# Haptic Feedback and Dynamic Active Constraints for Robot-Assisted Endovascular Catheterization

G. Dagnino, J. Liu, M. E. M. K. Abdelaziz, W. Chi, C. Riga, and G.-Z. Yang

***Abstract*— Robotic and computer assistance can bring significant benefits to endovascular procedures in terms of precision and stability, reduced radiation doses, improved comfort and access to difficult and tortuous anatomy. However, the design of current commercially available platforms tends to alter the natural bedside manipulation skills of the operator, so that the manually acquired experience and dexterity are not well utilized. Furthermore, most of these systems lack of haptic feedback, preventing their acceptance and limiting the clinical usability. In this paper a new robotic platform for endovascular catheterization, the CathBot, is presented. It is an ergonomic master-slave system with navigation system and integrated vision-based haptic feedback, designed to maintain the natural bedside skills of the vascular surgeon. Unlike previous work reported in literature, dynamic motion tracking of both the vessel walls the catheter tip is incorporated to create dynamic active constraints. The system was evaluated through a combined quantitative and qualitative user study simulating catheterization tasks on a phantom. Forces exerted on the phantom were measured. The results showed a 70% decrease in mean force and 61% decrease in maximum force when force feedback is provided. This research provides the first integration of vision-based dynamic active constraints within an ergonomic robotic catheter manipulator. The technological advances presented here, demonstrates that vision-based haptic feedback can improve the effectiveness, precision, and safety of robot-assisted endovascular procedures.**

## I. Introduction

Cardiovascular disease is the major cause of deaths in the Western world, of which vascular disease is a main contributing factor. The WHO predicts that by 2030, more than 23 million people will die annually from cardiovascular diseases [1]. Vascular disease is the most common precursor to ischemic heart disease and stroke, which are two of the leading causes of death worldwide. Advances in endovascular intervention in recent years have transformed patient survival rates and post-surgical quality of life. Compared to open surgery, it has the advantages of faster recovery, reduced need for general anesthesia, reduced blood loss and significantly lower mortality [2]. However, endovascular intervention involves complex maneuvering of pre-shaped catheters to reach target areas of the vasculature. One of the major risks of endovascular navigation involves unintentional yet frequent contact between wires and catheters with the vessel wall, with the potential for perforation, dissection, thrombosis and embolization. This can have catastrophic consequences including subsequent organ failure, stroke and fatal hemorrhage [3]. When using endovascular approaches for device delivery (e.g. stent graft and artificial valves), accurate control and precision during catheter navigation become even more pertinent. Misalignment during stent deployment can result in major complications such as endoleak, migration and occlusion of major branches, which may result in organ or limb loss [1]. Furthermore, flexible articulation and accurate control are essential to the wider clinical uptake of the technology as any safety risks will undermine the potential gain in health-related quality-of-life scores.

Thus far, there is a growing interest in robotic steerable catheter technology which brought benefits such as improved precision and stability, reduced radiation doses, improved comfort and access to difficult and tortuous anatomy [4]. Commercially available robotic platforms are currently used in both electrophysiology (EP) and endovascular (EV) applications. Hansen Medical (Mountain View, CA, USA) developed two major robotic platforms for both EP (*Sensei X2*) [5] and EV procedures (*Magellan*) [6]. Other commercial platforms include the *Niobe* (Stereotaxis, St. Louis, MO), *Amigo* (Catheter Robotics Inc. NJ, USA), *Aeon Phocus* (Aeon Scientific, Switzerland), *CorPath GRX* (Corindus Vascular Robotics, MA, USA), and the *R-one* (Robocath, France). A comprehensive review of these systems is provided in [1] and [4]. However, the design of such platforms tends to alter the natural bedside manipulation skills of the operator, as the controlling of the robot in most platforms is based on directional buttons or joystick. Therefore, the manually acquired experience and dexterity of the surgeon are not well utilized. Also, many systems (excluding the *Sensei X2*) lack of haptic feedback, so that the vessel/catheter contact forces are not transmitted to the surgeon. Along with commercial platforms, several research solutions have been proposed for both EP and EV applications [1], [4]. Most groups [7]–[12] focused on integrating force feedbacks in their teleoperated platforms by embedding force sensors at the proximal or distal portion of the catheter that allows force feedback through commercial haptic interfaces (e.g. Phantom Omni or Falcon) and joysticks. However, incorporating force sensors into small instruments like catheters is practically difficult and requires modifying commercially-available instruments (compromising their clinical usability) or developing new high-cost proprietary instruments that limit the wide application of such platforms. Moreover, as mentioned earlier, the use of commercial haptic interfaces and joystick to manipulate the catheters, implies that such instruments are not manipulated in a natural way and the surgeons' manipulation skills are lost.

