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Endovascular intervention robot with multi-manipulators for surgical procedures: Dexterity, adaptability, and practicability

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ABSTRACT

In this research, a novel vascular intervention robot with four manipulators that mimic the four hands of a physician and an assistant was designed for peripheral vessels. Each manipulator has three DOFs (degrees of freedom), namely, clamping, rotation, and push–pull of a guide wire and catheters. Manipulation is accomplished by four corresponding joysticks. A distributed control system is used to coordinate complex motions with high accuracy in real time. This robot can not only manipulate intervention devices but also deploy stents. We performed in-vitro experiments to verify the precise velocity and driving force. A complete endovascular intervention procedure in an in-vivo pig with the successful deployment of three stents and zero radiation damage to the surgeon validated the design. Results showed that the robot had high dexterity, precision, and efficiency, thereby meeting the demands of endovascular intervention surgical procedures.

1. Introduction

Vascular intervention therapy is an important and effective method of treating pathological and physiological angiostenosis. Billions of patients globally receive such treatment every year. However, the therapy needs the image monitor from an X-ray plate frequently to check the diseased region and the states of the intervention devices. The health of intervention physicians is harmed by the long-term cumulative radiation doses despite the wearing of thick and heavy lead aprons. Additionally, some special diseases, such as aortic dissection, need precise and accurate operation. Tele-operating robots are a promising solution to this problem [1–4]. For example, the da Vinci robot can perform precise operations under the remote control of surgeons. However, vascular intervention uses considerably varied long-segment devices that require frequent replacement, which cannot be operated easily by the da Vinci robot. An innovative method that matches the features of intervention devices and procedures is thus desired.

Several studies have explored tele-operating vascular intervention robots. Negoro developed a catheter system that can control catheters by an external controller [5]. This catheter tele-guiding system can perform intravascular procedures from distant locations. The Sensei robotic catheter system from Hansen Medical assists surgeons in locating catheters stably [6,7]. This catheter system allows for high-accuracy manipulation with reduced X-ray exposure through a master–slave remote control structure [8,9,10]. The CorPath system, which was developed by Corindus, Inc. [11], can push, pull, and rotate catheters under a specialized mechanism. A touch screen is used to remotely manipulate the catheter in the CorPath system. Granada reported a robot-assisted coronary angioplasty system of CorPath 200 [12]. This system can deliver and manipulate coronary guide wires, balloons, and stents in patients but needs specially designed components and was thus equipped with a joystick. Thakur proposed a remote catheter navigation system with tele-manipulation of conventional axial and radial motion [13] and evaluated the performance of the proposed system. Ma and Da developed a magnetic navigation system of Stereotaxis Niobe [14,15]. A controllable magnetic field was introduced to navigate magnetically enabled guide wires in performing accurate percutaneous coronary intervention. Guo proposed a robotic catheter system with force and visual feedback in 2012 [16]. Surgeons can insert and rotate a guide wire or catheter through remote control. The robotic system can also be used to practice endovascular intervention. Wang proposed a robot for manipulating intervention devices and tested the robot for manipulation capability and real-time performance [17]. Feng designed a surgical robot system with master–slave control structure. Two frictional gears are used to manipulate catheters with scaled motion factors [18]. Lu reported an endovascular

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interventional robot for use in cerebral angiography [19]. Master–slave control is adopted to manipulate catheters during surgery.

All of these explorations utilize remote control to manipulate guide wires or catheters while preventing X-ray damage. However, techniques such as the CorPath 200 System have not proven universality, and other works have had merely limited progress in terms of complete endovascular intervention operations. Tasks besides manipulation of guide wires or catheters should be achieved by robotic systems. Robots should be compatible with current commercial guide wires or guide catheters to broaden application. Additionally, dexterity is important to enhancing the tele-surgical experience. Robots should be able to perform many actions that are typically accomplished manually during operations and manipulate intervention devices with high precision and stability.

This research aims to solve the following concerns for future clinic applications. The first issue is gripping guide wires and guide catheters adaptably and reliably. For example, the Magellan uses a specialized catheter and is compatible with certain types of guide wires and catheters, such as and 0.018- and 0.035-inch hydrophilic wires and 6.5F and 9.5F catheters. The CorPath 200 system has improved well and is adaptable to a variety of commercial guide wires and catheters [20,21]. In our design, the robot is compatible with most commercial devices. The second concern addressed by the current work is enhancing operation dexterity. Single guide wire or catheter operation is only one step of an entire surgery. It fails to meet surgical requirements because of low dexterity. The Magellan and the CorPath 200 systems can manipulate guide wires and catheters but cannot perform complicated manipulation, such as stent release and coordination of wires and catheters. To provide a surgical solution that can overcome these drawbacks, i.e., lack of universality and poor dexterity, we design and realize a novel robot. We propose a manipulator with an adaptive end gripper for use as a general manipulator in operating intervention devices during such tasks as stent delivery and system deployment. Multi-manipulators are integrated to coordinate the complex motion of guide wires and catheters with high dexterity.

