A Robotic Catheter System for MRI-guided Cardiac Electrophysiological Intervention

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***Abstract*— Magnetic resonance imaging (MRI) techniques allow intra-operative monitoring of the ablation procedure during cardiovascular electrophysiology (EP). However, currently it is still challenging to carry out effective catheterization under MRI environment. In this paper, we present an MRI-conditional robotic system that can integrate intra-operative MRI techniques, real-time visual and position feedback and effective control interface for catheter manipulation. Experimental results verified the MRI-compatibility and the enhancement of manipulation.**

***Index Terms*— Cardiac Electrophysiology, MR-safe Robot, Robot-assisted Intervention, MR-safe Actuation.**

I. Introduction

Cardiac electrophysiology (EP) intervention is an effective treatment for heart rhythm disorders [1]. In EP procedures, a long catheter (> 1m) is delivered to the heart chamber, mostly from the femoral vein; Radiofrequency ablation (RFA) is performed on lesion tissue to isolate the abnormal electrophysiological signals. The safety and efficacy of the EP procedure depend mainly on: 1) the effectiveness of maneuvering cardiac catheters to the target tissues for both electro-anatomic mapping (EAM) and RFA, and 2) the ability to intra-operatively assess lesions and their location and ablation progress.

Intra-operative (intra-op) magnetic resonance imaging (MRI) can improve soft-tissue visualization during catheter manipulation, thus reducing complications [2]. T2-weighted MRI [3] can readily visualize the physiological change of tissues, and identify the scar or edema arising from successful or incomplete RF ablation. This allows electrophysiologists to promptly determine whether the treatment of particular lesions is complete or requires further ablation. Although even such intra-op MRI techniques are advantageous to the catheter navigation, the manipulation of the catheter tip to the desired location remains challenging. This is because the control of a thin, long and flexible EP catheter would be inconsistent especially within rapidly deforming cardiovascular tissue, such as the left atrium (LA). The challenges have drawn attention to the development of tele-operated robotic platforms, such as the Sensei® Robotic System for dexterous and accurate catheter manipulation for intracardiac EP intervention [4]. Provided with high-quality intra-op MR images to assist cardiac navigation, robotic catheterization can hence improve the safety and effectiveness of EP catheterization [2].

However, there is still not existing commercial or research prototype of a robotic catheterization platform for intra-cardiac EP intervention that is MR-compatible. For example, the catheter navigation system driven by non-ferromagnetic ultrasonic motors proposed in [5], could only provide two degree-of-freedoms (DoFs) of catheter manipulation. Similar to piezoelectric motors, these motors are driven by electric current and usually placed close to the MRI scanner. As a result, both the driving and encoding signals would induce electromagnetic (EM) noise to MRI, thereby deteriorating the image quality; This requires a complex EM-shielded enclosure to surround all sides of the motor drivers to minimize the EM interference [6]. Therefore, the research focuses have naturally shifted towards intrinsically MR-conditional actuators driven by other energy sources, such as pressured fluid, instead of EM power [7].

In this paper, we present an MR-conditional catheter robotic system integrates an MR-safe robot and corresponding techniques to enable MRI-guided cardiac electrophysiological intervention, such as intra-operative image processing, real-time positional tracking of the catheter in MRI and human-robot control interface. The robot is driven by hydraulic actuators for effective EP catheterization (**Fig. 1**). The system features a master-slave hydraulic actuation system that has small hysteresis, enabling precise manipulation of standard EP catheter in clinical use. The slave part of the robot is made of MR-safe materials, therefore can operate close to or even inside the MRI scanner without adversely affecting the MR image quality.

II. Catheter Robot Platform

A. Robot Design

The catheter robot consists of two parts — the master and slave actuation systems which are placed respectively in the control room and on the patient table of MRI scanner in the MRI room (**Fig. 1**). The robot has in total 4 DoFs, providing bending of the catheter in two directions of ± 90°, rotating from 0° to 720°, inserting finely in 30mm and coarsely in 200mm. These two insertion motions, namely coarse and fine insertions, are actuated by two independent actuation units along the same translational axis. Such design enables both the longer journey navigation from vessels to the heart chambers and the shorter