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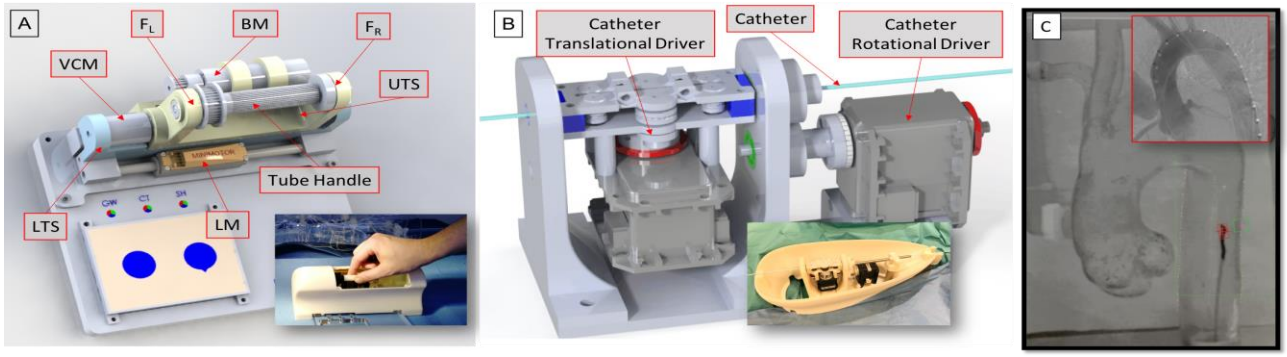



Figure 1. The CathBot surgical system. CAD renderings and photographs of the master manipulator (A) and the slave robot (B). The navigation system GUI showing the simulated fluoroscopic image of the aortic arch and the catheter used in this study. A real fluoroscopic image of an aortic arch (red-outlined) is showed for reference (C).

This paper presents a robotic platform for endovascular catheterization, i.e., CathBot, with vision-based haptic feedback. It allows the surgeons to precisely, naturally, manipulate the catheter through an ergonomic master interface (i.e. maintaining their catheterization skills), provide them with force feedback to "feel" contact forces between the catheter and the vessel, and based on conventional low-cost instruments. This work proposes a redesign of the Hamlyn's previous prototype [13], which was based on a master-slave force feedback system. That prototype allowed the surgeon to manipulate the catheter in a natural way, whilst providing robot assistance and force feedback (through strain gauges placed on the tip of a commercial catheter) during the insertion and retraction maneuvers. The key limitations of that system include the lack of robot-assistance and force feedback when twisting the catheter (which was done manually), and the need of embedding force sensors in the tip of the catheter. This restricted the system's usability in a real surgical environment. Building on the previous prototype, this paper introduces a new teleoperated robotic architecture with natural catheter maneuverability, new control system strategy, and new navigation system incorporating dynamic active constraints to provide vision-based haptic feedback to the surgeon whilst removing the need of incorporating force sensors in the catheter.

## II. CathBot: Surgical System Concept

Clinical requirement analysis of the system has defined two key aspects for the CathBot surgical system: (1) improved catheter maneuverability and ergonomic design of the master robot manipulator to capture natural skilled motion patterns and operation-tool interaction of existing catheter navigation workflow; (2) improved real-time catheter navigation and enhanced haptic feedback to minimize endothelial wall damages. The CathBot surgical system is based on a teleoperated master-slave configuration and is designed to address the above specifications. The main elements of the system (Fig.1) include:

