31st Annual International Conference of the IEEE EMBS
Minneapolis, Minnesota, USA, September 2-6, 2009

MRI-Guided Robotics at the U of Houston: EvolvingMethodologies for Interventions and Surgeries

Nikolaos V. Tsekos

I. INTRODUCTION

Currently, we witness the rapid evolution of minimally invasive surgeries (MIS) and image guided interventions (IGI) for offering improved patient management and cost effectiveness. It is well recognized that sustaining and expand this paradigm shift would require new computational methodology that integrates sensing with multimodal imaging, actively controlled robotic manipulators, the patient and the operator. Such approach would include (1) assessing in real-time tissue deformation secondary to the procedure and physiologic motion, (2) monitoring the tool(s) in 3D, and (3) on-the-fly update information about the pathophysiology of the targeted tissue. With those capabilities, real time image guidance may facilitate a paradigm shift and methodological leap from "keyhole" visualization (i.e. endoscopy or laparoscopy) to one that uses a volumetric and informational rich perception of the Area of Operation (AoO). This capability may eventually enable a wider range and level of complexity IGI and MIS.

Magnetic Resonance Imaging (MRI) offers certain unique to the modality properties (Table 1): a plethora of soft tissue contrast mechanisms, true 3D imaging, no-ionizing radiation, and on-the-fly control of imaging parameters. Endowed with an ever-growing number of innovative technological and methodological advances, MRI has emerged as a powerful and highly potential modality for planning, guiding and monitoring interventions. The limited access to patients inside an MRI scanner and the potential benefits of real-time image guidance have led to the introduction of several robotic systems for performing MR-guided interventions [1]. Several examples of MR-compatible robots have been developed includes robots for neurologic procedures [2, 3], breast interventions [4, 5], endoscope manipulation [6], and prostate procedures [7, 8]. General purpose systems have also been developed for use with standard cylindrical MR scanners [9-12].

At the Medical Robotics Laboratory at the University of Houston we are focusing on developing methodology to use real-time MR imaging to guide a procedure. This work is based on the current state-of-the-art MR scanners that offer the unique capability to interface it with the robot control computational core [11, 13]. Capitalizing on this enabling technology, the control core of our robotic systems also controls the acquisition parameters. This approach offers real time assessment of the AoO with minimal on-line processing and without the need of modeling [24, 25]. Endowing that with on-the-fly adaptable oblique multislice MRI, we are able to visualize multiple sites of an anatomy as fast as MRI allows. To further enhance our armamentarium of MRI imaging methods to guide procedures, our second area of focus is on both the data collection side (i.e. ways to selectively acquire the raw MRI data) and the data processing side. Specifically, we explore the ability of MRI effectively manipulate contrast and selectively visualize fast curved and moving structures. Using optimized signal suppression methods [26] and selective raw data acquisition [27] we are developing methods for fast 3D visualization of curved tubular structures. This allows us to view interventional tools such as catheters, robotic arms, or endoscopes in 3D and as fast as 300 ms per second.

Table 1: From MRI guided interventions to robot assisted MR-guided interventions

MRI for guiding interventions and Surgeries
•Plethora of contrast mechanisms for anatomical and functional information •True 3D and multislice 2D •No Ionizing radiation
MRI guided Robot assisted Interventions and Surgeries
•Access to the patient inside the MRI scanner (esp. high field cylindrical scanners) •Real-time imaging for guidance & response to adjust the procedure •Generic robot features; e.g. accuracy, stability, tremor reduction etc

II. THE DEVELOPMENTAL PLATFORM

Motivated by the concept that MRI is an information system that can be the basis of an IGI/MIS system, we have implemented a prototype developmental platform MR-compatible manipulator system [12]. Figure 1 illustrates the architecture, the processes and the flow of information of this system. The three inte rrelated elements of sensing, control and perception are delineated with the boxes shaded in gray Viewing this as a whole, rather than as a robot, we have embarked on a systems approach to develop and investigate different enabling-technologies and approaches for performing robot-assisted interventions with MR guidance [11-17]. Progressively this system has been modified to develop and demonstrated different MR-based enabling technologies listed in Table 2. Figure 2 illustrates the architecture and the primary components of this system: an MR compatible robotic manipulator, its associated control hardware and software components, human-machine

This work was supported in part by NIHLB RO1HL067924 and NCI CA81817. The author is grateful to Prof. A. Ozcan (Washington University) and E. Christoforou (University of Cyprus) for their contributions.

