Prototype system for developing MRI-guided and robot assisted minimally invasive intracardiac procedures
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Purpose
The goal of this work is to develop different hardware and software elements pertinent to magnetic resonance imaging (MRI) guided and robot-assisted intracardiac procedures, and integrate them into a modular platform suitable for further development and testing in the laboratory and at the MR suite. This prototype system, which has been partly inspired by our previous conceptual design [1], includes appropriate tools and dedicated software modules that operate synergistically for planning an operation, controlling a semi-autonomous robot based on MRI data and adjusting on-the-fly the image acquisition parameters of the scanner to better suit the particular conditions of the intervention as it evolves. Moreover, the practicality of a specific actuated heart phantom is also investigated in this work for future in vitro experiments.

Methods
The system consists of three major components: (1) a computational core, (2) a 7-degrees-of-freedom (7-DOF) robotic manipulator, and (3) an 18-DOF MR-compatible actuated heart phantom. Fig. 1 depicts the main architecture and the data flow within the system. Computational core, which is connected to both “MR Scanner” and “Data Server” for image acquisition via TCP/IP protocol, has dedicated modules not only for MRI based guidance but also for controlling actuated devices within the system. The visual information about the area of operation (AoP) is also provided to human-machine-information-interface (HIMI) by computational core [2].

The robotic manipulator was specifically designed for intracardiac procedures and has two parts: a 5-DOF extrathoracic unit (ExtraU) that resides outside the patient to provide access to the apex through an intracostally placed port and a 2-DOF intracardiac unit (IntraU) that maneuvers inside the beating heart toward the operational target point. ExtraU actively compensates heart motion and provides actuation to the IntraU [3].

The functionality of the prototype system was first tested virtually for transapical aortic valve replacement (AVR) in beating heart [4]. Cine MRI datasets (with true fast imaging, steady state precession pulse sequence) were used for surgical planning, while on-the-fly guidance was performed with real-time MR slices with repetition time of 48.4ms collected from healthy subjects (n=10). Computational core generated dynamic trajectories from the apex to the aortic annulus for simulating a prosthetic valve deployment with transapical approach.

For performing in vitro experiments, the system incorporates an MR-compatible, computer controlled and actuated phantom that mimics the motion and dimensions of certain anatomical landmarks in human heart [5]. The structure and kinematics of this phantom replicates the motion of the trocar/apex, access tube and aortic annulus, since through those structures the manipulator should maneuver in a transapical AVR. With 18 DOFs the cardiac phantom continuously positions three tubular structures (each representing one of the above listed anatomical landmarks). The current version of the phantom has an access tube with a diameter of 9mm, while the diameters of the aorta and the trocar are 23mm and 12mm severally.

Results
Our image guidance methodology showed that a cylindrical access tube can be defined inside the left ventricle for safe deployment of a catheter-like device. For 10 subjects, the average base diameter of this virtual tube was 9mm in systole and 22mm in diastole respectively. Transapical AVR was successfully simulated for several different combinations of initial
heart phases when deployment starts, robot actuation speeds and device dimensions. It was also shown that it was possible to design an MR-compatible robotic manipulator and a dynamic heart phantom for simulating the semi-autonomous deployment in the beating heart.

**Conclusion**

Recent studies presented herein illustrate the practicality of integrating appropriate computational tools to facilitate the MRI-based volumetric (3D) image guidance. Although it was designed for in vitro experiments, the phantom could be used also for extensive studies of developing imaging methods, robotic manipulators, and methods for practicing as well as for training. Aside from being a part of an ongoing study of developing a complete image-guided intracardiac surgical system, the main motivation for the implementation of such a device originates from the certain benefits to clinicians involved in the development of MR-guided robotic surgeries. We envision that the system will be applicable for in vivo testing upon its completion, allowing us to expand the approach to other sophisticated surgeries.

**References**


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**Fig. 1.** The core architecture of the prototype system with data flow is depicted.