*Master Manipulator (MM):* the hands-on manipulation design introduced in [13] has been extended improving the existing mechatronic design, interchangeability for both hand-on and remote operations, as well as ergonomic control and compactness of the device. Robot-assistance and force feedback are provided for both linear (push-pull) and rotational (twist) maneuvers of the catheter. By mimicking the manipulation of a manual catheter, it allows for more intuitive control of the robotic catheter while the skills of the operator are retained and enhanced with motion scaling and haptic feedback. The MM (Fig.1a) is composed by one tube handle, two independently translatable stages, three actuators, and two force sensors. The tube handle is manipulated by the surgeon in a manner that is similar to manual catheterization by allowing push, pull and twisting motions. The tube handle is mounted on the upper translatable stage (UTS) and connected to a brushless motor (BM) (DC2057B, Faulhaber) which provides rotational force feedback. The UTS is placed on the lower translatable slide (LTS) connected to a linear motor (LM) (LM1247- 040-01, Faulhaber) which is used produce the translational force feedback. Two unidirectional sensors $F_L$ and $F_R$ (FSS1500NS, Honeywell) are placed at the left and right end of the tube handle and used to make a bidirectional measurement for push and pull motions. A voice coil motor (VCM) (LVCM-019-022-02, Moticont) is connected to both UTS and LTS and provides catheter-vessel contact force feedback to the surgeon. The VCM was chosen as its analogue nature permits a quick translation of the contact forces to the surgeon (which was not possible using just the LM).

*Slave Robot (SR):* this device introduced in [14] (Fig.1b) works in conjunction with the MM to manipulate commercially available catheters. It consists of two servomotors (Dynamixel MX-28, RobotIS) that can push, pull and twist the catheter based on the motion commands generated by the surgeon manipulating the MM. The catheter is translated by a pair of friction wheels that are coupled to one of the servomotors. The steering is achieved by rotating the frame that holds the catheter.

*Navigation System with Dynamic Active Constraints:* by using the MM and SR described above, dynamic active constraints (DAC) with safety margins (adaptively enforced in real-time to constrain the catheter motion) are developed and integrated into the navigation system to provide vision-based haptic feedback. Unlike previous work [15], [16], dynamic motion tracking of both the vessel walls as well as their interaction with the catheter tip to minimize potential injury to the endothelial walls are incorporated. The navigation system presents a graphical user interface (GUI) that receives and display in real-time the intra-operative video of the surgical scene showing the patient anatomy and the catheter (Fig.1c).

*System Workstation:* it employs a host-target structure base on a PC (host), a real-time controller (target), and low-level motion controllers. The host PC runs the Navigation System and the CathBot configuration interface and is the first control layer through which the surgeon interacts with the surgical system (30Hz). The host PC communicates via Ethernet with the target (compactRIO 9022, National Instruments), which runs the control algorithms (1kHz) and process surgeon's input generating motion commands for the low-level motor controllers, i.e. MCBL3006S and MCLM3006S (Faulhaber) control the BM and LM respectively, LSC 30-2 (Maxon Motors) controls the VCM, and USB2Dynamixel (RobotIS) controls the MX-28. This configuration presents the following benefits: (1) the new design of the master manipulator allows the surgeon to fully manipulate (push, pull, twist) the catheter in a natural way, whilst providing haptic feedback to minimize the risk of damages to the vessel and potentially improving the overall precision and safety; (2) the slave robot, incorporating motion scaling, precisely replicates surgeon's input into the surgical field; and (3) the navigation system with dynamic active constraints provides vision-based haptic feedback with no need of incorporating force sensors in the catheter.

## III. Control Architecture

### A. Video Acquisition

Real-time 2D images of the surgical scene are used to create the DAC to regulate catheter motions and prevent catheter-vessel collision and endothelial damage. Real-time video of the surgical scene is acquired in the host PC (Windows 7, Intel i7-6700, 3.4GHz, 16GB RAM) and digitalized into image sequence for image processing. Either video provided by a camera (for lab experiment purpose) or x-ray fluoroscopy system (clinical experiments) can be acquired through an image grabber. In this study, we used a camera to provide visualization during the design phase and the experiments. We adjusted gain, contrast, brightness, and color intensity to simulate fluoroscopic images (see Fig.1c).

