A novel robotic catheter system with force and visual feedback for vascular interventional surgery

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Abstract: This paper proposes a novel master-slave robotic catheter operating system with force feedback and visual feedback for vascular interventional surgery (VIS). The robotic catheter system has good manoeuvrability, it can transmit the surgeon's skill to insert and rotate the catheter and avoids danger during VIS using force and visual feedback. In addition, it can be used to train unskilled surgeons to perform VIS. We performed a simulation experiment to validate our system using an endovascular evaluator (EVE). The experimental results demonstrated that the stability and response of the system were good. The robotic catheter system is suitable for performing VIS.

Keywords: catheter; endovascular evaluator; EVE; robotic surgery; force feedback; visual feedback; master-slave system; vascular interventional surgery; VIS.

Reference to this paper should be made as follows: Guo, J., Guo, S., Xiao, N., Ma, X., Yoshida, S., Tamiya, T. and Kawanishi, M. (2012) 'A novel robotic catheter system with force and visual feedback for vascular interventional surgery', *Int. J. Mechatronics and Automation*, Vol. 2, No. 1, pp.15–24.

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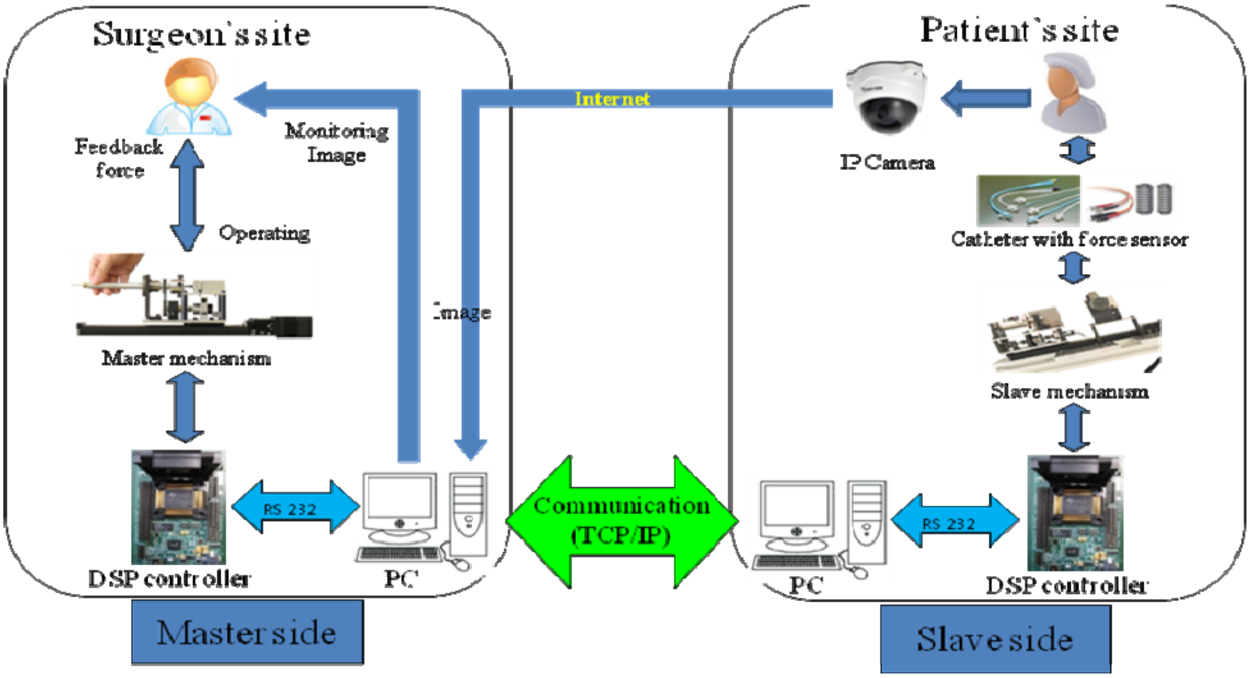
1 Introduction

