Open Access Library Journal
2026, Volume 13, e15812
ISSN Online: 2333-9721
ISSN Print: 2333-9705

Robotic System with Haptic Feedback for Intelligent Coronary Stent Implantation in Percutaneous Coronary Intervention

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How to cite this paper: Zhang, Y.X, Yin, M.Q. and Deng, D.D. (2026) Robotic System with Haptic Feedback for Intelligent Coronary Stent Implantation in Percutaneous Coronary Intervention. *Open Access Library Journal*, **13**: e15812.
https://doi.org/10.4236/oalib.1115812

Received: July 27, 2026
Accepted: August 23, 2026
Published: August 26, 2026

Abstract

Traditional percutaneous coronary intervention (PCI) exposes interventional cardiologists to long-term X-ray radiation and musculoskeletal injuries caused by lead aprons. Hand tremor during manual operation also leads to insufficient positioning accuracy of stent deployment, increasing risks of stent malapposition and in-stent restenosis. To address these limitations, this paper develops a master-slave teleoperated robotic system for intelligent coronary stent implantation. The platform consists of a surgeon master console, bedside slave manipulator, real-time force sensing module, and image navigation upper computer subsystem. The slave robot realizes multi-degree-of-freedom coordinated control of axial translation and rotation for guidewires, balloon catheters and stent delivery systems. A high-precision force sensor is integrated to detect vessel contact force at the catheter path, and an impedance-based haptic teleoperation algorithm is proposed. Combined with coronary angiography visualization, targeted positioning of stent deployment zones is realized. A segmented motion control strategy is designed for different PCI stages, enabling automatic velocity reduction during stent positioning and release. *In-vitro* experiments are carried out on a silicone coronary phantom with simulated vascular stenosis. Results demonstrate that the average axial positioning error reaches 0.32 mm, and the rotational angle error is less than 0.45˚. Two-level force thresholds are embedded in the control loop; the system actively limits pushing force to prevent vascular dissection or perforation when excessive contact occurs. Compared with manual operation, the robotic system eliminates radiation exposure for operators and improves positioning repeatability during stent implantation. Phantom experiments verify the mechanical stability and control performance of the proposed system, providing a feasible design scheme for next-generation intelligent interventional robotic platforms.

Subject Areas

Global Health

Keywords

Coronary Interventional Robot, Stent Implantation, Master-Slave Teleoperation, Haptic Force Feedback, Percutaneous Coronary Intervention, Vascular Phantom

1. Introduction

Coronary artery disease (CAD) remains one of the leading causes of mortality worldwide. Percutaneous coronary intervention (PCI) has become the primary minimally invasive revascularization strategy for symptomatic CAD patients. In conventional PCI procedures, physicians manipulate guidewires, balloons and stent catheters under continuous fluoroscopic guidance. Long-term occupational radiation exposure raises risks of cataracts and malignant tumors, while heavy lead garments trigger chronic lumbar and cervical lesions [1]. In addition, physiological hand tremors degrade manipulation precision. For complex lesions such as chronic total occlusion (CTO) and severely calcified vessels, inaccurate stent positioning easily causes geographic miss and poor long-term prognosis.

In recent decades, robotic endovascular intervention has attracted extensive attention in medical device research. Commercial robotic PCI systems including CorPath GRX and R-One have entered clinical use [2]. These platforms realize remote catheter manipulation, but obvious drawbacks remain: most systems lack native real-time haptic feedback; physicians rely only on fluoroscopic images to judge catheter–vessel interaction. Automatic intelligent constraints for stent release are insufficient, and the coordination between imaging navigation and robotic motion control needs further improvement. Domestic prototypes such as ALLVAS and ETcath200 have completed preclinical trials, yet integrated control strategies oriented toward precise stent deployment are still under exploration.

In parallel, academic communities have studied continuum soft robots, magnetic navigation systems and force sensing catheters [3]. Magnetic navigation robots can steer guidewires inside tortuous vessels, but they cannot directly complete stent delivery and expansion. Many existing teleoperation prototypes only focus on position tracking, ignoring safety protection against excessive contact force that may damage vascular endothelium [4].