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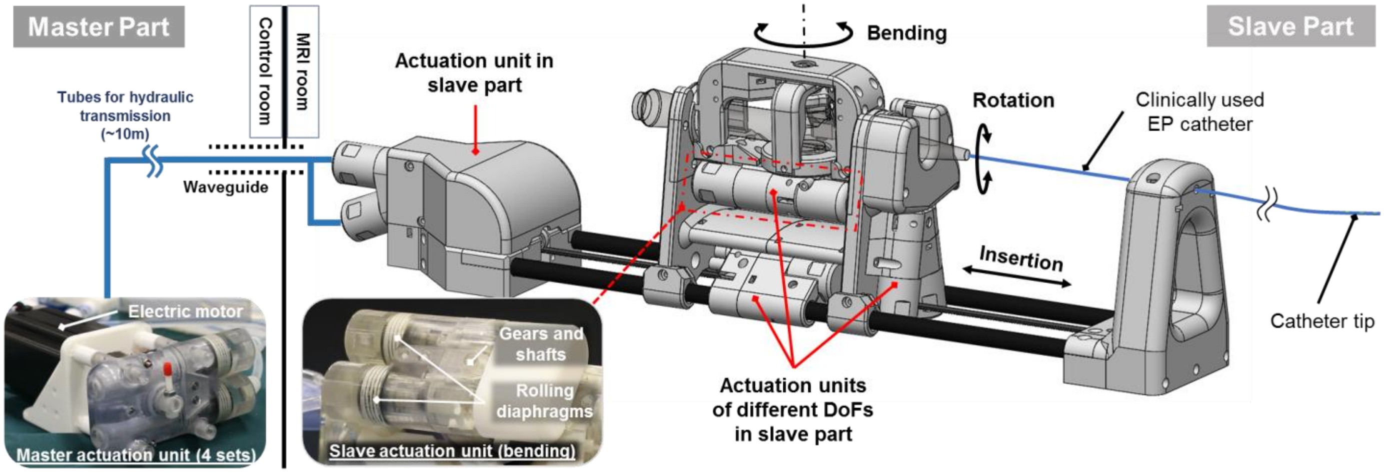

Fig. 1. The catheter robot platform with a clinically used catheter for EP ablation installed. Master actuation units in control room drive the slave units in pair, both of which contain rolling diaphragms for effective mechanical power transmission, providing rotation, bending, coarse and fine insertion of the catheter.

range of dexterous tip movement inside the heart chambers for EAM and delicate RF ablation.

Four pairs of hydraulic master-slave actuation units are adopted and each connected by 2 pipelines (**Fig. 1** and **Fig. 2)**. The master system is actuated by individual electric motors which operate in the control room. The motors actively drive the slave system and consequently the catheter, via hydraulic transmission along pipelines (≈10 meters) through a waveguide in-between the control and MRI rooms. The pipelines are filled with pressurized liquids (water) to ensure responsive synchronization between the master and slave motions.

To enhance power transmission efficiency, rolling diaphragms (MCS2018M, FEFA Inc.) are employed for sealing the two ends of pipelines as well as transmitting motion to pistons (**Fig. 2**). Compared to the traditional O-ring sealing, they can provide sealing with negligible friction during operation by reducing sliding between the seals and the inner wall of the cylinder.

Generally, the hysteresis of the actuation system will lead to a significant influence on the robot performance. For the proposed robot, it may be introduced by the backlash of the gears in actuation units as well as the compressibility of the transmission fluid. To minimize the hysteresis, we increase pressure in the pipelines before operating the robot. The high-pressure fluid will push the piston of cylinders against the gears at both master and slave side of the actuation unit, keeping a close contact of the tooth to reduce backlash (**Fig. 2**). In addition, the pressure in the pipeline will also increase the stiffness of the fluid, which will contribute to the decrease of hysteresis.

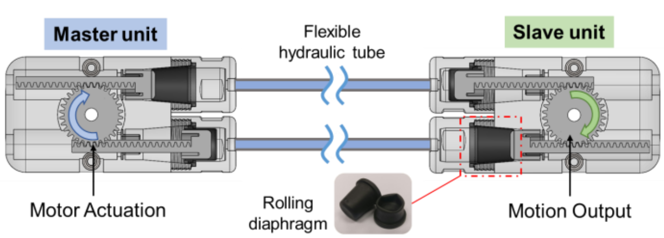

Fig. 2. The conceptual design of master-slave hydraulic transmission that ensures MRI-compatibility of robot actuation. Rolling-diaphragms can seal the fluid in pipes tightly with low friction.

