Towards A New Cyber-Physical System for MRI-Guided and Robot-Assisted Cardiac Procedures

Erol Yeniaras, Johann Lamaury, Zhigang Deng, and Nikolaos V. Tsekos

Abstract—**Image-guided and robot-assisted minimally invasive surgical procedures are rapidly evolving due to their improved patient management and potential cost effectiveness. Currently, robot-assisted intracardiac surgeries on the beating heart are still in their infancy due to the challenges associated with the dynamic environment of operation. An approach to address those challenges is the use of Magnetic Resonance Imaging (MRI) for preoperative planning as well as for real-time intraoperative guidance. The objective of this paper is to propose a novel cyber-physical system for planning and performing robot-assisted MRI guided interventions in the beating heart with particular focus on aortic valve implantations. Our ongoing research focuses on developing a computational core for MRI-based preoperative planning and generation of dynamic robot maneuvering trajectories, real-time tissue tracking, and a novel MR-compatible robotic manipulator for transapical access to the beating heart.**

I. INTRODUCTION

Currently, we witness the rapid evolution of minimally invasive surgeries (MIS) and image guided interventions (IGI) due to their potential impact on the future of healthcare since they provide improved patient management and cost effectiveness. It is well recognized that such a paradigm shift would require robust, scalable and efficient computational methodology for integrating multimodal sensing (including imaging), controlled systems (including robots and smart actuators), the patient, and the interventionalist (e.g., surgeon, cardiologist etc.) [1-5]. In the present and future operating rooms, this multitude of components constitutes a complex and evolving cyber-physical system (CPS). Major efforts by pioneering groups in developing innovative computational methods, robotic manipulators and visio-haptic human-machine interfacing have paved the way toward the aforementioned quantum leap [1-5].

Among the sought directions in MIS is the incorporation of real-time image guidance (RTIG) that can provide volumetric and high-informational-content visualization of the Area of Operation (AoO) that includes: (1) assessing in real-time tissue deformation and motion, natural or secondary to the procedure, (2) monitoring the tool(s) in 3D, and (3) updating information about the pathophysiology of the targeted tissue. Effective implementation of RTIG's will facilitate a paradigm shift and methodological leap from "keyhole" visualization (i.e., endoscopic or laparoscopic) to a more global and informational rich perception of the AoO that can enable a wider range and levels of complex surgeries [1-5]. Along those lines, extensive work has been performed with several imaging modalities, such as ultrasound, computer tomography (CT) and MRI, for free-hand or robot-assisted IGI and MIS.

Motivated by the potential impact of RTIG in cardiac surgeries, we are developing a novel CPS (reviewed in Fig. 1) for performing MRI-guided and robot-assisted surgeries on the free-beating heart. To implement this CPS we are currently focusing on three areas: (1) the development of a computational core that processes raw MR data to generate a real-time dynamically updated model of the AoO, (2) generation of dynamic robot trajectories based on real-time tissue tracking from MR images, and (3) a novel MR compatible robotic manipulator.

II. MRI-GUIDED SURGICAL PROCEDURES

MRI was selected since it offers certain unique to the modality features (Table I) that include a plethora of soft tissue contrast mechanisms, true 3D imaging, no-ionizing radiation, and on-the-fly control of the imaging parameters. Endowed with an ever-growing number of innovative technological advances, MRI has emerged as a powerful modality for planning, guiding and monitoring interventions. To address the limited access to the patients inside high field cylindrical MRI scanners and to harvest the benefits of RTIG, robotic systems have been introduced for MR-guided

TABLE I
THE BENEFITS OF MRI GUIDANCE AND ROBOTIC MANIPULATORS

MRI for guiding interventions and Surgeries
• Wide range of morphological and functional soft-tissue contrast mechanisms • No Ionizing radiation (compared to x-ray-based modalities) • Operator-independent image quality (compared to ultrasound) • Standard and oblique 3D and multislice 2D imaging • On-the-fly computer-control of imaging parameters.
MRI based Robotic Manipulators
• Access to the patient inside the MRI scanner • Real-time imaging for guidance & response to adjust the procedure • Negotiation of complex static and moving anatomies • Co-registration and fusion of multimodal data at the data collection stage • Generic robot features; e.g., accuracy, stability, and tremor reduction.

