Learning Based Sim-to-Real Autonomous 3D Navigation for Robot-Operated Right Heart Catheterization

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INTRODUCTION

Cardiovascular Disease (CVDs) were responsible for 20.5 million deaths in 2021, comprising approximately one-third of all global fatalities and maintaining their position as the leading cause of human mortality. [1] Right Heart Catheterization (RHC) stands out as a highly effective clinical diagnosis for some conditions of CVDs. The procedure involves the use of a specialized Swan-Ganz catheter, which is inserted through a minor incision in either the patient's femoral or jugular vein. It is then meticulously navigated into the inferior vena cava (IVC), right atrium (RA) and right ventricle (RV), and precisely positioned within the pulmonary artery (PA).

Numerous research have been launched to advance the development of robotically operated cardiac interventions, with the goal of reducing the physical strain on clinicians associated with manual procedures. Additionally, there is a growing interest in the integration of machine learning (ML) and artificial intelligence (AI) algorithms for enabling autonomous functionality in interventional robots. [2], [3], [4] For example, Chi et al. achieved trajectory optimization for catheter interventions in various cardiac phantoms through Learning from Demonstrations (LfD) using Gaussian mixture models (GMM). [5] A new trend is emerging, focusing on the use of virtual environments for policy learning and training, with seamless transfer from simulation to real robotic autonomous operations (Sim-to-Real). Y. Cho et al. successfully implemented Percutaneous Coronary Intervention (PCI) using a Behavioral Cloning algorithm, where policies were initially trained in a simulation environment before being applied in real-world 2D autonomy scenarios. [6]

This paper presents a novel, learning-based robotic system designed for 3D navigation of a catheter, specifically targeting Right Heart Catheterization (RHC). Experiments demonstrate that the transfer from simulation to the real-world can be achieved by using Behavioural Cloning (BC) algorithms, which in turn enable autonomous robotic operated interventions within patient-specific phantoms.

MATERIALS AND METHODS

As illustrated in Fig 1. The system comprises a 2-DoF MR-compatible interventional robot, pulmonary artery phantoms, NDI Aurora tracking system (Aurora, NDI, Canada) and a depth camera (D435i, Intel, USA). The Sim-to-Real transfer process initiates with a SOFA simulation, which encompasses both catheter modeling and the creation of a virtual scene, as illustrated in Fig 2(a). A keyboard controller was utilized to operate and record 50 repetitive operations for each phantom, which facilitated the collection of a dataset detailing the behaviors and positions of the catheter tip. Following the SOFA simulation, a Convolutional Neural Network (CNN) was developed using Behavioral Cloning algorithm to train the robot's decision-making policy. (See Fig 2(b))

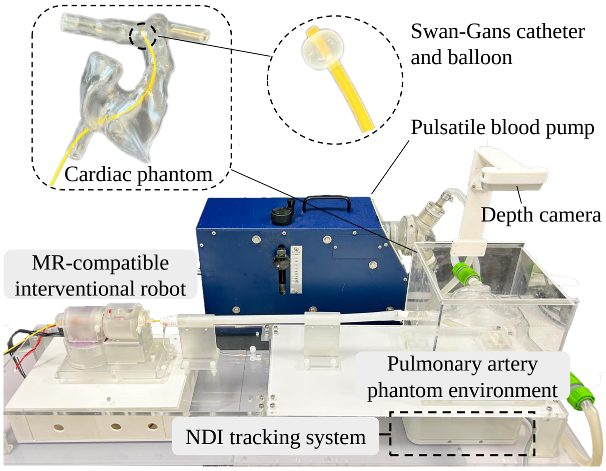
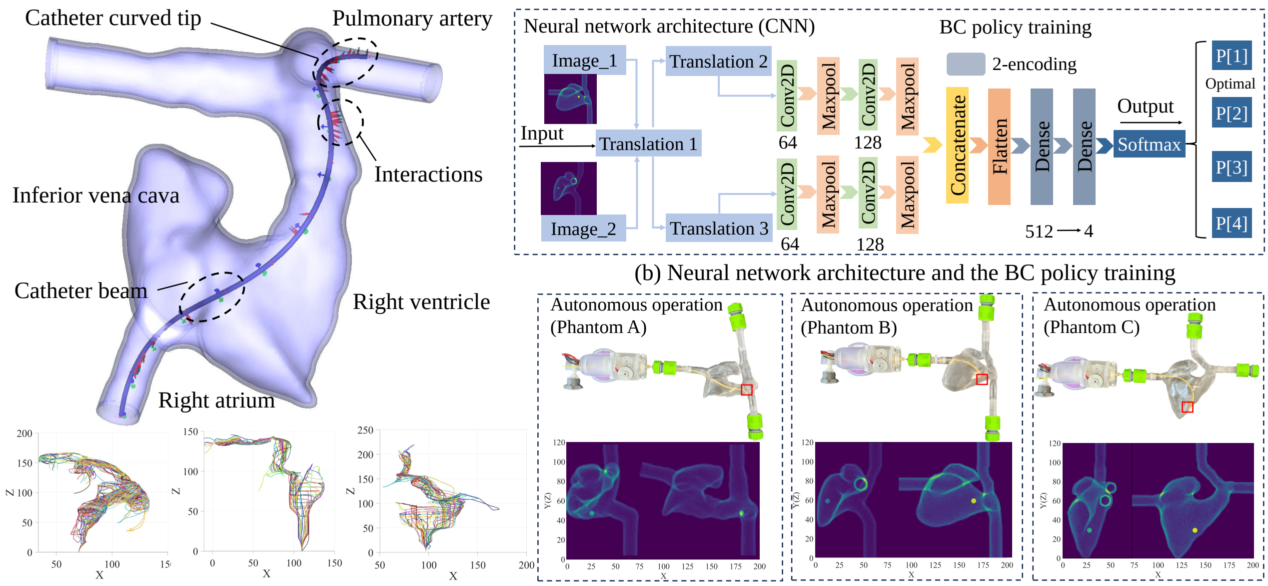