N. V. Tsekos is with the Medical robotics Laboratory at the Department of Computer Science, 4800 Calhoun - 501 Phillip G. Hoffman, University of Houston, Houston, TX 77204-3010 ntsekos@cs.uh.edu.

978-1-4244-3296-7/09/$25.00 ©2009 IEEE

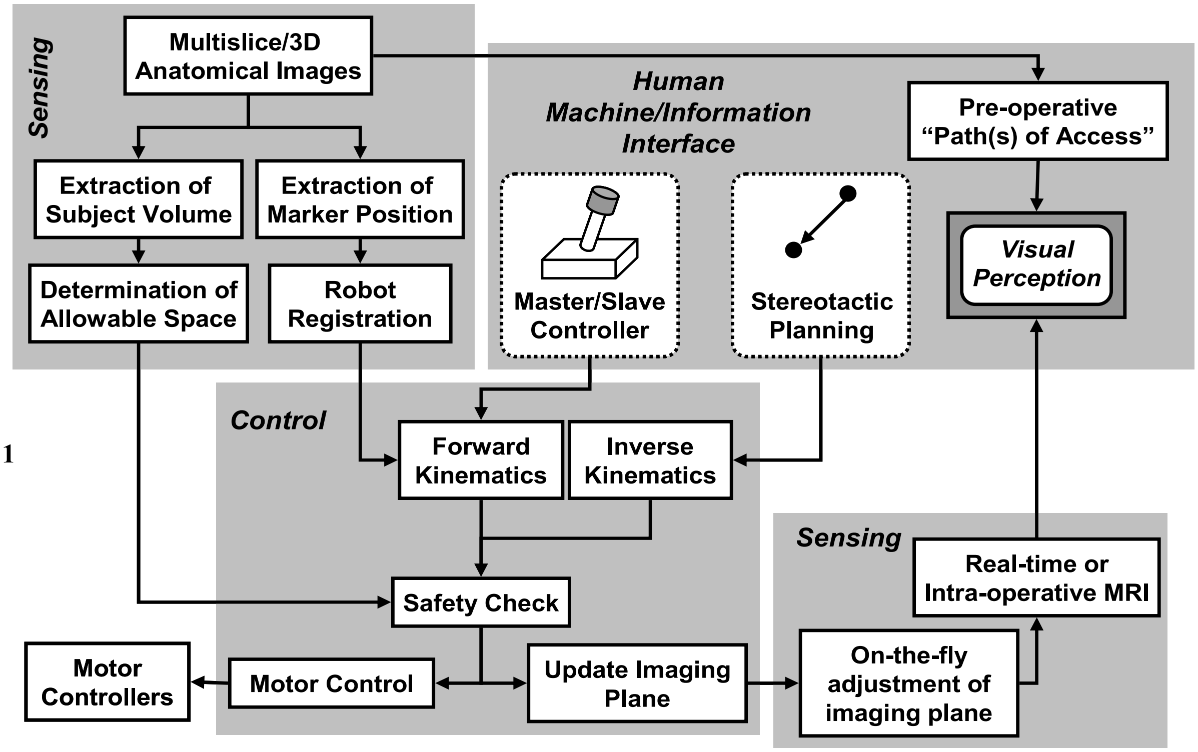

Figure 1

interfacing and an MRI scanner interconnected through a computational core component