The slave part of the robot is made of only MR-safe and non-ferromagnetic materials, in order to minimize the interference to the MR images. The main structural components are 3D-printed with nonmetallic materials (VeroWhitePlus/VeroClear, Stratasys, USA). Key components for mechanical motion transmission, such as gears, are made of nylon. In addition, some other materials are included in the robot as well, such as PolyVinyl Chloride (PVC), Polyetherimide (PET) and rubber.

The slave system is designed to be mechanically compatible with different types of clinically used catheters. An EP ablation catheter can be plugged-in easily and tightly incorporated with the catheter holder (**Fig. 1**), which can be tailor-made for bi-directional and steerable EP catheters (e.g. Biosense Webster Inc. and St. Jude Medical).

B. Experimental Results

An MRI-compatibility test was conducted to evaluate the EM interference to the MR images during operation. The master

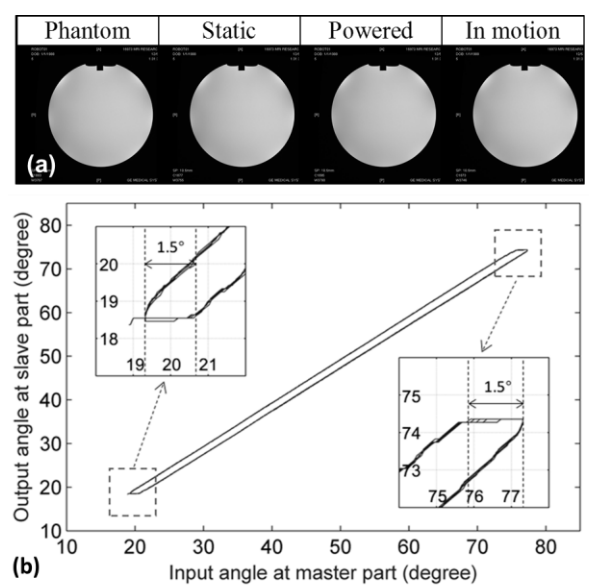

Fig. 3. **(a)** Resultant MR images of the phantom under four different robot operation conditions; **(b)** Hydraulic transmission performance validated based on the angle response and corresponding hysteresis loops. Small hysteresis of approximately 1.5° was observed in 10 cycles of repeatable clockwise and counter-clockwise motion of the bending DoF.

system of the robot was operated inside a 1.5T MRI scanner (SIGNA, General Electric Company, USA) and was placed near a commercial MRI phantom (J8931, J.M. Specialty Parts, USA) at the isocenter of the scanner. **Fig. 3a** shows the resultant MR images of the phantom under four different conditions: i) Phantom: only phantom placed in the scanner; ii) Static: robot involved and remained power OFF; iii) Powered: robot kept still, but with the hydraulic and electric power ON; iv) In motion: robot in operation. This SNR analysis followed the standard evaluation of general MR-conditional devices. The first condition served as the baseline for evaluation. No observable artifact was found in the MR images under the different robot operation scenarios. The maximum SNR loss in the successive conditions was found within 2% only.

Hysteresis is the primary concern for robotic intra-cardiac catheterization that requires responsive manipulation of the catheter. The hysteresis of the pair of master-slave actuation units is measured and shown in **Fig. 3b**. During the experiment, the hydraulic pipelines were filled with distilled water of 2 bar pressure without visible air bubbles. The master actuation unit was actuated by an electric motor (HFmotor-40150, Chengdu Hangfa Hydraulic Engineering Co., Ltd) at a frequency of 0.1 Hz with a peak-to-peak amplitude of approximately 60°. This slow and steady actuation could avoid damping effect of the transmission media. The result of 10-cycle movements in **Fig. 3b** indicates that the bending actuation was highly repeatable with small hysteresis of about 1.5°.

III. Enabling Techniques for MRI-guided Robot-Assisted Catheterization

Apart from the MR-safe robot we presented, several components need to be involved to achieve MRI-guided cardiac catheterization, including intra-operative image processing, real-time positional tracking of catheter in MRI (**Fig. 4**). These essential techniques should be integrated with the human-robot control interface illustrated in **Fig. 5**.

