A Novel Haptic Interface for the Simulation of Endovascular Interventions

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Abstract. Endovascular interventions are minimally invasive surgical procedures that are performed to diagnose and treat vascular diseases using flexible instruments known as guidewire and catheter. A popular method of developing the skills required to manipulate the instruments successfully is through the use of virtual reality (VR) simulators. However, the interfaces of current VR simulators have several shortcomings due to limitations in the instrument tracking and haptic feedback design. A major challenge in developing training simulators for endovascular interventional procedures is to unobtrusively access the central, co-axial guidewire for tracking and haptics. In this work, we designed a haptic interface using novel approaches to both. Instrument tracking is performed using a combination of an optical sensor and a transparent catheter. Haptic feedback is supplied by both off-the-shelf actuators and a bespoke electromagnetic actuator embedded within the catheter hub. Initial test results by expert interventionists have shown positive responses and further development is ongoing.

Keywords: Haptic interface, Endovascular interventions, Simulator training

1 Introduction

Cardiovascular disease (CVD) is the number one cause of death around the world. The projected estimation is that the annual death count attributed to CVDs will reach 23.3 million by 2030 as it continues to be the single leading cause of death in the future [1]. The seriousness of the situation led to the introduction of a new form of minimally invasive surgery over two decades ago, which enables the diagnosis and treatment of many major vascular diseases and has become a vital part of vascular health care today [2]. Unlike traditional open surgery, these endovascular interventions involve the use of long, thin and tubular specialised instruments, called catheters and guidewires, that are inserted into the patient's vascular system via a small incision in the groin or arm. With this approach, patients suffer much less trauma, leading to faster recovery, reduced risk of infection and lower treatment costs since they can usually be performed as day cases.

A popular method to develop the skills required to manipulate the instruments successfully is through the use of virtual reality (VR) simulators [3]. VR simulators have the potential for significant development as computational technology improves. Unconstrained by any physical factors, training in the virtual realm offers many different possibilities. This includes the ability to offer a number of training scenarios, featuring a variety of anatomical models on which to operate, with different types and levels of pathology. Advancements in haptic technology help to ensure the tactile aspect of the procedures can be experienced in the simulators through the use of bespoke haptic interfaces.

There are several design issues in current haptic interfaces for the simulation of endovascular interfaces that may negatively affect the validity of the simulation experience and its effectiveness. These include: limited instrument range of movement, loss of instrument position information and unrealistic haptic feedback. The design issues are mostly due to the fact that, during endovascular interventions, the guidewire is positioned concentrically within the catheter while it is navigated within the blood vessels. This significantly reduces the line of sight and point of contact to the guidewire and is the main design challenge, referred here as "concentric occlusion". In this work, we present a novel haptic interface design aiming to addresses this issue.

2 Methodology

The haptic interface is equipped with two separate, but equally important systems that work in parallel during the simulation: instrument tracking and haptic feedback. Each of these systems is now described in more detail.

2.1 Instrument Tracking

The requirements for instrument tracking are relatively simple. The system needs to track the translational and rotational movements of both the guidewire and catheter to a resolution of 1 mm. Previous interface designs have utilised either optical or mechanical sensors to detect and track instrument movements [4, 6, 7]. The sensors are normally spaced apart and dedicated to one specific instrument. A problem occurs when the catheter is advanced past the guidewire's sensor, thus blocking and disrupting the guidewire tracking. In the proposed design, movement of the catheter is still tracked by an off-the-shelf optical sensor, but a slightly different approach is used to enable concentric tracking of the guidewire. It combines a transparent catheter and a second optical sensor (Fig. 1). Thus, the transparent catheter provides a line of sight for the guidewire to be detected by the second optical sensor.

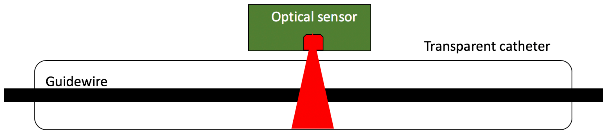

Fig. 1: Illustration of the optical sensor setup for concentric guidewire tracking

2.2 Haptic Feedback

Similar to the sensor configuration, previous interfaces have implemented separate haptic actuators spaced out and assigned to a certain instrument [5-7]. The actuators used are typically servo motors or electromagnetic clamps. In our design, a servo motor is used to apply force to the catheter, whilst a bespoke electromagnetic actuator was designed to apply force to the guidewire.

The concept was to embed the custom actuator inside the catheter hub in order to address the concentric occlusion problem. The catheter hub refers to the plastic case that forms the entrance at the proximal end of the catheter (Fig. 2 Left). It has a unique cylindrical shape measuring 8 mm x 20 mm (Diameter x Length) with 'wings' extruding from the sides. During operation, the guidewire will always pass through the catheter hub to enter the catheter tubing. Therefore, by placing an actuator within the hub, it will have direct contact with the guidewire at any time without requiring or causing any movement restrictions.

An electromagnetic actuator approach was selected due to the minimal parts required that are relatively simple to miniaturise, easy to obtain and with the potential for producing varying levels of resistance. Fig. 2 (Right) shows the design of our electromagnetic actuator. When haptic feedback is required, current is supplied to the copper coil producing an electromagnetic field that reacts with the electromagnetic field of the surrounding permanent magnets, pushing the coil casing (3D printed) and activating the sphere brakes. The "arms" of the coil casing will push the brakes towards the guidewire (passing through the channel inside the ferromagnetic core) applying certain amount of resistance.