This work constructs an integrated intelligent robotic platform dedicated to coronary stent implantation. The main contributions are summarized as follows:

1) A modular master-slave robotic system compatible with clinical standard PCI consumables is established, integrating force sensing and haptic feedback;

2) An impedance-based teleoperation control algorithm with force limiting safety mechanism is proposed to avoid over-pushing injuries;

3) A segmented motion control framework is developed for the whole PCI workflow, adopting low-speed fine-tuning mode in stent positioning and release phase;

4) *In-vitro* phantom experiments are performed to evaluate positioning accuracy, force tracking performance and overall surgical workflow feasibility.

2. System Overview

The robotic system contains four core subsystems: master haptic console, bedside slave manipulator, force sensing unit, and upper computer control & angiography navigation module. Real-time Ethernet communication is adopted with a control cycle of 1 ms to reduce teleoperation delay [5]. The overall architecture is shown in **Figure 1**.

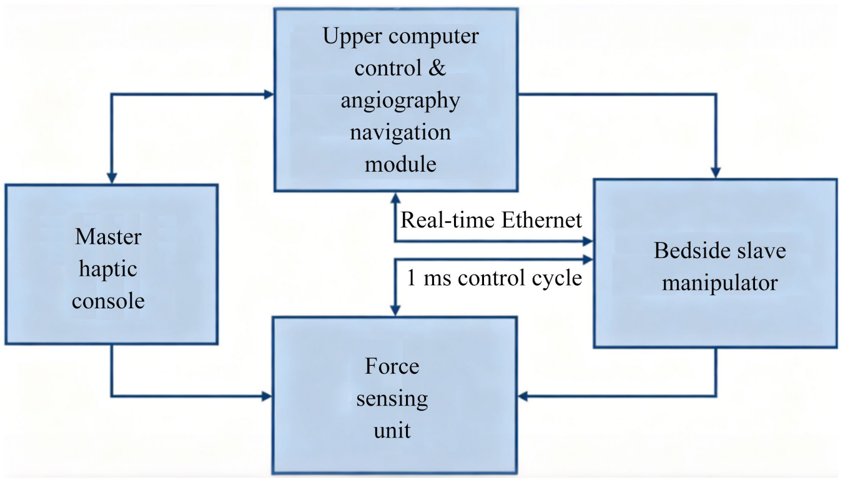

Figure 1. Schematic diagram showing the overall architecture of the robotic system.

2.1. Slave Manipulator Design

The slave robot provides three fundamental degrees of freedom: guidewire axial feed, catheter axial feed, and continuous catheter rotation. Servo motors and timing belt transmission are adopted to achieve compact layout suitable for limited space in catheter laboratories [6]. Key mechanical specifications: Maximum travel: 180 mm; Adjustable feed speed: 0 - 15 mm/s (0 - 3 mm/s fine mode for stent deployment); Rotation range: 0˚ - 360˚ continuous rotation; Repetitive positioning accuracy ≤ 0.1 mm.

A disposable sterile cassette mechanism is designed for rapid assembly before surgery to avoid cross-contamination. Elastic roller clamping ensures stable fixation without scratching the outer surface of clinical catheters.

2.2. Master Haptic Console

The master manipulator adopts impedance-type haptic handles. Vascular contact force detected on the slave side is mapped to the operator's hand in real time. Resistance feedback is generated when the catheter touches vascular walls or stenotic lesions, restoring natural operation sensation similar to manual PCI [7].

2.3. Force Sensing Module

A miniature high-precision load cell is installed along the catheter access path. Measuring range: 0 - 5 N, resolution: 0.01 N. According to clinical PCI experience, safe contact force between catheter and coronary vessel is recommended below 0.8 N; forces exceeding 1.2 N significantly increase risks of intimal injury. Two threshold strategies are implemented: warning threshold = 0.8 N, limiting threshold = 1.2 N. Once the limiting threshold is reached, the robot automatically reduces feed speed; sustained overload triggers temporary stop of propulsion [8].

2.4. Software and Hardware Platform

The underlying motion controller is based on STM32 microcontrollers, and the upper computer runs on an industrial PC [9]. Human–machine interface is developed based on Qt, supporting motion parameter configuration, real-time force curve display, DICOM angiogram loading, lesion marking and surgical data recording. The software framework consists of servo driving layer, communication layer, control algorithm layer and visualization interaction layer.

3. Teleoperation Control Algorithm

3.1. Master-Slave Position Mapping

Define the master workspace coordinate X_m and slave actuator coordinate X_s. A linear scaling mapping is established as the relational expression: $X_s = k \cdot X_m$ where k represents the scaling factor adjustable by operators [10]. A smaller scaling factor is adopted during stent positioning to realize precise micro-manipulation.