A. Intra-operative Image Processing

Advances of MRI create a new realm of intra-operative (intra-op) guidance for intervention. Post- or pre-ablation lesions/landmarks can be visualized and selected on T2-weighed intra-op images (**Fig. 4**), which will have to be instantly aligned on the EP roadmap showing the EAM data. Such a roadmap acts as a fundamental visual reference, on which the electrophysiologist primarily relies during the EP procedures. However, the intra-op MR images are mostly obtained at different cardiac cycle with respect to the pre-operative (pre-op) images that construct the EP roadmap. Non-rigid image registration is the prerequisite technique used to reduce the misalignment of the selected landmarks from the roadmap in 3D (**Fig. 5**). Moreover, ECG-gated contact points collected during the EAM will have to be promptly co-registered to the roadmap based on the cardiac morphology. Overall, fast and continuous co-registration between the pre- and intra-op images could significantly smoothen the repeated workflow of RF ablation planning and catheterization. It also allows one to readily identify the locations of the next point collection regions, as well as the arrhythmia origins.

B. Real-time Positional Tracking of Catheter in MRI

Online update of catheter tip position in 3D is essential in many cardiac interventions. Not only does it act as the feedback data to close the loop of robot control, but it also allows the operator to visualize the catheter configuration with respect to the cardiovascular roadmap constructed by the MR images.

Two micro RF coils are incorporated into a clinically-use cardiac catheter (**Fig. 5)**, which can directly signal with the scanner via two pairs of coaxial cables connected to a custom-built receiver interface. A dedicated MR tracking sequence could be applied to acquire the MR signals from the micro coils along the XYZ directions of the magnetic field gradient. To correct the inhomogeneities of the static magnetic field, both zero-phase-reference and Hadamard multiplexing methods could be employed. Such an MR sequence is able to achieve a spatial resolution up to 0.6×0.6×0.6 mm^3, and a sampling rate

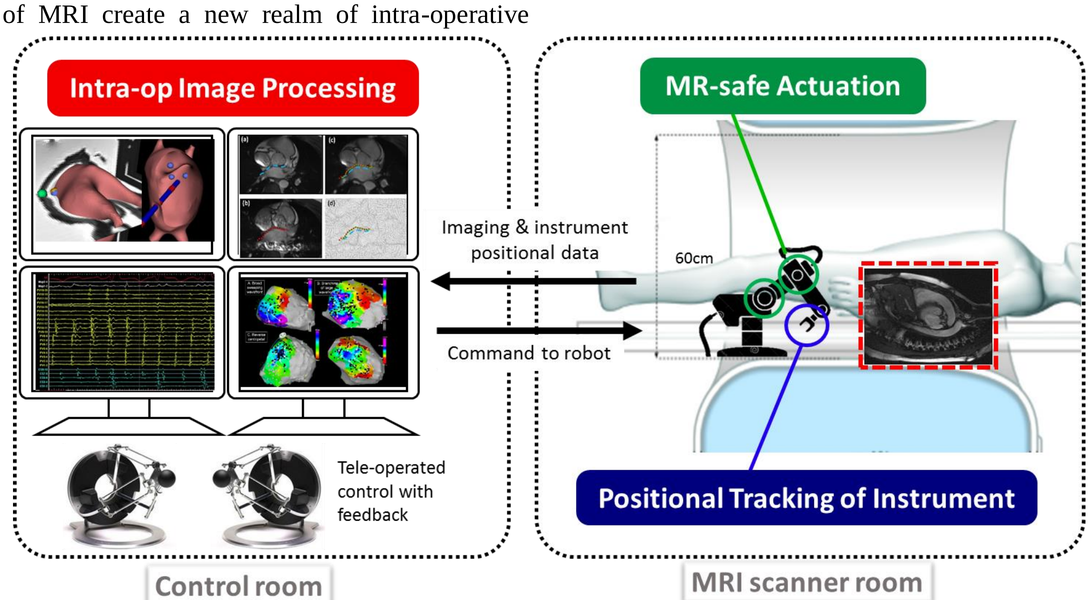

Fig. 4. Integrated robotic system showing the basic components located separately in the MRI scanner and control room.