Fig. 1 MR-compatible catheter navigation system for intervention to realize autonomous right heart catheterization (RHC) within the cardiac phantoms.

In real-world scenarios, a specialized interface was established to enhance communication among the robot controller, the decision-making policy and the tracking system. A 6-DoF tracker is affixed to the catheter's tip, facilitating the real-time position output which and orientation ($P(t, T_x, T_y, T_z, R_x, R_y, R_z)$) for the feedback. This tracker communicates with the magnetic field generator (Aurora, NDI, Canada). The patient-specific phantoms are 3D printed by Vero Clear material, utilizing a PolyJet Objet 500 Connex 3D printer. The autonomous robot-operated catheterization within 3 patient-specific phantoms is depicted in Fig 2(c).



(a) SOFA simulation and data collection

(b) Neural network architecture and the BC policy training

(c) Autonomous robot operation and position feedback

Fig. 2 3D autonomous robot-operated catheter's navigation by sim-to-real using behavioural cloning. (a) SOFA simulation. (b) Neural network architecture and policy training. (c) Autonomous robot operation and real-time positional feedback.

TABLE I Autonomous cardiac phantom intervention

Scenarios	Fastest time	Average time	**Success rate**
Phantom A (dry)	28.20s	30.54s	**85.0%**
Phantom A (water-filled)	26.22s	28.61s	**90.0%**
Phantom B (dry)	24.33s	26.90s	**88.0%**
Phantom B (water-filled)	23.71s	24.60s	**92.0%**
Phantom C (dry)	23.50s	24.20s	**92.0%**
Phantom C (water-filled)	20.57s	22.60s	**96.0%**

RESULTS

Table I summarizes 50 autonomous operations performed on various patient-specific models under two scenarios: dry and water-filled. Success in these operations is defined by the robot's ability to autonomously navigate the catheter from the IVC to the Pulmonary Artery. The results indicate that the autonomous robotic catheter interventions consistently achieved a success rate exceeding 85% in both scenarios. Notably, in the water-filled scenario, the robotic catheter demonstrated enhanced performance, with success rates of 90%, 92%, and 96% in accessing the PA. Furthermore, the performance of the autonomous operations varied depending on the geometry of the cardiac models. For models with more complex geometries and narrower pulmonary arteries, such as Phantom A, the time required for the robotic catheter to access the PA was more time-consuming recording of 30.54 s and 28.61 s, respectively.

DISCUSSION

The observed enhancement in performance within the water-filled phantom scenario, as opposed to the dry scenario, is primarily attributed to the reduced friction between the catheter and the inner wall of the phantom during autonomous catheter interventions. This reduction in friction leads to fewer instances where the catheter becomes lodged, thereby facilitating smoother navigation through the cardiac chambers and towards the pulmonary arteries. Nonetheless, in cardiac phantoms featuring more intricate geometries—especially those with narrower pulmonary arteries. This complexity stems from the necessity for additional maneuvers to circumvent points of obstruction and to counteract the heightened frictional resistance. Future research will aim to validate the policy using a soft heart model coupled with a pulsatile blood pump (Harvard Apparatus, USA) to foster robotic autonomy in a dynamic, heart-beating environment. Additionally, the integration of a Reinforcement Learning algorithm is anticipated to enhance the stability of the RHC procedure.

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