III. IMAGE-GUIDED CONTROL

From multislice anatomical MR images, the software determines the "Allowable Space" inside the MR scanner for use by the Safety Check routine to ensure avoidance of collision of the robot on the subject. The robot has been registered relative to the coordinate system of the MR scanner using cross-shaped fiducial markers [12] The operator enters either stereotactic (Fig. 3A and 3B) or 'freehand" master/slave (Fig. 3C) controls. In the former case the inverse kinematics are solved to determine the appropriate set of DOF values as well as their compliance with the Safety routine. In the latter case, the forward kinematics are solved to determine the coordinates of the requested final position; this kinematic configuration of the robot is then tested for compliance with the safety routine. If the requested motion is within the allowable space, it is executed otherwise the motion is rejected. With the

Table 2: Certain methodological and technical features of MRI and their application in robot-assisted interventions

FEATURE	APPLICATION
Multi-contrast	Complementary pathophysiologic information for: -pre-operative path planning *and* -intra-operative monitoring (e.g. ablations)
Endogenous "absolute" coordinate system of the MR scanner	•Registration of the robotic manipulator •Forward kinematics calculations •Multi-contrast image co-registration •Stereotactic planning
Surface RF coils	High SNR for a specific volume of interest (example, the targeted area as in Fig. 5)
True 3D or multislice 2D *and* arbitrary definition of imaging planes/volumes	•Stereotactic planning based on 3D data •Automatic or semi-automatic determination of access corridors: (1) automatic alignment *OR* (2) image-based manual guidance
On-the-fly: adjustment of imaging planes and/or contrast mechanism	•Manipulator-driven control of planes to follow the end-effector •Freehand (manual) control of the robotic manipulator and automated forward-looking •Interactive on-the-fly adjustment of the acquisition strategy
Fast (sub-second) MR imaging	•On-the-fly adjustment of the procedure •Motion tracking for compensation
Miniature passive or active MR markers	•Visualization of tools in MR images •Initial registration of the robotic manipulator •MR-based calculation of spatial position for position validation and closed-loop control

freehand control method, the operator needs to manually adjust the robot.

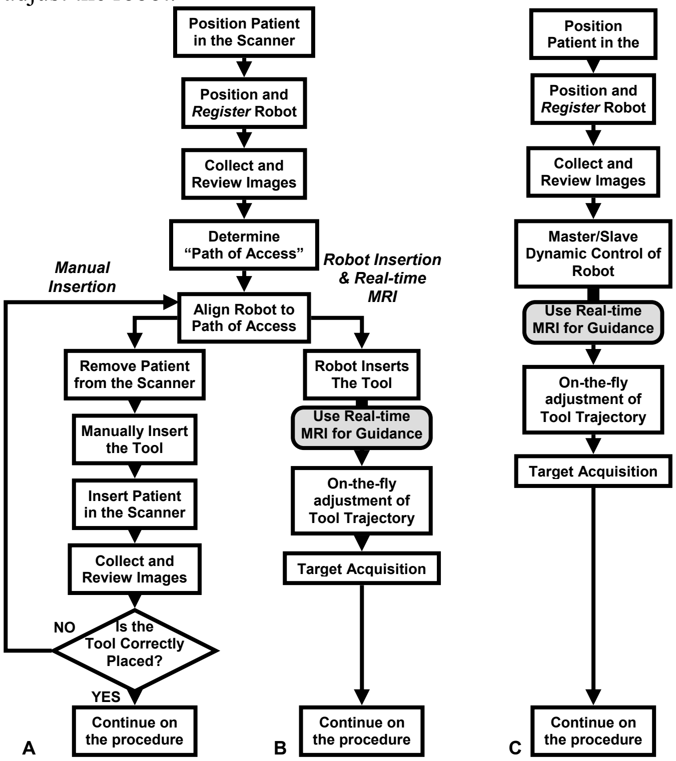

Figure 2: *Flowcharts of the steps and processes involved in the performance of stereotactic (A) and (B) and freehand (C) MR-guided procedures with the integrated robotic system described in fig. 5. Comparing the three strategies, the benefit of a robotic system with rela-time image guidance can be appreciated when comparing practice (A) with those depicted in (B) and (C). In (A), the robot aligns the interventional tool along the desired trajectory but the insertion is perfofmed manually after removing the patient form the scanner. This results to both increase of the duration of the procedure as well as the chance to miss the target due to tissue dislocation. In (B) and (C), the man-in-the-loop strategies allow the operator to directly alter the path of insertion using dynamic imaging (refer to Fig. 3)*