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interventions, as reviewed in [6]. Examples of such anatomy-specific systems have been developed for neurological, breast and prostate procedures, as well as endoscopic manipulation. In addition, general purpose systems have also been developed for use with standard cylindrical MR scanners [6, 7].

Based on the concept that MRI is by itself an information system that can be the basis of an IGI/MIS system, we have implemented a novel prototype developmental platform as a major progression of an ongoing effort [8]. Fig. 1 illustrates the architecture, processes, and flow of information of this new system. The three interrelated elements of sensing, control, and perception are delineated with the boxes shaded in gray. Viewing this as a whole system, rather than as a mere robot, we have embarked on a systems approach to develop and investigate enabling-technologies for performing robot-assisted interventions with MR guidance [7, 9-12]. Progressively this system has been evolved to develop and demonstrate different MR-based enabling technologies listed in Table II. Fig. 1 also illustrates the primary components of this system: an MR compatible robotic manipulator, its associated control hardware and software components, human-machine interfacing [13], and an MRI scanner interconnected through the computational core component.

III. MRI-GUIDED CONTROL

Intracardiac procedures on the beating heart are among the procedures that may benefit from MR guidance and are of particular interest due to the potential reduction of side effects associated with cardiopulmonary bypass, the option for assessing the results of the procedure at the natural beating condition of the heart, and the general benefits associated with faster patient recovery [14]. However, cardiac motion introduces a major challenge associated with the safe maneuvering of the interventional tools. Currently, 3D ultrasound imaging is the most commonly used modality due to its real-time volumetric data collection, especially when robotic systems are used to synchronize the motion of a device with that of the heart, and lack of ionizing radiation. MRI can be a possible solution to address the limitations of ultrasound, as well as to offer the aforediscussed inherent to the modality capabilities for improved assessment of tissue pathophysiology *in situ*. The efficacy of MRI guided intracardiac procedures has been demonstrated recently [15, 16]. In this work we investigate the preliminary results from an early-stage prototype CPS that is based on a computational core composed of dedicated software modules, which run on a general purpose GPU (NVIDIA® Tesla™ C1060; 240 Streaming Processor Cores; and total dedicated memory of 4 GDDR3), for MR-guided intracardiac procedures via transapical access on the beating heart (Fig. 2A).

TABLE II
NEEDS AND MRI METHODS FOR ADDRESSING THEM

Needs	Corresponding MRI methodology
Pre-, intra-, post-operative assessment	Plethora of soft-tissue contrast mechanisms (with or without contrast agents)
Tracking of the surgical (manual or robotic) tools	• Miniature passive or active MR markers • MR protocols that track the markers in 3D • Use of the endogenous "absolute" coordinate system of the MR scanner • Co-registering everything without need for computational fuse tools and modalities
Tracking of anatomical landmarks	• Multislice and intraoblique imaging • High contrast for tracking algorithms
On-the-fly adjustment of imaging	Interactive adjustment of the acquisition strategy as needed during the procedure

The system has a dedicated visualization environment and associated computational modules that process raw MR data (offline or online connected to the MR scanner) to generate and update an augmented reality environment of the AoO (Figs. 1, 2B, and 2C). This environment is based on a 3D space that can include any combinations of the different aspects of a procedure (shown in Figs. 2B, 2C): MR images, the segmented endocardium, guiding points, access corridors, and a virtual robot. The AoO is built relative to the coordinate system of the MR scanner, thereby offering a realistic representation of the 3D geometric structures.

