantages. The choice of modality is based on the type of intervention as well as on the economical and practical reasons. Regardless of the preference, the robotic device must make use of all the imaging capabilities of the modality of choice. The software component must display all the available information to the interventional radiologist. This goal in our work is achieved by using a powerful graphical user interface which presents the information in 2D and 3D virtual environments, that makes it extremely easy for the physician to command the robotic device.

There are robotic devices for CT modality [14], [15]. However, they carry the inherent inability of CT to adjust the orientation of the image slices. In addition, the medical staff are exposed to harmful radiation to operate these devices. Undeniably, the CT modality has the advantage of having a better accessibility to the patient due to the smaller size of CT gantry compared to closed MR gantry.

In this manuscript we have described the elements that command the prototype MR closed gantry compatible device [1] and the algorithmic comparison of CT based and MR based interventions. The radiologist with the information coming from oblique MR slices can complete the procedure in a faster and more efficient manner by choosing among different oblique insertion paths. Moreover, as the physician and the medical staff are not exposed to the radiation the operation can be conducted from a single room. By removing the trips in and out from the operation room during imaging stage, the medical staff can quickly complete the procedure with much less effort and without high levels of radiation. The short duration of the intervention with no displacements is also beneficial for the comfort of the patient. MRI has the capability of obtaining images of the same slices with different tissue enhancing properties. This is very important for the final decision on the result of the intervention without causing extra discomfort for the patient. The result can be judged in a multidimensional manner by using different imaging sequences. For example, in RF ablations the determination of the exact size of the thermal ablation zone with CT is difficult, if possible at all in many cases. The superior tissue characterization in MR may allow better determination that the physician has reached the thermal endpoint.

It is important to note that MR modality brings with itself several engineering challenges to achieve compatibility with a strong magnetic field, RF signals and fast changing magnetic field gradients [1], [8], [9]. CT compatible devices are easier to design from an engineering point of view. The details and issues related to the construction, MR compatibility, effects of the device on MR images (e.g. signal to noise) are presented in [1], [8], [9]

The future research encompasses different topics: design of fast MR pulse sequences, complete control of slice orientations from the GUI, improvement of the different aspects of the mechanical design, design of different feedback control strategies, 3D volume image based planning, distant operations over the internet. The subjects of needle deformation, automatic avoidance of non–target organs, control strategies for compensating patient motion, optimal path choice for maximization of the effects of the therapy are also future topic of research that will be incorporated in the design of the whole system.

Obviously, the prototype must be first tested on animals to obtain a better understanding of the requirements and obstacles that will present themselves long before any test on human subjects.

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