A. IMAGE Guided Stereotactic Control

Stereotactic guidance and (semi-) autonomous control of the robotic manipulator in one form or the other is used in the majority of the current MR compatible systems. Based on the 3D and multi-contrast nature of the MR modality, stereotactic control is an excellent demonstration of the power and benefits of combining MR guidance and robotic. The prototype system described herein offers the means to perform stereotactic guidance as described and demonstrated previously [12, 14, 15]. With this approach the operator inspects MR images to prescribe a path for the insertion of the interventional tool to a targeted tissue. It should be emphasized that with MRI collection of those images may occur while the patient and the robot are inside the MR scanner (i.e. just prior to the procedure). Since the robotic manipulator is registered to the MR scanner, and the patient does not change position (or transferred between the imaging and stereotactic suite), this eliminates the need to (re-) register the images and/or the patient to the stereotactic system. Using some type of graphical marking on the MR images, the operator defines the targeted tissue (e.g. a lesion) and a point of insertion on the external surface of the patient (i.e., on the skin). Due to the 3D nature of MRI and the capability to collect images with any oblique orientation, the two points can be selected to two different planes not even parallel to each other. The operator may also use images of different contrast to assess different anatomical and pathological features thereby defining the most appropriate approach to the targeted anatomy.

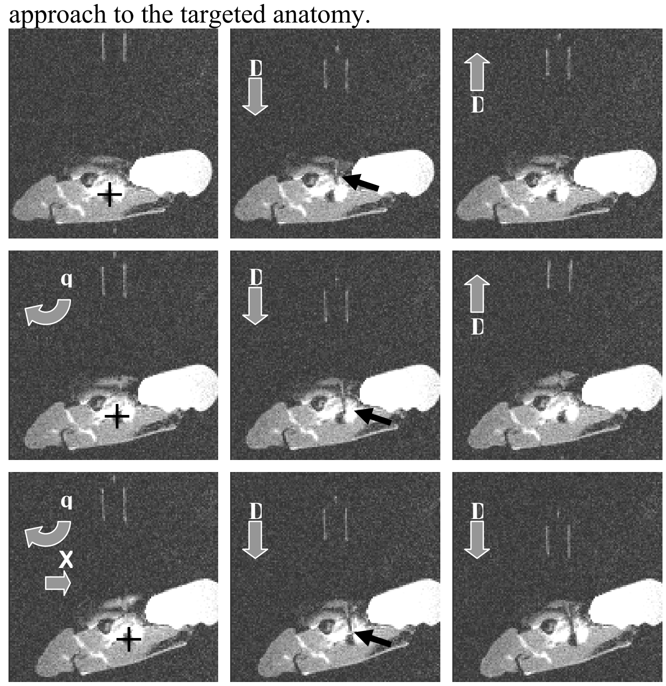

Figure 3: *Selected frames from a study using the freehand master/slave control method depicted in Fig. 2C with direct on-the-fly adjustment of the imaging plane to always include the end-effector (delineated by the two parallel Gd-filled tubes). In this study, the operator performed three consecutive insertions of an MR compatible needle toward a target (identified by the cross) to simulate on-th-fly adjustment of the needle trajectory to account for needle bending. This panel depicts nine out of over 300 hundred frames collected during the meneuvers. Adopted from [13]*