The incidence of cardiovascular and cerebrovascular diseases has been increasing with the quickening pace of modern life. These diseases are a major cause of death, killing about 17 million people annually worldwide or accounting for 29.2% of all mortality based on a World Health Organization survey. Intracavity intervention is expected to become increasingly popular in medical practice, both for diagnosis and treatment because of the small incision, short recovery time and reduced burden on patients. In addition, it can prevent the surgeon from exposure to X-rays. Increasing numbers of minimally invasive diagnostic and surgical procedures are being performed using endoscopes or catheters. Recently, telesurgery performed using a microscopic micromanipulator system called the ‘NeuRobot’ was reported in neurosurgery. In this case report, the authors proved that the use of the NeuRobot was feasible using a private network (Goto et al., 2009). Many technological advances have been reported, including the following: a new prototype of a microcatheter with an active guidewire that has two bending degrees of freedom and is made using ionic conducting polymer film (ICPF) with a shape memory alloy (SMA) actuator fixed at its end to act as a servo actuator (Fukuda et al., 1994; Guo et al., 1996); a master-slave catheterisation system for positioning a steerable catheter (Fu et al., 2011); a new catheter driving method using a linear step mechanism for intravascular neurosurgery (Arai et al., 2002); bio-feedback application of an electromyography (EMG) signal (Wu and Chen, 2011); a robust internal model for controlling the depth of anaesthesia (Abdulla and Wen, 2011); force sensors based on a catheter operating system (Guo et al., 2007, 2010a, 2010b; Feng et al., 2006; Wang et al., 2008); research on an tele-operating system for medical application (Marcelli et al., 2008); state-of-the-art in force and tactile sensing for minimally invasive surgery (Puangmali et al., 2008); a feasibility study measuring the tip and side forces of a novel catheter prototype (Polygerinos et al., 2009) and contact and friction between the catheter and blood vessel (Takashima et al., 2005, 2007); and a novel hybrid wireless microrobot for medical application (Pan et al., 2011). Wang and Meng (2011) reported on the actuation and localisation of an active capsule endoscope and Marcelli et al. (2008) reported a novel telerobotic system to navigate standard electrophysiology catheters remotely. Further, Preusche et al. (2002) reported the concept of teleoperation in minimally invasive surgery. In addition, a robot mechanism for the remote steering and positioning of interventional devices has been fabricated (Srimathveeravalli et al., 2010), remote-controlled vascular interventional surgery robot was reported (Wang et al., 2010). Overview of the vascular interventional robot was reported by Da et al. (2008).

Figure 1 Conceptual diagram of the robotic catheter system (see online version for colours)



Typically, a skilled surgeon is needed to guide a catheter or endoscope. No existing robotic catheter system can match a surgeon's skill at inserting and rotating a catheter for training unskilled surgeons.

In this paper, we proposed a master-slave robotic catheter system that can transmit the surgeon's skill at inserting and rotating a catheter. It avoids danger and improve the safety during vascular interventional surgery (VIS) by making use of force feedback and visual feedback.

2 The overview of the robotic catheter system

A conceptual diagram of the master-slave robotic catheter system is shown in Figure 1. On the master side, the surgeon views a monitor and operates the catheter. The control instructions are transmitted to the slave side. On receiving instructions, the slave mechanisms drive the catheter; the motions of the catheter on the slave side follow the motions of the catheter on the master side. Consequently, the surgeon appears to operate the catheter as though adjacent to the patient, controlling the position and velocity of the catheter. An IP camera is used to monitor the operation and give visual feedback. If the catheter contacts a blood vessel wall, the force is detected and transmitted to the surgeon's hand, realising force feedback. Figure 2 is a flow chart of the control instructions for our robotic catheter system. The robotic system avoids danger during the operation via force and visual feedback.

Both master manipulator and slave manipulator employ DSP (TI, TMS320F28335) as their control units, communication between master manipulator and slave manipulator is realised by the TCP/IP protocol communication.

2.1 Master mechanism

On the master side, the slide platform is fixed on the supporting frame (Figure 3). The master system devices, including a left handle with one switch, a right handle, step motor, load cell, and maxon motor, are on the slide platform. A switch placed on the left handle is used to control these two graspers in slave side, only one switch is enough because the catheter is clamped by one grasper at the same time. Operator's action is measured by using the right handle. The handle takes the same movement motion with the slave manipulator, it has two DOFs, one is axial motion and the other one is radial motion. The handle is sustained by a bearing, and is linked to a loadcell, a pulley is fixed on the handle, a DC motor is applied to generate torque feedback, and a pulley which is couple to the upper one is fixed to the axle of the motor. The step motor is used to drive the slide platform forward and backward.

Figure 2 Flow chart of the control instructions for the robotic catheter system (see online version for colours)

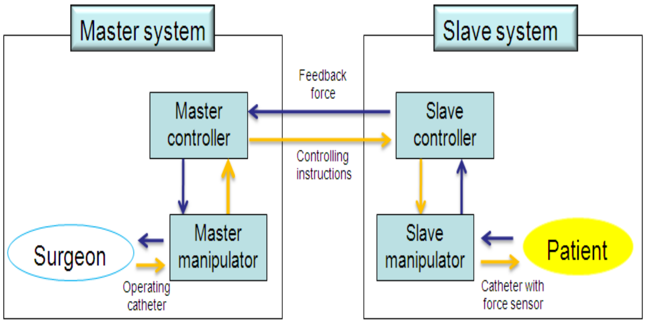
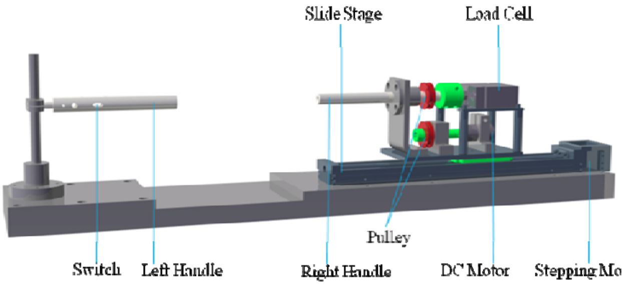


