Continuous Hydraulic Actuation for MRI-guided Robotic Catheterization: Design, Evaluation and Application

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***Abstract*—Magnetic resonance imaging (MRI) can provide images with superior soft tissue contrast, fulfilling the demand for precise tele-manipulation of interventional instruments. However, there is still lack of choices of magnetic resonance (MR) safe actuators that can enable high-torque, precise and continuous actuation of robot. In this paper, we present a hydraulic actuation method using rolling-diaphragm-sealed cylinders, which can provide continuous bidirectional rotation in unlimited range. We also integrated the actuator into a robotic catheter platform capable to perform full degree-of-freedom cardiac catheterization under MRI.**

***Index Terms*—Hydraulic actuators, medical robotics, MR safe robot, robot-assisted intervention, Catheterization.**

I. Introduction

Advanced magnetic resonance imaging (MRI) techniques allow intra-operative (intra-op) monitoring of the ablation procedure during cardiovascular electrophysiology (EP). However, it is still challenging to carry out effective catheterization under MRI environment [1]. This may attribute to the high demand on dexterous manipulation of a long flexible catheter (>1 meter) in MRI environment.

Magnetic resonance (MR) conditional pneumatic motor is one common type of actuation compactible with high magnetic field environment. However, the long transmission distance (>8 meters) of air between MRI room and control room will greatly degrade the output torque/force, also and inducing much delay of mechanical transmission, which is unacceptable in certain applications demanding for responsive manipulation, e.g. EP catheterization.

Hydraulic motor using incompressible fluid (e.g. water, oil) as transmission media typically features with instant response and high power density [2]. However, large frictional force is one of the major drawbacks as seen in the conventional approaches which employ O-ring sealing components. Rolling-diaphragm-sealed cylinders can greatly reduce such mechanical friction in the seals [3]. These cylinders were already incorporated in a newly designed MR safe robotic manipulator for cardiac catheterization [4]. But the short stroke of the diaphragms limits its application towards long-range actuation that is required to navigate the catheter from the incision port to heart chamber.

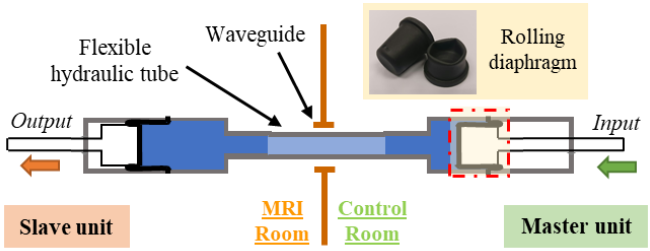

Fig. 1. Pair of cylinders enabling MR safe power transmission through a long hydraulic tube via waveguide in-between control room (master control side) and MRI suite (slave robot side).

In this work, we present a novel actuation design using rolling-diaphragm-sealed cylinders. Not only is the proposed actuator MR-safe, but it also can allow continuous bidirectional rotation in unlimited range. This actuator is also integrated into a robotic platform for MRI-guided cardiac catheterization.

II. Rolling Diaphragm-based Hydraulic Transmission

Fig. 1 shows a pair of cylinders which enables action-and-reaction transmission via a 10-meter long hydraulic tube passing through the waveguide in between MRI and control rooms. Incompressible liquid, such as water or oil, is fully filled in the pipelines to ensure responsive, accurate power transmission in both directions. The core components in our current prototype, such as piston rods and cylindrical housings, are 3D-printed with polymer composites (VeroWhitePlus and

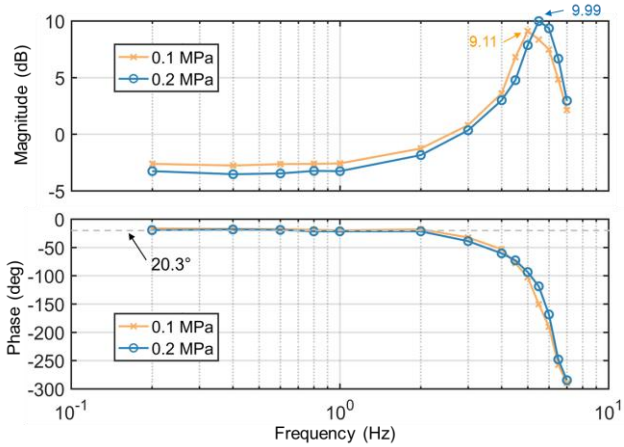

Fig. 2. Experimental frequency response of the three-cylinder actuation at four levels of hydraulic pressure. The input is positional signal, and the output displacement was measured by encoder at slave-side actuation unit.