2. Overview of vascular intervention robot

In the total design of our intervention robot, such constraints as mounting spaces, ergonomic handles, and maintenance are considered. Likewise, DSA image equipment, cardiogram monitors, and infusion support are taken into account. The available workspace includes the space on the patient and under the chest. Therefore, the robot is designed to be of lift-on-lift type with a length of less than 1.5 m. From an ergonomic view, a handle should integrate the motions of clamping, rotation, and pushing. To an operator, the handle is equivalent to the guide wire or catheter. To maintenance personnel, modular designs and related controllers are favorable for easy examination and dismount.

A general intervention procedure needs two doctors, namely, one operator and an assistant, totaling four hands. Each hand's classic actions include pinching, pushing, and rotating. Inspired by these manual procedures, the vascular intervention robot in Fig. 1(a) is proposed. Four manipulators on the guide rail of the manipulator frame can be translated to push or pull the device. A steel rope mechanism is designed for long stroke linear driving for compact structure [22]. For example, Manipulator 4, shown in Fig. 1(b), is pulled by Wire Ropes 4A and 4B. One end of the wire is fixed on the manipulator. 4A is tied to Disc 4 through Pulleys A and B, whereas 4B is tied the opposite direction to Disc 4 through Pulley B. Then, Motor 4 drives Disc 4 to pull the manipulator forward or backward. The maximum translation is 1.3 m, and the total length is 1.4 m.

Each manipulator has an end gripper with two fingers that pinch the guide wire, catheter, or other intervention devices. The maximum distance of the two fingers is set as 25 mm, which can cover most devices' diameter specifications. The pushing force is designed to be 10 N to meet the requirements of intervention. Two fingers are driven by two nuts on the lead with an inverted screw, and the lead is driven by a clamping motor through a gear pair. When the lead is actuated, the two nuts approach each other with the same translation. Therefore, the clamping center remains unchanged. The end gripper is rotated by a step motor through a gear pair. The rotary center is coincided with the clamping center. Clinical applications require a rotary precision of approximately 1°. Thus, the step angle is 0.18°.

The manipulator frame hangs on a stand by a hanger bar. A hand wheel is used to adjust the pitch angle and lateral distance of the manipulator frame. A locking handle can fix the hanger bar once the manipulator is well adjusted. The control panel is placed far away from the robot. One-to-one communication is present between four handles on the panel and four manipulators. Three commands, namely, button push, right–left swing, and forward–backward swing, are performed with the joystick to control the manipulator's clamping, movement, and rotation. The corresponding control panel can control all the 12 degrees of freedom (DOFs) independently and adjust the velocity. To reduce the burden of the main controller and meet the real-time performance requirements, a distributed control system is used in the robot. This system is composed of a panel controller, push–pull controller, and four manipulator controllers. Each controller is connected by a supply cable and a CAN bus. The manipulator controller is connected with the other controllers by spiral cables. Information about the robot design is listed in Table 1.

3. Design and control of dexterous manipulators

3.1. Manipulator design

The manipulators are designed according to the characteristics of intervention devices, such as guide wires, catheters, balloons, metallic stents, and covered stents. One type of device can have a large number of specifications with different diameters and shapes. Some long segments measure over 2 m and thus require large workspaces. Additionally, these devices need frequent replacement during operations.

The designed multi-manipulators are shown in Fig. 1(b). Four manipulators are installed on four sliding blocks on one guide rail. These manipulators are actuated by four motors via discs and wire ropes. Two wire ropes (Wire Ropes 4A and 4B) are rolled on a disc in two opposite directions. The end of Wire Rope 4A is tied to the anchor point of Manipulator 4′s sliding block through Pulleys B and A. The end of Wire Rope 4B is tied to the same sliding block through Pulley B. The detailed wire rope configuration is shown in Fig. 1(b). When the discs are driven by the motor, the sliding blocks move forward or backward.

Each manipulator has two DOFs, namely, clamping and rotation. The end gripper is actuated by a clamping motor. A gear pair and two symmetrical screw nuts are on the screw rod with opposite turning directions. When the clamping motor is driven, two end grippers can clamp the catheter with centration. The comb-shaped end gripper is adaptive to different specifications. The clamping mechanism is supported on the manipulator frame by a bearing and actuated by the gear pair and rotating motor. The clamping center is coincident with the bearing, and this mechanism enables the manipulator to rotate around the clamping center.

3.2. Dexterity analysis

Dexterity is a quantitative index used to evaluate the accuracy of inverse kinematics matrices [23,24]. The proposed robot is composed of four manipulators, and each manipulator can be simplified into a three-dimensional (3D) PR arm with two DOFs, as shown in Fig. 2(a). The clamping degree is ignored because it does not influence the arm motion. The two joints' variables are θ_1 of translating velocity and θ_2 of rotation angular rate. The clamping center is fixed on the rotation joint axis, which lies parallel to the X axis. The distance between the joint