Figure 3 Mechanism of master system (see online version for colours)

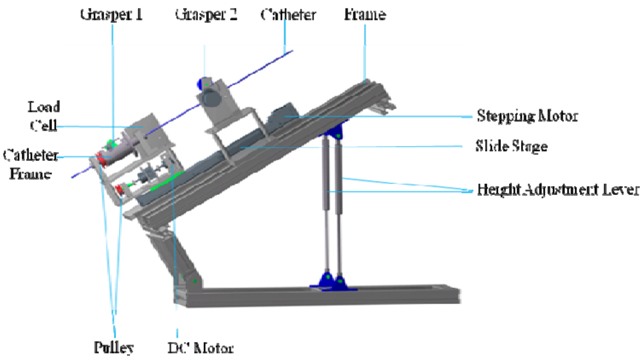


The surgeon moves the catheter forward and backward or rotates the right handle on the master side as though the surgeon was beside the patient. The operating information from the handle is transmitted to the slave side, where the catheter clamp inserts and rotates the actual catheter as commanded from the master side. If the catheter contacts a blood vessel wall, the load cell detects it and the information is transmitted to the surgeon's hand. Force feedback is realised by the master-slave robotic catheter operating system. The surgeon feels the contact, and no X-rays are required during intravascular neurosurgery.

2.2 *Slave mechanism*

The slave side mechanism shown in Figure 4 is similar to the master side, it also has two DOFs, one is axial motion along the frame, and the other one is radial motion, two graspers are placed at this part. The operator can drive the catheter to move along both axial and radial when the catheter is clamped by grasper 1. The catheter keeps its position and the catheter driven part can move smoothly when the catheter is clamped by grasper 2. The slave side consists of a catheter clamping device, two DC motors, a slide platform, step motor, maxon motor, load cell, torque sensor, and support frame. a slide platform is fixed on the supporting frame. The devices of the slave system are on the slide platform. The step motor is used to the drive slide platform forward and backward and the maxon motor is used to rotate the catheter. The two DC motors are used to control the catheter graspers. The load cell is used to measure the force between the catheter and blood vessel wall and the torque sensor and maxon motor are used to measure the information of catheter rotation during the operation. The measured force information is transmitted to the surgeon's hand, so that the surgeon can feel the feedback information from the slave side. A switch on the left handle on the master side controls the catheter graspers. When the operator wants to insert or rotate the catheter, grasper 2 is raised and grasper 1 clamps the catheter. The catheter navigator moves forward with the catheter for insertion or rotation. The grasper 2 then clamps the catheter; grasper 1 is raised and the catheter navigator moves backward. Repeating these actions, the actions of the slave side follow the commands of the master side. If the catheter contacts the blood vessel wall, the force information is detected and transmitted to the surgeon's hand.

Figure 4 Mechanism of slave system (see online version for colours)



2.3 *Mechanism control*

In order to ensure the consistency and stability of the robotic catheter system, for both the rotating and inserting motions, a proportional-integral-derivative (PID) control method was developed for the robotic catheter operating system. A numerical simulation indicated that the response of the system was good using the PID control method. Furthermore, we did a simulation experiment using the robotic catheter system with the PID control strategy. The experimental results show that the response and consistency were good, enabling a surgeon to perform intravascular neurosurgery.

2.3.1 *Control strategy for inserting motion*

We used the PID algorithm to assure accurate inserting motion, while reducing the hysteresis in real time. The following dynamic equation represents the control in the inserting direction:

$$F(t) = m\,\ddot{x}(t) + c\dot{x}(t) + kx(t) \tag{1}$$

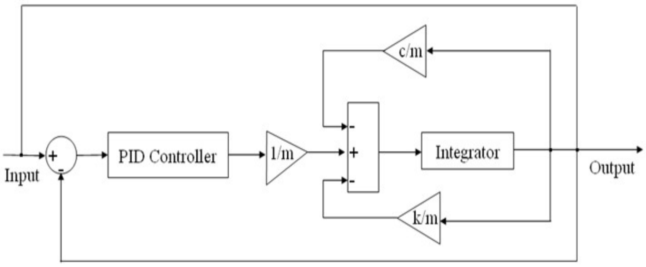
where $F(t)$ is the force applied by the operator, $x(t)$, $\dot{x}(t)$, and $\ddot{x}(t)$ are the displacement, velocity, and acceleration of the operator's hand, respectively, m is the quality of the robotic catheter operating system (on the slide platform on the master side), c is the viscous damping coefficient, and k is the stiffness.

When the operator operates the right handle on the master side, the load cell measures the force. Using a dynamic equation based on the relationship between the operating force and resistance, the PID control strategy is used to adjust the consistency of the operating force in order to avoid overshoot. Figure 5 outlines the control of the inserting motion. The parameters of the operating system are as follows:

$$m = 2\text{ kg}, c = 0.02\text{ N/(m/s)}, k = 10\text{ N/m}$$

As on the master side, based on the input and output of the step motor, we used the same PID control strategy on the slave side to control the consistency and response of the slave mechanism during insertion.