Figs. 2B and 2C show the output of the preoperative planning module from sets of CINE MR Images collected from a healthy volunteer. In the approach discussed herein, we make a fundamental assumption: the component of the robot that enters the left ventricle (LV) via the transapical access is kinematically independent from the component associated with the entrance port. This is the case if we want to perform a procedure in a true free-beating heart. Fig. 2A illustrates the local topography of the area of interest and indicates a potential trajectory of access (dotted black line):

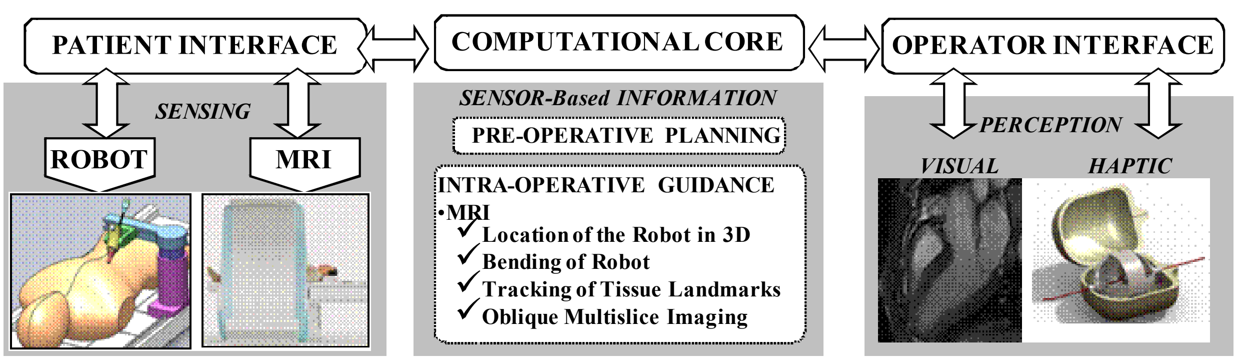

Fig. 1. The architecture of the prototype Cyber-Physical System developed for MRI-guided robot assisted surgeries in the beating heart.

after the robotic manipulator enters through the apex, it must deploy toward the base of heart, where it should steer (at the "steering point") toward the center of the entrance of the aortic annulus. It should be pointed that during its deployment inside the free-beating heart from the apex to the aortic annulus, the manipulator must maneuver within a globally and locally continuously changing environment.

For a manipulator to follow such a trajectory, the transient coordinates of the aforediscussed three points of interest are needed; the apex, the steering point, and the entrance of the aortic annulus. From those coordinates the control module of the computational core can calculate the appropriate commands needed to drive the actuators of the robot in order to deploy [12], as well as to hold its position at a certain coordinate (thus compensating for the tissue motion). MRI offers appropriate methods (reviewed in Table II) that are used for the determination of the coordinates of those points. An important feature of MRI pertinent to robotic control is that MR spatially-encoded information (e.g., a point in an image) are all measured (i.e., they are known) relative to an absolute coordinate system, that of the MR scanner.

Assuming that the base of the intracardiac unit is anchored on the apex, then it will follow the apical motion through the heart cycle. The motion of this point can be measured in real-time using miniature RF coil beacons attached to the apical base of the robot, as for example is done with tracking catheters with MRI [17]. In the studies shown in Fig. 2B and Fig. 2C, the coordinates of the apical point for any given time frame were determined from CINE MR Images (like the one shown in Fig. 2A). In an *in vivo* operation, to address the inappropriate long duration of a complete CINE set for real-time imaging, either a single or a limited number of intraoblique slices can be used for fast imaging of the areas of interest. The coordinates of the targeted point (i.e., the aortic annulus in this paradigm) can be extracted from a single or a limited-number of slices with the fast tissue tracking algorithm we developed for this CPS[18]. This specific module of our CPS has demonstrated the ability to track specific anatomical landmarks with average speeds of 25 fps from MR images. The coordinates of the targeted point were determined from the segmentation of long and short axis views that include the aortic valve annulus, as the point of the aortic annulus midline at the level of the aortic valve leaflets. The steering point for any time frame was then assigned as the intersection of the aortic annulus midline (known from the previous step) with the access corridor and the first-to-cross short axis slice.