### B. Catheter Tracker

A commercial 5-Fr angiography catheter with radiopaque tip (Cook Medical, USA) has been used in this study. As the proximal end of the catheter is darker than the rest of the body, this information can be used to track the tip. A local descriptor for the tip of the catheter is initially created by using a low discrepancy sampling algorithm. This description data is stored in the system and then used to search for the catheter tip in each frame of the video. The IMAQ Match Pattern algorithm of the NI Vision 2013 library (National Instruments) was used for this purpose. This algorithm provides the position ($\boldsymbol{P_{TIP}} = [X_{TIP}, Y_{TIP}]$ in pixels) and orientation ($\theta_{TIP}$ in degrees) of the catheter tip in the video frame (Fig.2). Once the first tip position and orientation are calculated, a region of interest ($ROI_{TIP}$) around the tip is automatically generated (centered in $\boldsymbol{P_{TIP}}$) in order to reduce the processing time and the overall tracking accuracy and reliability.

### C. Vessel Tracker

The vessel tracking algorithm is schematized in Fig.2. A snapshot of the real-time video showing the vessels is initially captured. The surgeon draws the contour of the vessels ($\boldsymbol{V_{up}}$ and $\boldsymbol{V_{dw}}$) on the snapshot and this initial information are stored in the systems. Then – on each frame of the real-time video stream – the actual position of the catheter tip is compared with the vessel contours, and the points $\boldsymbol{P_{v_up}}$ on $\boldsymbol{V_{up}}$ and $\boldsymbol{P_{v_dw}}$ on $\boldsymbol{V_{dw}}$ with minimum distance from $\boldsymbol{P_{TIP}}$ are calculated. If the vessels were rigid and motionless, the distance between $\boldsymbol{P_{TIP}}$ and $\boldsymbol{P_{v_up}}$ and $\boldsymbol{P_{v_dw}}$ would be sufficient to create static active constraints and decide whether the catheter is in a "safe" area. However, blood vessels deform due to heartbeat, blood pressure and respiration. Therefore, the vessel walls must be tracked continuously as the initial – static – estimation is not accurate, reliable, and safe. Based on this initial estimation, two regions of interests, $ROI_{Vup}$ and $ROI_{Vdw}$ are placed in $\boldsymbol{P_{v_up}}$, and $\boldsymbol{P_{v_dw}}$ respectively. The area covered by these ROIs can be manually adjusted by the surgeon through the GUI based on the endothelial walls motion magnitude. An edge detector algorithm is then applied in both $ROI_{Vup}$ and $ROI_{Vdw}$ in order to extract the actual local contours of the vessel, i.e. $\boldsymbol{V_{up_act}}$ and $\boldsymbol{V_{dw_act}}$. Each local contour is approximated with a linear equation and its orientation calculated, i.e. $\theta v_{up}$ and $\theta v_{dw}$ (in degrees). The IMAQ Extract Contour and IMAQ Fit Contour algorithms of the NI Vision 2013 library (National Instruments) were used for this purpose. The actual position of the catheter tip $\boldsymbol{P_{TIP}}$ is then compared with the extracted local contours $\boldsymbol{V_{up_act}}$ and $\boldsymbol{V_{dw_act}}$ and the minimum distances between the catheter tip and the two vessels walls calculated, i.e. $d_{up}$ and $d_{dw}$. Finally, the actual local vessel diameter is calculated as $D = d_{up} + d_{dw}$, whilst the actual catheter-vessel distance as $d_{c\text{-}v} = min\ (d_{up}, d_{dw})$. In summary, the outputs of the algorithms described above are: (1) distance between the catheter and the closest vessel wall ($d_{c\text{-}v}$); (2) local vessel diameter ($D$); (3) local vessel walls orientations ($\theta v_{up}$, $\theta v_{dw}$); (4) catheter tip orientation ($\theta_{TIP}$).

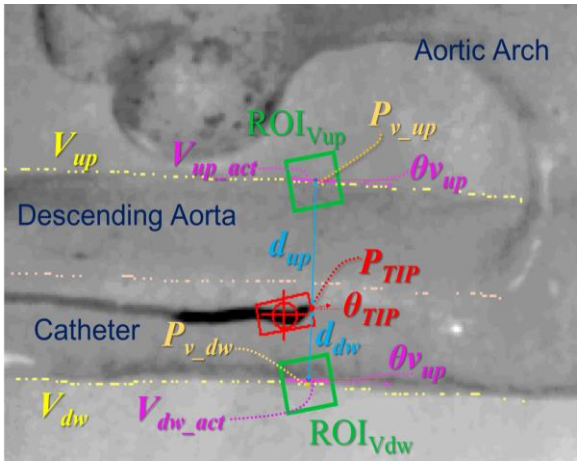


Figure 2. Components of the Catheter and Vessel tracker algorithms.