Figure 5 The control of the inserting motion



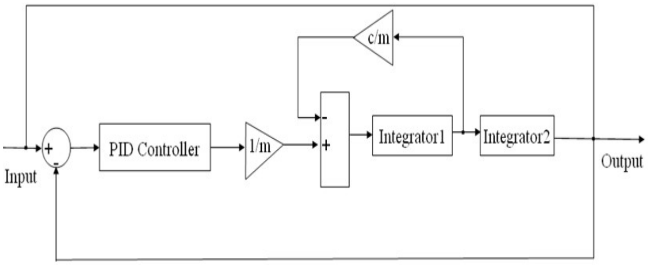
2.3.2 *Control strategy for rotating motion*

Equation (2) represents the dynamic equation based on the torque balance for the rotating motion on the master side, where m is the quality of the catheter operating system (on the slide platform on the master side), *c* is the viscous damping coefficient, $m = 2$ kg, $c = 0.02$ N/(m/s), θ is the rotating angle of the right handle, $u(t)$ is the variation in the torque, which is the torque of the maxon motor, $\dot{\theta}$ is the angular velocity, and $\ddot{\theta}$ is the angular acceleration. The control of rotation is shown in Figure 6.

$$m\ddot{\theta} + c\dot{\theta} = u(t) \tag{2}$$

As on the master side, based on the input and output of the maxon motor, we used the same PID control strategy on the slave side to ensure the consistency and response of the slave mechanism for rotation.

Figure 6 The control of the rotating motion



3 Characteristics evaluation

3.1 *Evaluation method*

3.1.1 *Evaluation of master manipulator*

To evaluate the measurement precision of controller in master side, Two experiments were carried out. One is to evaluate the measurement precision of axial movement and the other one for radial movement. For the first experiment, we pulled and pushed the handle to make the movement stage go forward and backward for about two minutes, then measured the axial displacement by a laser sensor (KEYENCE Inc., LK-500, high precision mode, 10 μm/mV). An A/D convert board (Interface Inc., PCI3329) was applied to get the displacement data to the computer (HP, z400), the sampling frequency was 100 Hz. And at the same time, the measurement data of the controller was send to the same computer by serial port, the sampling frequency of the controller was set to 100 Hz, baud rate of the serial port was set to 9,600. After comparing these two groups of data, the axial measurement precision of the controller could be evaluated, the conceptual diagram is shown in Figure 7. In the second experiment, radial measurement precision is evaluated. As well as the first experiment, we rotated the handle in clock wise and anti clock wise for two minutes, then measure the rotation angle by outside sensor and by the encoder couple to the handle of controller. A three-axis inertial sensor (Xsens Inc. MTx, resolution 0.1 deg) is fixed on the handle to get the rotation angle. The sampling frequency of the inertial sensor is set to100 Hz as the same as the controller. Sampling data of the controller was send to the computer by serial port, the conceptual diagram is shown in Figure 8.

Figure 7 The evaluation for axial motion (see online version for colours)

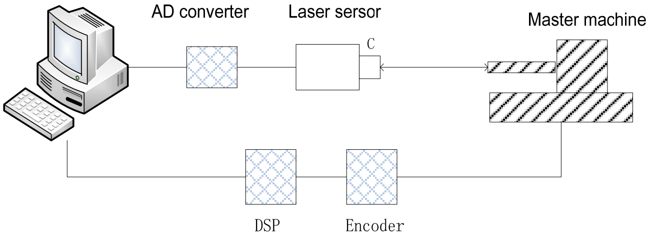
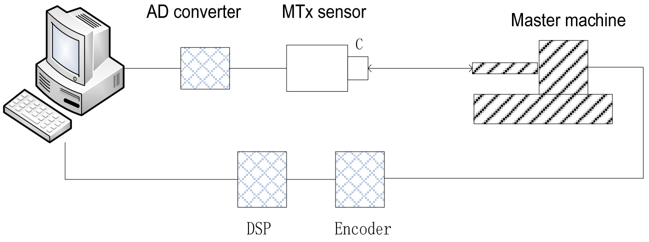


Figure 8 The evaluation for radial motion (see online version for colours)



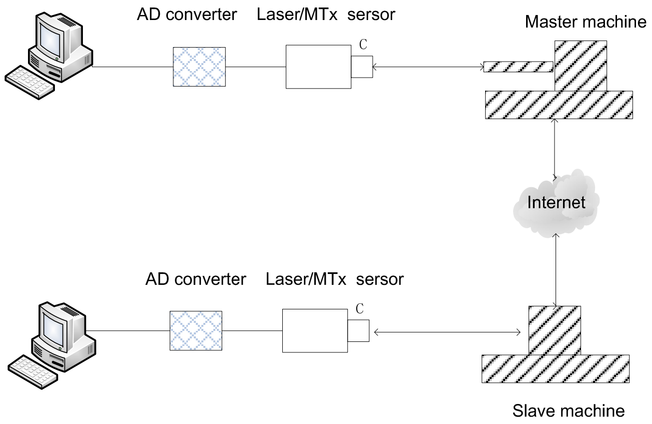
3.1.2 *Evaluation of slave manipulation*

To evaluate the measurement precision of the slave manipulator, there are two experiments. The first experiment is to evaluate the axial movement precision. The slave manipulator was programmed to move along a reciprocating trace in axial. Then the actual displacement of the machine is measured by laser sensor. The second experiment is to evaluate the radial precision. We programmed the machine to make the catheter frame rotated back and forth. The actual rotation angle is measured by inertial sensor. In these two experiments, actual data and theoretical date were compared to obtain the precision of the slave manipulator.