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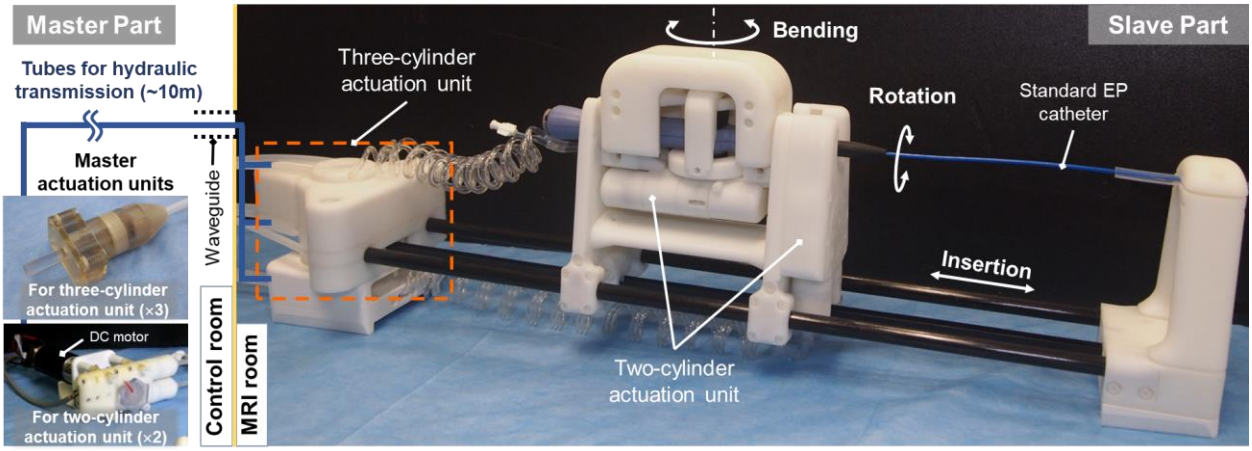

Fig. 3. MR safe robot prototype incorporating three sets of hydraulic transmission actuation units for 3-DoF manipulation of a standard EP catheter. A three-cylinder unit pushes and pull the catheter precisely for long-range navigation. Bending and rotation are actuated by the two separated two-cylinder units. Master-slave motion transmission from control room and MRI room is conducted through a 10-meter long hydraulic pipelines.

VeroClear, Stratasys, US), thus ensuring the MR safety.

Each cylinder unit is sealed by a rolling diaphragm (MCS2018M, FEFA Inc.) made of fabric-reinforced rubber. The diaphragm can be flipped inside out and roll over the piston rod to allow 35-mm stroke linear motion. Its working principle inherently averts the static contact and sliding friction of conventional O-ring seal for cylinder.

However, the transmission can only take place when the piston rod is pushed onto the diaphragm hat. Therefore, one pair of cylinders alone is *incapable* to conduct bidirectional transmission. To this end, the integration of multiple cylinders pairs is proposed to generate actuation in both directions. It can be customized to facilitate various robot degrees-of-freedom (DoFs), namely insertion, steering and rotation of cardiac catheter.

The configuration containing three pairs of cylinder can provide controllable and bi-directional rotary motion with unlimited range. The output torque could also be further increased when it is configured with additional cylinders (> 3). We have conducted experiments to evaluate the performance of the three-cylinder continuous motor. The experiments have demonstrated the master-slave actuator can lift 2.5 kg at a constant velocity of 50.24 mm/s, corresponding to an output torque of 0.49 N·m and a net power of 1.23 W. The dynamic performance of the three-cylinder continuous actuator (**Fig. 2**) was investigated with a frequency response method. The phase lag of the transmission is kept at around 20.3° for low actuation frequency (≤ 2 Hz) with no loading. The transmission with preloaded fluid pressure 0.2 MPa had smaller time delay: 60 ms and 52 ms at actuation frequency 1 Hz and 5 Hz, respectively.

III. MR Safe Robotic Platform for Cardiac Catheterization

The proposed hydraulic transmission is incorporated to drive a catheter robot capable to operate under intra-op MRI [4] (**Fig. 3**), which can provide full manipulation of a standard EP catheter in 3 DoFs. The robot comprises master and slave actuator in control room and MRI suite. None metallic material is integrated into the slave actuation, ensuring the MR safety and minimal interference to the MR images. The master units are actuated by electric motors in the control room.

The proposed three-cylinder unit is incorporated to actuate the insertion of robot. Not only does it enable the catheter advancement in the human body with a long range of 340 mm, but it also ensures high fidelity of pushing/pulling motion in short range. This feature is crucial for delicate EP tasks, such as electro-anatomic mapping (EAM) and radiofrequency (RF) ablation. The bending and rotation DoFs employ the two-cylinder actuation units. They can drive the robot with a motion range of ±45° for catheter bending and ±360° for catheter rotation.

IV. Conclusion

In summary, the proposed rolling-diaphragm-based hydraulic actuation, which enables high-performance tele-manipulation of the catheter, would set a new benchmark of MR safe robot. It could be further applied to other types of MRI-guided interventions. Functional and stereotactic neurosurgery [5] is our recent example. It is anticipated that, not only would the surgical workflow be simplified by the presented tele-operation of robot from the control room to MRI suite, but it would also add much confidence to surgeons with sufficient MRI-based guidance revealing on multiple displays in control room, which is particularly crucial to cardiac EP.

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