B. image-guided Freehand master Slave Control

Recent technological innovations available on the state-of-the-art MRI scanners offer some intriguing opportunities: performing procedures with the operator manually controlling on-the-fly both the robotic manipulator and the MR scanner in accord. Modern MRI scanner can offer this capability by means of interactively adjusting the imaging planes. Recently, Christoforou et al. demonstrated the integration of the prototype MR compatible robotic manipulator discussed herein with a commercial MRI scanner [13]. A dedicated component of the Control Core of the system calculates from the forward kinematics the transient position of the end-effector and sends them to the controller of the MR scanner which adjusts the position and orientation of the imaging plane to visualize the end-effector of the system. This mode allows the operator to maneuver the end-effector above the area of interest while scanning the anatomy. The ability for man-in-the-loop direct control of the interventional tool combined with the on-the-fly update of the imaging plane corroborate to a simple and intuitive image guidance in a way similar to this with ultrasound guided interventions image guided interventions or with endoscopy-based surgical robots. The manipulator-driven real-time imaging provides for scouting the subject, identifying a target and setting the path of the interventional tool to clear for obstacles and align it to the target. Man-in-the-loop image guided control may also provide the means of practice for compensation of needle bending, a major source of error observed in previous studies with MR compatible systems error [18, 19], since the operator can use dynamic imaging 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 straight-foreword way of directing the tool, while a simple software routine can place a line-of-sight on any frame without any special image processing.

IV. FUTURE PERSPECTIVE

The inherent to the modality unique properties and a wide range of enabling technologies, reviewed in tables 1 and 2, have advanced the field of MRI-guided robot assisted interventions. From the technological and methodological points of view, MRI is a very versatile and powerful imaging modality and, when combined with robotic manipulators may improve current practices and open new horizons in interventional medicine. Looking into the future we believe that of paramount importance is the effective integration of MR imaging with the operation and control of the manipulator in order to harness the capabilities of the modality in simple, intuitive and effective ways. One ex ample of such integration has been demonstrated by our group that implemented a manipulator-driven MR guidance ([13]; figs. 3 and 5). A similar concept has also been tested in accord with stereotactic guidance [14]. Those preliminary studies indicated that both methods are benefited from controlling the MR scanner from the control software of the manipulator taking advantage of the 3D and multislice capabilities of the modality. Current work focuses on incorporating pre-operative high resolution and high contrast images. However, it is the clinical merit of this exciting technology that is of paramount importance and will determine its future evolution and eventually fate [11].

REFERENCES

[1] N. V. Tsekos, A. Khanicheh, E. Christoforou, and C. Mavroidis, "Magnetic resonance-compatible robotic and mechatronics systems for image-guided interventions and rehabilitation: a review study," *Annu Rev Biomed Eng,* vol. 9, pp. 351-87, 2007.

[2] K. Masamune, E. Kobayashi, Y. Masutani, M. Suzuki, T. Dohi, H. Iseki, and K. Takakura, "Development of an MRI-compatible needle insertion manipulator for stereotactic neurosurgery," *J Image Guid Surg,* vol. 1, pp. 242-8, 1995.

[3] G. R. Sutherland, I. Latour, and A. D. Greer, "Integrating an image-guided robot with intraoperative MRI: a review of the design and construction of neuroArm," *IEEE Eng Med Biol Mag,* vol. 27, pp. 59-65, May-Jun 2008.

[4] W. A. Kaiser, H. Fischer, J. Vagner, and M. Selig, "Robotic system for biopsy and therapy of breast lesions in a high-field whole-body magnetic resonance tomography unit," *Invest Radiol,* vol. 35, pp. 513-9., 2000.

[5] B. T. Larson, A. G. Erdman, N. V. Tsekos, E. Yacoub, P. V. Tsekos, and I. G. Koutlas, "Design of an MRI-compatible robotic stereotactic device for minimally invasive interventions in the breast," *J Biomech Eng,* vol. 126, pp. 458-65, Aug 2004.

[6] Y. Koseki, T. Washio, K. Chinzei, and H. Iseki, "Endoscope Manipulator for trans-nasal neurosurgery, optimized for and compatible to vertical field open MRI," in *Medical Image Computing and Computer-Assisted Intervention*, Tokyo, Japan, 2002, pp. 114-121.