3.1.3 *Evaluation of the tracking performance*

In this part, we did experiment to evaluate the tracking performance. In the experiment, we ignored the time delay between the master manipulator and slave manipulator. We just evaluated the tracking performance of the axial displacement and rotation. Firstly, we pulled and pushed the controller in master side from right end to left end then go back, we kept the axial displacement by laser sensor in both master manipulator and slave manipulator. To compare these two groups of data, the synchronisation of the master manipulator could be obtained. This procedure was carried out for four times. Similarly, the synchronisation of rotation could be obtained. The conceptual diagram for evaluating tracking performance is shown in Figure 9.

Figure 9 The evaluation for tracking performance (see online version for colours)



3.2 *Evaluation results*

3.2.1 *Evaluated results of the master and slave manipulators*

In master side, mean value and variance of the error between the laser sensor and the master manipulator are calculated. Similarly, we got mean value and variance of the error between the actual value and the theoretical value. The results are listed in Tables 1 and 2.

Table 1 Precision evaluated result (master manipulator)

Master manipulator	*Mean*	*Variance*
Axial (mm)	0.35	0.025
Radial (deg)	3.1	2.1

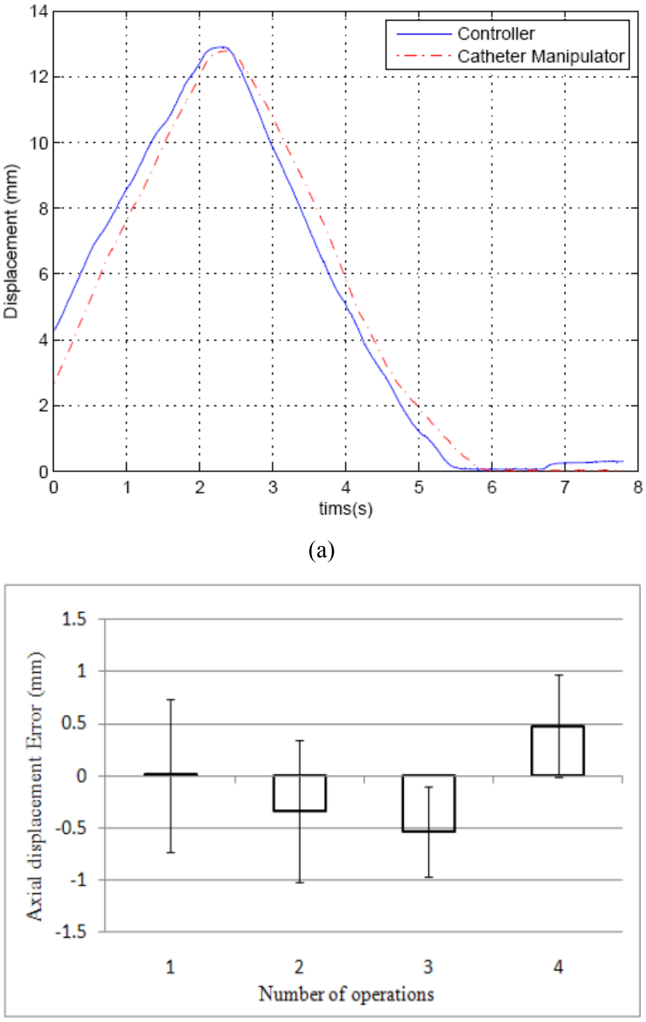
Table 2 Precision evaluated result (slave manipulator)

Slave manipulator	*Mean*	*Variance*
Axial (mm)	0.23	0.04
Radial (deg)	2.2	3.0

3.2.2 *Evaluated results of the synchronisation*

In the evaluated experiments, we measured the axial displacement and rotation of both master manipulator and slave manipulator for four times. Figure 10(a) shows the axial tracking experimental results of four operations. Figure 10(b) shows the axial tracking statistic. Similarly, Figure 11(a) shows the rotation tracking evaluated results, Figure 11(b) shows the rotation tracking statistic.