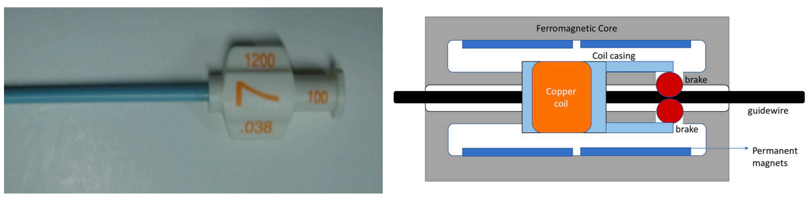

Fig. 2: Left – Catheter Hub; Right – Bespoke actuator activated and its components

2.3 Prototype Integration

Both the tracking and haptic feedback systems are integrated within the prototype interface shown in Fig. 3. The prototype featured two ports for interaction with two different sets of instruments to allow for the simulation of different stages of the intervention. The tracking sensors and haptic feedback actuators are controlled by an Arduino board that communicates with a 3D virtual simulator environment (Fig. 4). Movement of the instruments inserted into the haptic interface by an operator is tracked and mirrored by the virtual instruments. Collision between the instruments and vasculature in the virtual environment causes the actuators to feed back the corresponding force onto the operator.

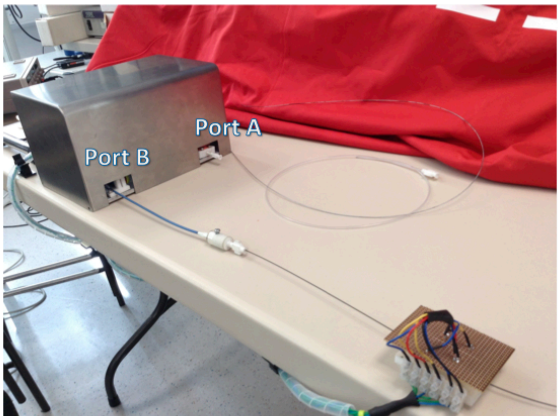

Fig. 3: Prototype interface device setup for testing

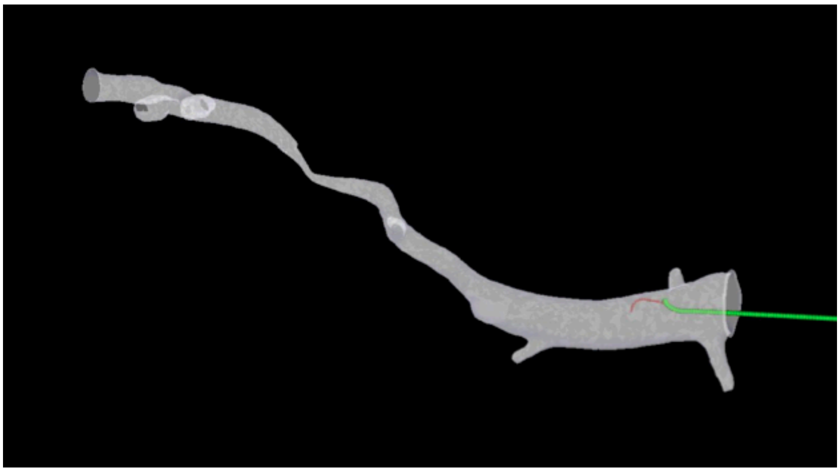
Fig. 4: 3D generated virtual environment with simulated vasculature and set of guidewire and catheter

3 Results and Discussion

The prototype system was presented to an interventional cardiologist at the London Heart Hospital for testing of the proof of concept. Ethics approval was obtained from the Imperial College Research Ethics Committee (Ref ICREC_13_6_12). Informed consent was obtained from all study participants.

During the testing stage, the cardiologist was asked to perform simple tasks using the haptic interface, including advancing the guidewire and catheter from one end of the virtual vessel to the other. This includes manipulating the instruments to navigate past a narrowing in the vessel, which activates the actuators to recreate the feeling of resistance through the collisions between the virtual instruments and the vessel. After 15 minutes of testing the prototype, the cardiologist was asked to complete a questionnaire evaluating the tracking and haptics systems, as well as the general concept.

The cardiologist reviewed the tracking system and scored it highly in terms of responsiveness and accuracy, with the movements of the real-life instruments being adequately translated into the virtual environment. The haptic feedback system was said to be effective for both the catheter and guidewire. The resistance effect produced on the guidewire using the new hub actuator was highlighted as being subtler than that in current interfaces. This could be an advantage of using the bespoke actuator. Use of transparent catheters instead of the regular blue colored catheters was deemed acceptable, as long as they felt the same when manipulated. However, embedding the actuator within the catheter hub has increased its size and changed its handling. It was suggested that future iterations of the actuator will need to be miniaturized further to minimise disruption to the operator. Lastly, the concept of using more than one port during the simulation was not as well received and needs further consideration.

4 Conclusion

We have presented a novel haptic interface for the simulation of endovascular interventions designed to address the shortcomings of current interfaces. The tracking and haptic feedback systems were tested in a proof of concept prototype that was positively reviewed by an interventional cardiologist. Future work will include miniaturization of the actuator hub and further testing by subject matter experts.

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