3.2. Segmented Control Strategy for Stent Implantation

The whole stent delivery workflow is divided into three stages with automatic parameter switching:

1) Vascular access stage: high allowable speed for rapid catheter advancement;

2) Lesion approaching stage: velocity reduction and force warning activation;

3) Stent positioning and deployment stage: minimum speed mode, increased haptic gain and restricted large-amplitude rotation to guarantee accurate alignment.

4. *In-Vitro* Experimental Validation

4.1. Experimental Setup

The test platform includes: silicone phantom mimicking coronary artery branches with 70% and 90% simulated stenosis; circulating pump simulating hemodynamic pressure; commercial guidewires, balloon catheters and drug-eluting stents; laser displacement sensor, multi-channel force acquisition system and the proposed robotic prototype [11].

4.2. Experimental Schemes

Three groups of experiments are designed: positioning accuracy test, force tracking & safety protection test, and complete simulated PCI workflow test [12]. Each test is repeated 2 times for statistical averaging.

4.3. Results and Analysis

4.3.1. Positioning Accuracy

Target displacements of 5 mm, 10 mm and 20 mm are set. The measured average axial positioning error is 0.32 mm with maximum error 0.57˚. The average rotational error is 0.31˚, maximum 0.45˚ [13]. The accuracy satisfies clinical requirements (positioning error < 1 mm for stent implantation).

4.3.2. Force Safety Test

Continuous automatic propulsion is set to simulate catheter collision with stenotic lesions. The system triggers warning at 0.8 N. When contact force reaches 1.2 N, propulsion speed decreases rapidly and eventually stops. The overload protection function effectively limits excessive thrust [14].

4.3.3. Simulated Stent Implantation

Complete procedures including guidewire crossing, predilation, stent delivery and deployment are implemented on the phantom [15]. Operators can distinguish normal vascular segments and stenotic regions via haptic cues. Compared with manual manipulation, the robotic system suppresses hand tremor and improves repeatability of stent deployment position [2].

4.4. Limitations of *In-Vitro* Tests

All experiments are conducted on static silicone phantoms. The mechanical properties differ from *in-vivo* pulsating coronary arteries. Further animal tests under physiological blood flow and cardiac motion are required to validate system robustness [16].

5. Discussion

5.1. Advantages of the Proposed System

1) Remote operation enables physicians to work outside fluoroscopy rooms, eliminating occupational radiation hazards;

2) Closed-loop proximal force sensing and haptic feedback solve the missing tactile information problem of mainstream commercial robots;

3) Segmented intelligent control strategy is specially optimized for stent deployment procedures;

4) Modular mechanical design facilitates disinfection and compatibility with existing catheter room facilities.

5.2. Existing Limitations

This system belongs to an extracorporeal catheter-driving robot without onboard distal actuation [17]. Active bending inside vessels cannot be realized. For extremely tortuous and heavily calcified lesions, operation still relies on surgeon experience. At present, only 2D angiography is used. Future work will integrate IVUS and OCT multimodal imaging registration [18]. The platform remains human-in-the-loop teleoperation; fully autonomous stent implantation requires further exploration [19].

5.3. Future Directions

1) Multimodal registration of angiography, IVUS and OCT to realize automatic lesion measurement and stent size matching;

2) Introduce deep learning for preoperative path planning to achieve semi-autonomous navigation;

3) Develop integrated soft continuum robotic catheters with distal steering capability;

4) Combine intelligent sensing stents to realize "robotic precise implantation + long-term postoperative vascular monitoring".

6. Conclusion

This paper presents a master-slave teleoperated robotic system for intelligent coronary stent implantation. Mechanical structure, hardware circuit and impedance-based haptic control algorithm are fully designed [20]. The robot realizes multi-degree-of-freedom coordinated driving of interventional devices, equipped with overload force protection and segmented motion control for stent release. *In-vitro* phantom experiments verify that the system achieves clinically acceptable positioning accuracy and can effectively prevent vascular injury caused by over-pushing [21]. The robotic platform allows remote PCI operation to avoid radiation exposure and improves the stability of stent implantation. Future work will focus on multimodal image navigation and *in-vivo* animal trials to promote clinical translation for minimally invasive cardiovascular interventions.

Conflicts of Interest

The authors declare no conflicts of interest.

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