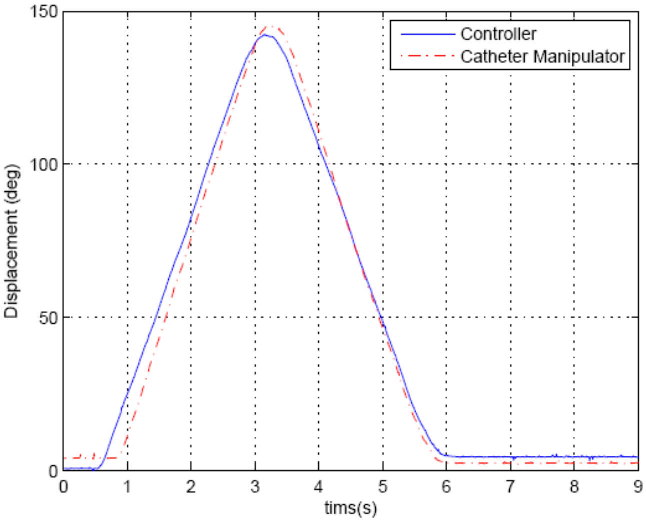
Figure 10 Axial displacement of both side, (a) axial tracking curve (b) axial tracking statistic (see online version for colours)



(a)

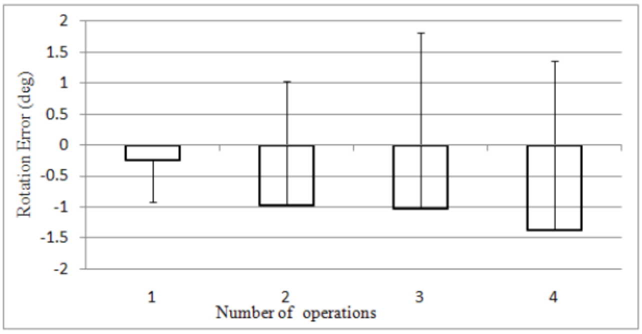
(b)

Figure 11 Rotation of both sides, (a) rotation tracking curve (b) rotation tracking statistic (see online version for colours)



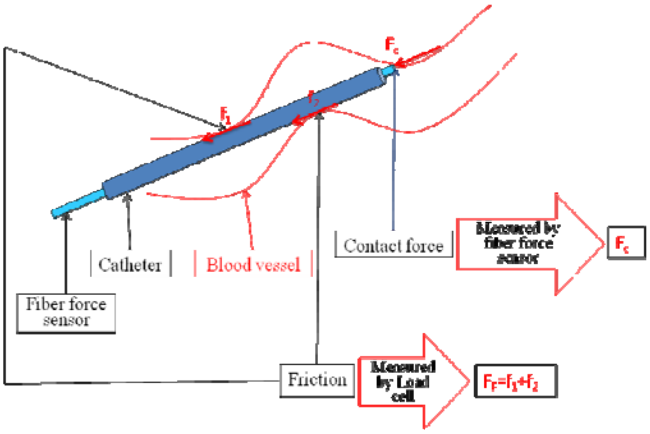
(a)

Figure 11 Rotation of both sides, (a) rotation tracking curve (b) rotation tracking statistic (continued) (see online version for colours)



(b)

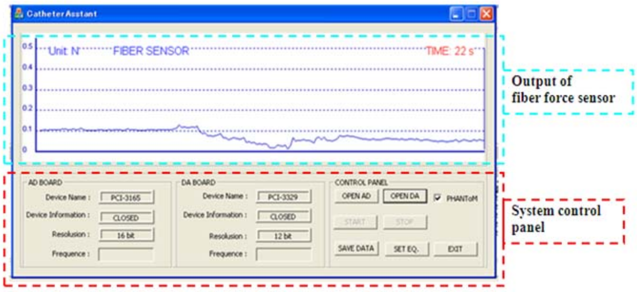
Figure 12 Measuring contact force and friction (see online version for colours)



4 Force and visual feedback

In order to enhance the security of the robotic catheter system during VIS, we added force feedback and visual feedback to the robotic catheter system. An IP camera is used to monitor the operation. It is connected to a personal computer (HP, z400) on the master side. There are two kinds of force between catheter and blood vessel, one kind of force is contact force between catheter tip and blood vessel, and the other kind of force is friction between catheter and blood vessel. Figure 12 shows the conceptual diagram of measuring force between catheter and blood vessel. The contact force between catheter tip and blood vessel measured by the optical fibre force sensor is transmitted to the operator using our force information monitoring system shown in Figure 13. The optical fibre force sensor is passed through inside the blood vessel, it served as a guidewire to lead the catheter during insertion and rotation. We used an FOP-M optical fibre force sensor made by FISO Technologies in this experiment. The measurement accuracy of optical fibre force sensor is 0.0005 N. A flow chart of the visual feedback is shown in Figure 14. The force between the catheter and blood vessel wall is measured by the load cell, and transmitted to the operator's hand in real time. The measurement accuracy of the load cell is 0.01 N. A flow chart of the force feedback signal is shown in Figure 11.