### D. Interactive Control with Dynamic Active Constraints

The information provided by the catheter and vessel trackers are used to create DAC. In this paper, two types of DAC algorithms are explored and integrated into the control system to provide to the surgeon with vision-based haptic feedback through the MM: (1) *viscous frictions* which increase proportionally to the catheter-vessel distance (i.e. the closer the catheter is to the vessel, the higher is the force feedback generated into the master manipulator to inform

the surgeon of the proximity of the wall); and (2) catheter-vessel *contact force* when the catheter touches the vessel wall. The control architecture is summarized in Fig.3.

Viscous frictions are generated through the BM an LM mounted on the master manipulator. The LM generates the linear friction (perceived when pushing and pulling the catheter), whilst the BM generates the rotational friction (perceived when twisting the catheter). The viscous friction for both BM and LM is modeled by:

$$v_{MM} = \frac{1}{k_d k_\vartheta} I \qquad (1)$$

where $I$ is the surgeon input, i.e., the current that goes through the motor when a force is applied on the tube handle, $v_{MM}$ is the control output (i.e. the master motor velocity), and $k_d k_\theta > 0$ is the damping of the virtual contacts. Two virtual contacts are considered in this study and used together to generate the vision-based haptic feedback. $k_d$ is generated by the proximity of the catheter tip to the vessel wall, and $k_\theta$ by the direction and orientation of motion of the catheter with respect to the vessel wall. These virtual contacts are modeled as described in (2) and (3).

$$k_d = \left|\frac{2d_{c-v}}{D} - 1\right| (M_d - 1) + 1 \qquad (2)$$

where $d_{c\text{-}v}$ is the distance between the catheter and the closest vessel wall, $D$ is the local vessel diameter (obtained as described in the previous section, Fig.2), and $M_d \geq 1$ is maximum damping achievable. In this study $M_d$ was empirically set to 40. According to (2), the damping of the virtual contact $k_d$ is minimum ($k_d = 1$) when the catheter is in the center of the vessel and increases while moving towards the wall. This is perceived by the surgeon as an increased viscous friction (generated by the motors through (1)).

$$k_\vartheta = \begin{cases} 1, & F_L > 0, \quad \theta \leq 0 \\ \theta M_\vartheta, & F_R > 0, \quad \theta > 0 \end{cases} \qquad (3)$$

where $\theta = \theta_{TIP} - \theta v$ is the difference between the orientation of the catheter and the closest vessel wall (calculated as described in the previous section), and $M_\theta \geq 1$ is a gain factor. In this study $M_\theta$ was empirically set to 60. The direction of motion is provided by the unidirectional force sensors placed at the left and right end of the tube handle on the MM. Given the configuration of the maser-slave robots (Fig.4), if the surgeon translates the tube handle on the MM towards "right", then the slave robot pushes the catheter. Otherwise, if the translation is towards "left", then the slave robot retracts the catheter. Direction of motion is captured by the force sensors accordingly (see Fig.1), i.e. $F_R > 0$ (pushing) and $F_L > 0$ (pulling). This information is processed by the control system to calculate $k_\theta$. According to (3), if the catheter is pushed towards the wall ($\theta > 0$ and $F_R > 0$), then the damping of $k_\theta$ is proportional to $\theta$. Therefore, the viscous friction generated by the motors (equation (1)) increases accordingly. On the other hand, if the catheter is parallel to the vessel wall (θ = 0), pushed away ($\theta < 0$ and $F_R > 0$) or retracted ($F_L > 0$), then the friction is minimum ($k_\theta = 1$).