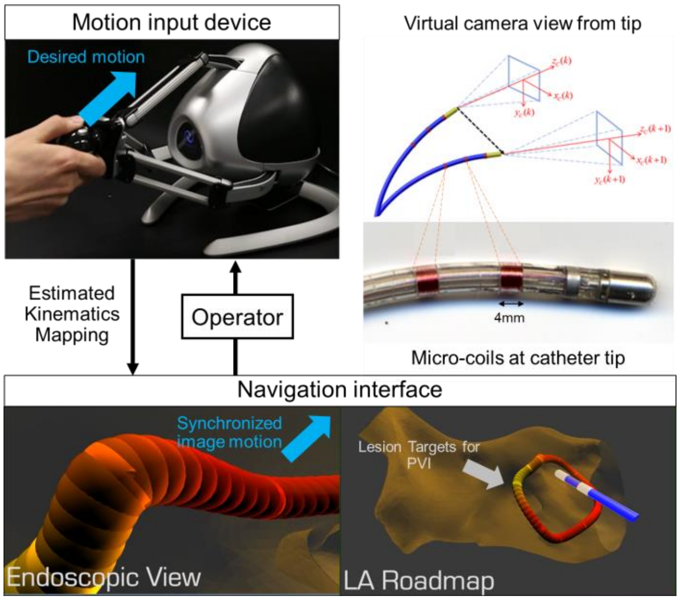

Fig. 5. Human-robot control interface for effective and precise catheterization. Cardiac roadmap is indicated with circular lesion target in red. The virtual camera is augmented from the catheter tip's point of view.

of up to 40 Hz.

Such frequent and accurate localization of the micro coils catheter tip enables the estimation of both 3D position and orientation of the catheter tip. In this way, the entire catheter localization takes place with the MR imaging coordinate system. Therefore, it does not require any external tracking reference, thereby avoiding potential disparity caused by relative registrations between tracking and imaging system. As a result, the tracked catheter tip position shares the same coordinate space with the MR images, facilitating precise placement of catheter tip at the ablation target registered on the roadmap.

C. Human-robot Control Interface

We developed a control interface capable of providing effective tele-operated control of a clinically-used catheter. The MR-tracking can be applied in conjunction with the intra-op imaging such that the tracking is interleaved with the MR image sequence. These MR-based tracking data can be continuously streamed into the EP navigation system and the robot control interface.

The reference point-of-view at the catheter tip is simulated and provided. It gives the operator a consistent motion reference to maneuver the catheter tip aiming at the desired target in unknown or unstructured constrained environment, like inside the cardiovascular tissues. As shown in **Fig. 5**, a virtual camera view is defined and attached at the catheter tip. This could provide the operator with an intuitive visual coordination of catheter, aiming at the lesion targets, rather than just referring to the fixed point of view.

Note that the entire MR-based catheter tracking takes place in the same MR imaging coordinate system. Unlike conventional EP, our MR-based approach does not require external tracking reference, thereby avoiding potential disparity caused by relative registrations between tracking and imaging system. This enables virtual endoscopic view from the viewpoint of the catheter tip. Such virtual view would facilitate fine placement of the catheter tip while approaching the ablation targets registered on the roadmap (**Fig. 5**).

IV. CONCLUSIONS

Currently, there is no such commercialized robotic system that is MR-compatible. We presented a robotic catheter system that is the first of its kinds to be incorporated with intra-op MRI, real-time positional tracking, human-robot interface, and high-performance actuation. The robot is driven by a master-slave hydraulic actuation system that features with small hysteresis, enabling precise manipulation of standard EP catheter. The slave part is capable of operating close to or even inside the MRI scanner without deteriorating the intra-op imaging quality. This may serve as a benchmark for the design and integration of MR-conditional robotic devices in MR image processing, robot actuation and catheter tracking under MRI.

Realization of MRI-guided cardiac EP intervention requires not only MR-conditional robotic platform, but also other key components such as accurate positional sensing of catheter and intra-operative image processing techniques. We developed a control interface that could integrate advance MR-based catheter tracking and fast image registration techniques, where the catheter tracking was interleaved with the intra-op imaging. This catheter tracking shared the same coordinate system with the MR images, avoiding disparity due to relative registrations between tracking and the imaging systems. This enables construction of virtual endoscopic scene from the viewpoint of the catheter tip, facilitating precise tele-manipulation of the tip towards the ablation targets registered on the cardiac roadmap (**Fig. 5**). Thus, electrophysiologists could have better performance when conducting RF ablations, consequently improving the safety of catheter navigation during the EP procedure.

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