Figure 13 User interface for monitoring contact force (see online version for colours)



AD BOARD
Device Name : PCI-3165
Device Information : CLOSED
Resolution : 16 bit
Frequence :

DA BOARD
Device Name : PCI-3329
Device Information : CLOSED
Resolution : 12 bit
Frequence :

CONTROL PANEL
☑ PHANToM

Figure 14 Transmission flow chart of visual feedback

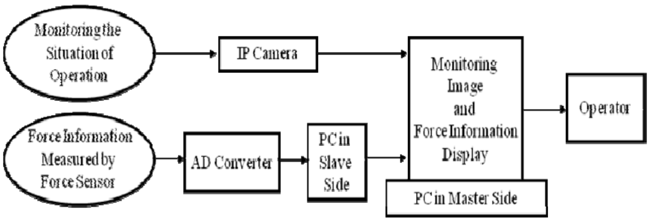
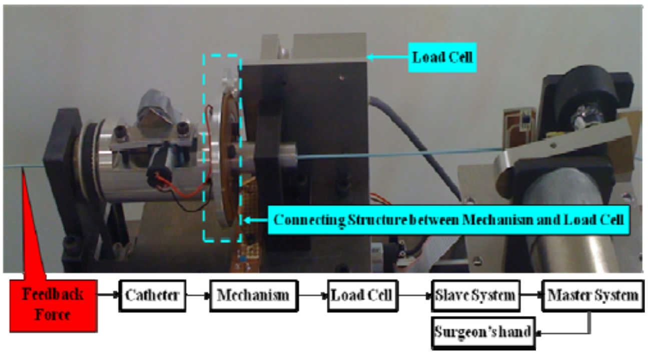


Figure 15 Transmission flow chart of force feedback (see online version for colours)



Based on the force feedback system and visual prompting information system, the operator can feel and know the contact information between catheter and blood vessel clearly, according to the contact information, the operator can ensure the safety during VIS.

5 Catheter insertion experiment

5.1 Insertion experiment

To validate the effectiveness of the robotic catheter operating system, we performed a simulation experiment to evaluate the characteristics of the master-slave robotic catheter operating system using an endovascular evaluator (EVE) (Figure 16), which consisted of a fluid control unit and blood pressure monitoring instrument. The bending angles and radii of the tubes in the EVE are close to those of human arteries. The tubes were made of silicon rubber. The elasticity of the tubes was similar to that of a blood vessel wall. In order to keep the blood pressure of the EVE close to the blood pressure of a human, the fluid control unit was used to adjust the blood pressure, which was monitored with the blood pressure monitoring instrument. The operator operates the right handle on the master side to insert and rotate the catheter, which is inserted into the EVE from the femoral artery, controlling the speed and position of the catheter. The simulation experiment is shown in Figure 17.

Figure 16 The EVE model (see online version for colours)

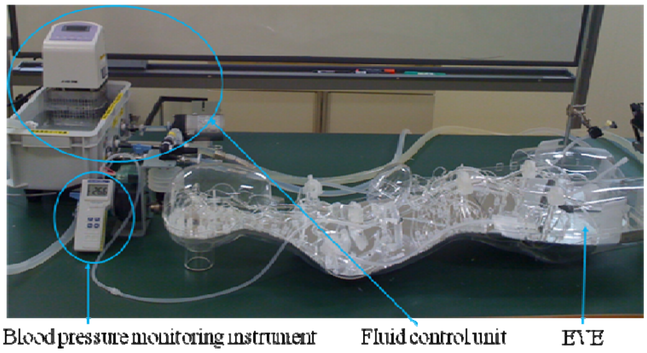
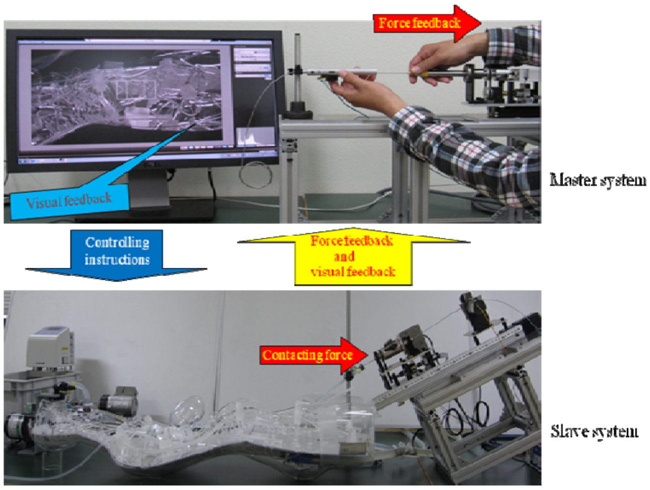


Figure 17 Simulation experiment in vitro by using EVE model (see online version for colours)



5.2 *Experimental results*

We evaluated the robotic catheter system in a simulation experiment. Figure 18 shows the results for the inserting motion, where the x-axis is the time axis and the y-axis is the displacement of the right handle on the master side (blue curve) and the catheter on the slave side (red curve). An upward slope is forward movement and a downward slope is backward movement. Figure 19 shows the evaluation of rotation, where the x-axis is the time axis and the y-axis is the rotation of the right handle on the master side (blue curve) and the catheter on the slave side (red curve). From Figures 18 and 19, the motions of the slave side follow the operating motions of the master side coincide very well in real time.