Using this computational core and its augmented reality interface, we have simulated and analyzed numerous scenarios of transapical procedures extracting dynamic trajectories [8] and investigating the relative motion of tissue with tracking[18]. Based on this analysis we have completed the virtual prototyping (on Solidworks®) and the kinematic and dynamic analysis (on Simulink and SimMechanics®) of a novel MR compatible robotic device shown in Fig. 3 for transapical interventions on the beating heart.

Compared to previous works in this area, the proposed CPS introduces certain innovations with primary one being the integration of the imaging scanner and the robot into a system, thereby allowing on-the-fly control of both the scanner and the robot. In turn this allows that the same control algorithm controls the sensor (to receive exactly information it needs for its processing) and the manipulator (based on those information). The specific robotic device (Fig. 3) we develop will allow access to the beating heart without restricting its motion as previous systems [15], while alleviates the limitations of manual manipulations [16].

IV. FUTURE WORK AND PERSPECTIVES

Currently, our effort is focused on: (1) completing the construction and bench-top testing of the robotic device shown in Fig. 3, and (2) the interfacing the computational core (Fig. 1) to an MR scanner (Siemens 1.5T Espree) for on-the-fly transfer of raw MR data for processing and for updating the imaging parameters from the core.

The versatility of MRI, due to both its inherent properties and its programmability (reviewed in Tables I and II) makes this modality a strong candidate for preoperative planning and intraoperative guidance of minimally invasive cardiac surgeries. From the engineering perspective, there is an ever-growing body of enabling technologies that underscores that the modality can practically address current and future needs

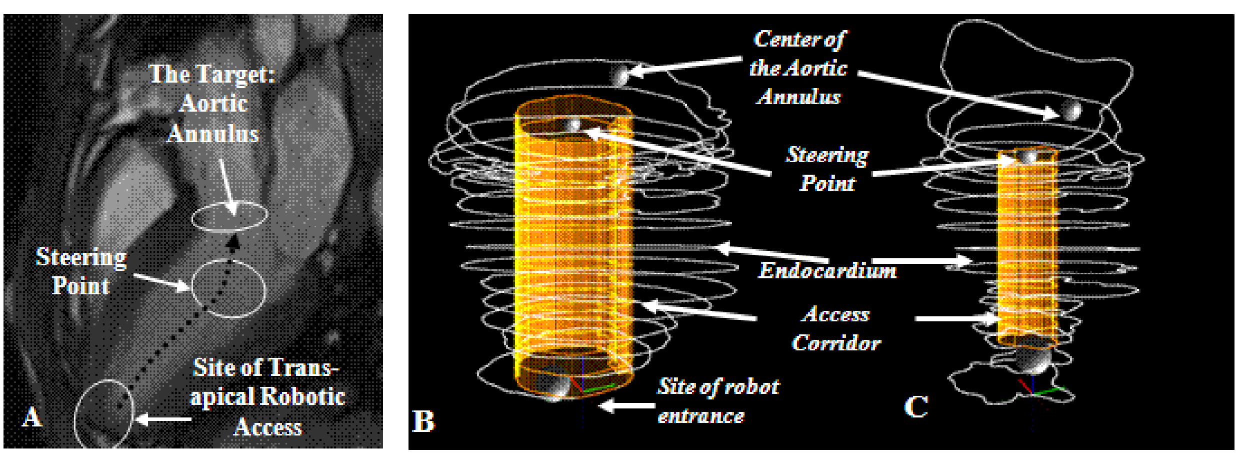

Fig. 2. (A) A long axis view of the heart illustrating the Area of Operation in the case of access to the aortic annulus via a transapical entrance through the LV. (B) and (C) results from the preoperative planning and robot control modules of the computational core showing the extracted endocardium boundaries of all short axis slices and the common *LV access corridor* of end-diastolic (B) and end-systolic (C) phases.

in this field. MRI may eventually facilitate the means for achieving a quantum leap from the “keyhole” visualization with endoscopy to high quality volumetric or 3D assessment of the area of interest. Looking into the future of image-guided surgeries, the maneuverability of current devices is inadequate and limited. This becomes apparent when it is needed to maneuver inside complex and dynamically changing access corridors, e.g., in the beating heart or the abdomen. Such paradigms dictate the need for new robotic manipulators and often the evaluation of unconventional approaches.