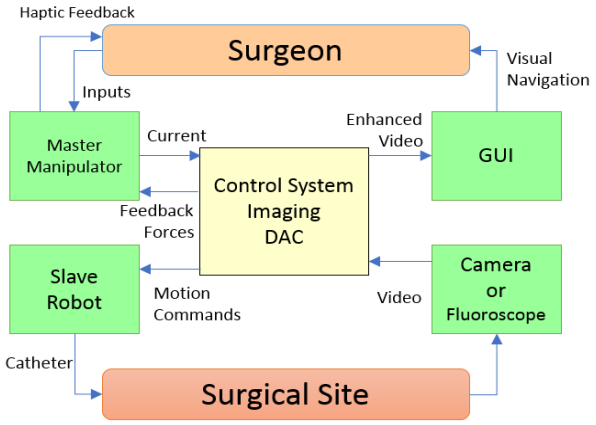



Figure 3. Block diagram of the CathBot vision-based haptic feedback.

Contact forces between the catheter and the vessel are generated through the VCM. When a collision between the catheter tip and the vessel wall is detected, i.e., $d_{c\text{-}v} = 0$, then the VCM is actuated in the opposite direction of motion, so that unidirectional force feedback is provided in the direction opposing the catheter insertion. This is obtained by adjusting the voltage $V_{VCM}$ supplied to the VCM. The voltage supplied to the VCM is proportional to the translational force $F_R$ applied by the surgeon to the tube handle and measured by the force sensing on the master manipulator. When no collision is detected (i.e. $d_{c\text{-}v} > 0$) the VCM is actuated in the same direction as the force exerted by the surgeon. The gain G was empirically determined and set to 1.2.

$$V_{VCM} = GF_R \qquad (4)$$

It worth noting that the contact forces and the linear viscous frictions should be perceived by the surgeon as decoupled. This feeling is obtained through the two independently translatable stages of the MM which physically decouple the LM (which transmits the viscous friction) and the VCM (which transmits the contact forces).

Finally, the velocity $V_{MM}$ calculated in (1) is used as the input for the slave robot motors, which are controlled in velocity:

$$v_{slave} = Sv_{MM} \qquad (5)$$

The velocity of each actuator of the slave robot is proportional to the corresponding actuator of the master robot by a scaling factor $S$. If needed, $S > 0$ can be varied by the surgeon during the experiment.

## IV. Experimental Validation

To demonstrate the effectiveness and usability of the CathBot system, a user pilot study was conducted. The study was designed to compare the robot-assisted cannulation of an artery using the CathBot system with and without the haptic feedback. Moreover, for further comparison, this user study was designed to exactly replicate the study conducted in [13] to compare the previous prototype with manual catheterizations. The experimental setup (Fig.4) consisted in a phantom of an anthropomorphic aortic arch (Elastrat Sarl, Switzerland) connected to a water pump to simulate the heartbeat, a commercial 5-Fr angiography catheter with radiopaque tip (Beacon Tip Van Schie 1 by Cook Medical, USA), and the CathBot system. A 6DOF load cell, (Nano17, ATI Industrial Automation, Inc., USA) was mounted below the phantom as described in [13] in order to measure the force exerted on the phantom during the cannulation