[7] R. C. Susil, A. Krieger, J. A. Derbyshire, A. Tanacs, L. L. Whitcomb, G. Fichtinger, and E. Atalar, "System for MR image-guided prostate interventions: canine study," *Radiology,* vol. 228, pp. 886-94, Sep 2003.

[8] A. Krieger, R. C. Susil, C. Menard, J. A. Coleman, G. Fichtinger, E. Atalar, and L. L. Whitcomb, "Design of a novel MRI compatible manipulator for image guided prostate interventions," *IEEE Trans Biomed Eng,* vol. 52, pp. 306-13, Feb 2005.

[9] E. Hempel, H. Fischer, L. Gumb, T. Hohn, H. Krause, U. Voges, H. Breitwieser, B. Gutmann, J. Durke, M. Bock, and A. Melzer, "An MRI-compatible surgical robot for precise radiological interventions," *Comput Aided Surg,* vol. 8, pp. 180-91, 2003.

[10] A. Melzer, B. Gutmann, T. Remmele, R. Wolf, A. Lukoscheck, M. Bock, H. Bardenheuer, and H. Fischer, "INNOMOTION for percutaneous image-guided interventions: principles and evaluation of this MR- and CT-compatible robotic system," *IEEE Eng Med Biol Mag,* vol. 27, pp. 66-73, May-Jun 2008.

[11] N. V. Tsekos, E. Christoforou, and A. Ozcan, "A general-purpose MR-compatible robotic system: implementation and image guidance for performing minimally invasive interventions," *IEEE Eng Med Biol Mag,* vol. 27, pp. 51-8, May-Jun 2008.

[12] N. V. Tsekos, A. Ozcan, and E. Christoforou, "A prototype manipulator for magnetic resonance-guided interventions inside standard cylindrical magnetic resonance imaging scanners," *J Biomech Eng,* vol. 127, pp. 972-80, Nov 2005.

[13] E. Christoforou, E. Akbudak, A. Ozcan, M. Karanikolas, and N. V. Tsekos, "Performance of interventions with manipulator-driven real-time MR guidance: implementation and initial in vitro tests," *Magn Reson Imaging,* vol. 25, pp. 69-77, Jan 2007.

[14] A. Ozcan and N. V. Tsekos, "The Interconnection of MRI Scanner and MR Compatible Robotic Device: Synergistic Graphical User Interface to Form a Mechatronic System," *IEEE/ASME Transactions on Mechatronics,* vol. 13, pp. 362-369, 2008.

[15] A. Ozcan, E. Christoforou, D. Brown, and N. Tsekos, "Fast and efficient radiological interventions via a graphical user interface commanded magnetic resonance compatible robotic device," *Conf Proc IEEE Eng Med Biol Soc,* vol. 1, pp. 1762-7, 2006.

[16] M. Karanikolas, E. Christoforou, E. Akbudak, P. E. Eisebeis, and N. V. Tsekos, "An Archetype for MRI guided Tele-interventions," *International Federation for Information Processing,* pp. 476-483, 2006.

[17] E. Christoforou and N. V. Tsekos, "Robotic manipulators with remotely-actuated joints: Implementation using drive shafts and u-joints," in *Proc. IEEE Int Conf on Robotics and Automation* Orlando, FL, 2006, pp. 2886-2871.

[18] R. C. Susil, K. Camphausen, P. Choyke, E. R. McVeigh, G. S. Gustafson, H. Ning, R. W. Miller, E. Atalar, C. N. Coleman, and C. Menard, "System for prostate brachytherapy and biopsy in a standard 1.5 T MRI scanner," *Magn Reson Med,* vol. 52, pp. 683-7, Sep 2004.

[19] S. O. Pfleiderer, J. R. Reichenbach, T. Azhari, C. Marx, A. Malich, A. Schneider, J. Vagner, H. Fischer, and W. A. Kaiser, "A manipulator system for 14-gauge large core breast biopsies inside a high-field whole-body MR scanner," *J Magn Reson Imaging,* vol. 17, pp. 493-8, Apr 2003.