What will determine the fate of those innovations, including MR-guidance with or without robotic manipulators, are not achievements in engineering but their merit as bread-and-butter clinical tools. Among the numerous non-technology-related factors that should be considered, two primary questions should be addressed at every step of this endeavor: “do we really need this?” and “what is the final cost of this?” In regard to the first question, the benefits should be considered as compared to both current practices and to the capabilities of the approach to facilitate new procedures, which otherwise may not be possible. Substantial benefits exist by transitioning from laparoscopic visualization to an MR-guided robot-assisted one. Another critical factor of paramount importance is the identification of “killer applications” and the performance of large number of clinical trials. The cost factor is as important as this of clinical merit; especially in an era of limited financial resources. At the level of the provider, there are several interrelated factors, for example: capital cost and maintenance of equipment, training of personnel, and consumables. This investment should be viewed, however, within the context of two powerful factors: mechanisms of reimbursement and overall cost to the system or the society in general. Based on aforediscussed aspects, we conclude that the future research directives in MR-guided robot-assisted surgeries should focus on:

- Real-data based perception of the AoO (eliminating any model and prediction-based information),
- Seamless integration of the robot, the MR scanner, the patient, and the operator into a CPS to better assess the AoO and the ever-changing needs of the procedure, and
- Simple and intuitive perception of the information needed and avoidance of directing a cascade of data to the operator that leads to an increased work-load.

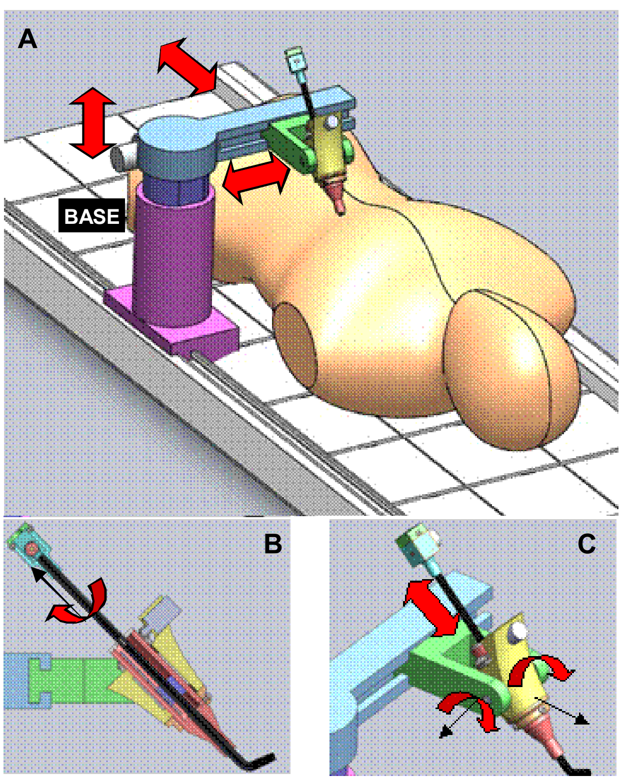

Fig. 3. The model of the MR-compatible robotic manipulator that is currently constructed in our laboratory for performing MRI-guided transapical procedures in the beating heart. The manipulator consists of two units. The external or “Thoracic Unit” facilitates access from the thorax to the apex of the heart and carries (B) and provides actuation to the Intracardiac Unit (C). The base structure (Base) in (A), is only used for dynamic simulations of the model and in the final system will be compacted for fitting into a 70 cm wide MR gantry.

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