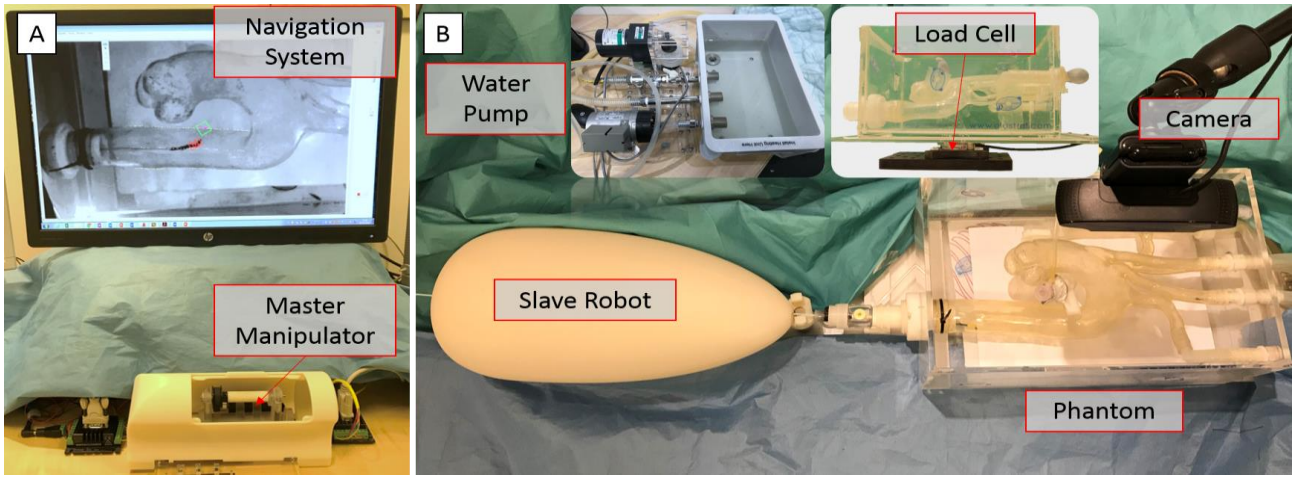



Figure 4. The master manipulator placed in front of the GUI (A). Just to its right (B), the slave robot manipulates the catheter inserted into the phantom, whilst the camera provides real-time video. A load cell is placed below the phantom to measure the force exerted during the experiments.

TABLE I. RESULTS: SYSTEM ASSESSMENT

| | Vision-based Haptic Feedback | No Haptic Feedback | *p* |
|---|---|---|---|
| Mean Maximum Force [N] | 0.21 | 0.54 | $1.2x10^{-4}$ |
| Overall Mean Force [N] | 0.03 ± 0.07* | 0.10 ± 0.13* | 0.005 |
| Mean Completion Time [s] | 21.2 ± 2.1* | 17.2 ± 8.9* | 0.111 |
| Mean Catheter-Vessel Distance [mm] | 8.98 ± 3.31* | 6.74 ± 2.88* | 0.035 |

* mean ± standard deviation

TABLE II. RESULTS: SUS SCORES

| | Questions | Vision-based Haptic Feedback | Robot-Assisted | Variation |
|---|---|---|---|---|
| | | Mean % | Mean% | % |
| S1 | I would like to use this system frequently | 73 | 50 | 45 |
| S2 | I found the system unnecessarily complex | 88 | 70 | 25 |
| S3 | I felt very confident using the system. | 58 | 28 | 109 |
| S4 | I found the various functions in this system were well integrated. | 83 | 65 | 27 |
| S5 | I thought the system was easy to use. | 80 | 60 | 33 |
| S6 | I thought there was too much inconsistency in this system. | 73 | 63 | 16 |
| S7 | I found the system very cumbersome | 88 | 63 | 40 |
| S8 | I think most people would learn to use this system very quickly. | 93 | 63 | 48 |
| S9 | I think that I would need the support of a technical person to be able to use this system. | 83 | 68 | 22 |
| S10 | I needed to learn a lot of things before I could get going with this system. | 95 | 73 | 31 |
| | **Global Score*** | **81** | **60** | **35** |

* p-value = 0.001

procedures. A camera was placed over the phantom to provide the visualization of the surgical site. As mentioned earlier, the images provided by the camera were processed to be well representative of the fluoroscopic images used in the clinical practice (Fig.1c). The phantom was covered so that the users could not directly look at it during the trials. The catheter was introduced into the phantom through an introducer sheath and tubing and connected to the CathBot. 10 non-medical users (8 male, 2 female) with no catheterization experience were asked to cannulate the left subclavian artery up to the left axillary artery by using the CathBot system with two different control conditions: (1) without haptic feedback, (2) with haptic feedback and dynamic active constraints. Each user was asked to perform four trials per each condition. Each first trial was used for training, thus not considered in the data analysis. The starting condition was randomly chosen. A two-stage procedure was conducted: (1) an objective assessment using the mean and maximum force exerted on the phantom, the mean and minimum catheter-vessel distance, and the mean completion time; and (2) a subjective assessment through a System Usability Scale (SUS) questionnaire (as used in [17]). Objective and subjective results are reported in Table I and II respectively. Results reported in Table I show a statistically significant (according to the Student's t-test) reduction of both the overall mean and maximum forces and the mean catheter-vessel distance when the haptic feedback is provided. The mean overall force exerted on the phantom is reduced of 70% ($p = 0.005$). The haptic feedback provided the necessary information to minimize the contact force between the catheter tip and the endothelial wall. This is confirmed by the 61% ($p = 1.2x10^{-4}$) reduction of the mean maximum forces. Also, the mean catheter-vessel distance is lower when the force feedback is not provided ($p = 0.035$). This, together with the force data analysis, suggests that the catheter tip spent more time in contact with the vessel wall when in such condition. These metrics are strictly related to the safety of the procedure and the effectiveness of the surgical system. High values of exerted force on the vessel and low catheter-vessel distances give an account of how far the catheter is from the ideal path. This implies that in case of

a real surgery, dangerous injuries can be procured to the endothelial wall. On these metrics, it is clear that the users performed better when the CathBot system with haptic feedback was used. The mean completion time is longer when haptic feedback is provided. This seems related to the system control law which slows down the actuator velocity due to the dynamic virtual fixtures, as explained in Section III. However, this comparison is not statistically significant ($p = 0.111$). The SUS questionnaire allowed the evaluation of general usability of the two control conditions using CathBot. The questionnaire (Table II) demonstrates that the users attribute a significant ($p = 0.001$) overall higher usability score to the haptic feedback condition (81%). More in detail, the users found the CathBot with haptic feedback easy to use (S5, 33% better), intuitive (S8, 48% better) and with a quick learning process (S10, 31% better). Finally, Fig.5 shows the force results of this study together with those conducted to compare our previous prototype with manual catheterization [13]. In the previous prototype, a commercial catheter was instrumented with strain gauges to provide force feedback to the user through the master-slave robotic manipulator. It worth noting that the result obtained with the CathBot system with vision-based haptic feedback are comparable (slightly better) to those obtained with the previous prototype, and better than manual catheterization results on the metrics evaluated. This demonstrates that vision-based haptic feedback is potentially effective. It can be successfully used instead of force sensor-based devices, thus avoiding incorporating force sensors into catheters, which would require to modify them, thus limiting their clinical usability.

## V. Conclusions

In this paper a new robotic system for endovascular catheterization, the CathBot, was presented with the objective to provide improved precision, ergonomics, haptic feedback, and safety for endovascular interventions. This was achieved with the new CathBot system architecture: an ergonomic master-slave system with navigation system and integrated vision-based haptic feedback. Unlike other commercial and research platforms [4], the system maintain the proximity of the surgeon to the patient as in traditional endovascular surgeries. Unlike previous work reported in literature [15], [16], dynamic motion tracking of both the vessel walls the catheter tip was incorporated to create dynamic active constraints and minimize potential injury to the endothelial walls. Surgical capabilities are augmented through motion scaling and intuitive control. The system was evaluated through a combined quantitative and qualitative evaluation demonstrating that the vision-based force feedback can improve the effectiveness, precision, and safety of endovascular procedures (70% decrease in mean force and 61% decrease in maximum force were observed when force feedback was provided). Also, the CathBot system with force feedback was perceived by the users as easy to use and intuitive. To the best of authors' knowledge, no robotic systems for endovascular procedures integrating the CathBot technical features have been reported in the relevant literature. Such integration is novel and represents the main contribution of this work. Next steps of development aim to optimize of the navigation system. Currently, the system requires continuous fluoroscopy to provide vision-based haptic-feedback, which would increase the radiation dose to the patient. Furthermore, the 2D nature of fluoroscopic imaging limits the navigation and the DAC to the imaging plane. Future work will focus on the implementation of 3D imaging through real-time shape instantiation [18], which will allow the implementation of 3D DAC, thus 3D vision-based haptic feedback.

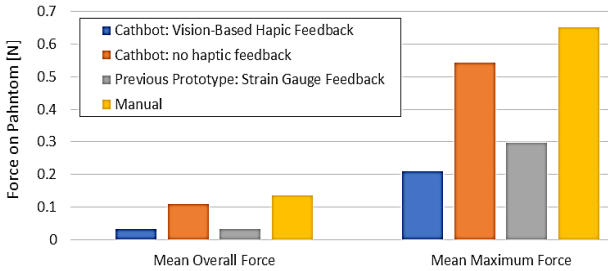



Figure 5. Box plot comparing the forces exerted on the phantom for this study and the study reported in [13].

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