Figure 18 Evaluated results for catheter insertion (see online version for colours)

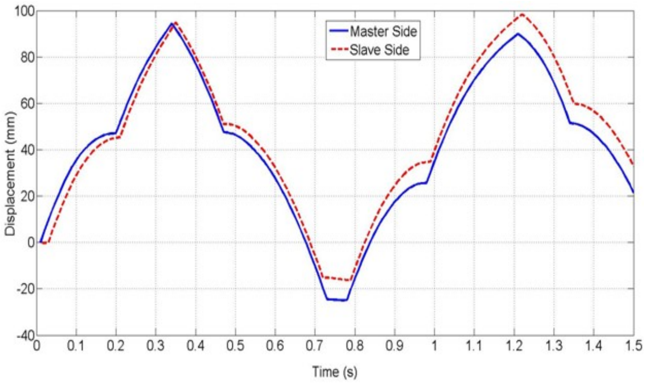
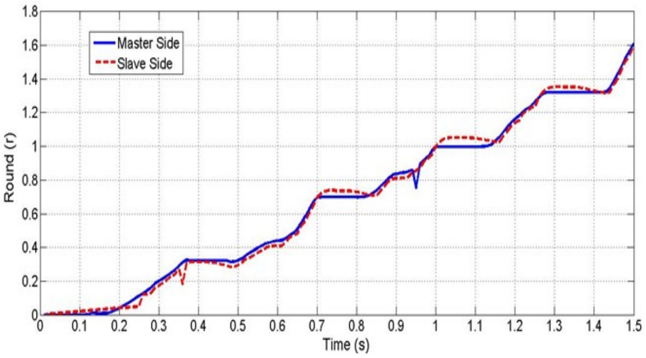


Figure 19 Evaluated results for catheter rotation (see online version for colours)



The load cell on the master side measures the operating force of the operator's hand. As shown in Figure 20, the average operating force is about 1.5 N. The measured insertion force is shown in Figure 21, and this is also the feedback force transmitted to the operator's hand. The force sensors measure the contact force between the catheter and blood vessel wall. The fibre force sensor measures the force between the tip of the catheter and the blood vessel wall, the output of the fibre force sensor is shown in Figure 22.

The experimental results indicate that our robotic catheter system can be used to perform VIS, without risk. The insertion force of the catheter is measured and fed back to the operator's hand, as is the contact force measured by the force sensor and load cell.

Figure 20 The operating force of the surgeon's hand (see online version for colours)

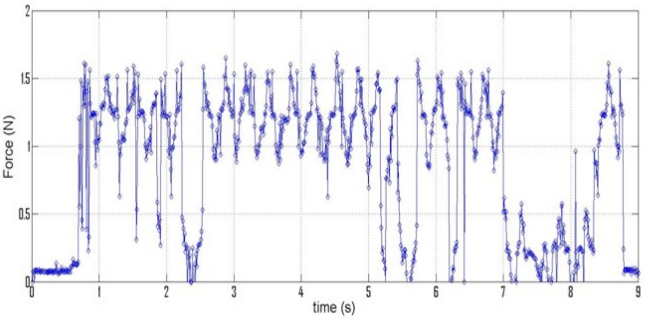


Figure 21 The feedback force from the slave side (see online version for colours)

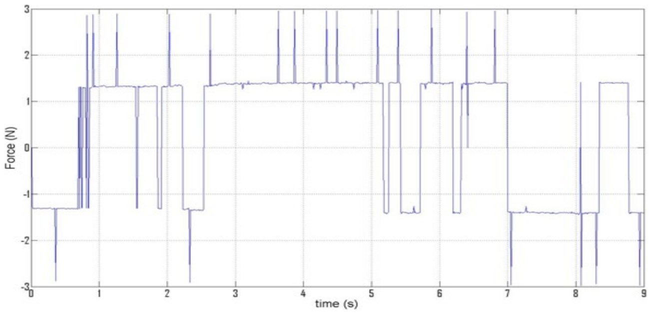
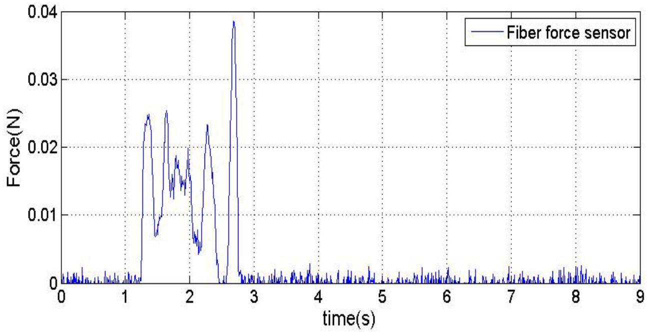


Figure 22 Contact force between catheter tip and blood vessel (see online version for colours)



6 Discussion

The performance and a simulation experiment were carried out to validate our robotic catheter system. The evaluated results listed in Tables 1 and 2 show the precision of the catheter system, the precision of master manipulator measured is 0.35 mm, and it has a very small variance. Rotation precision of the master manipulator is 3.1° with the variance of 2.1°. In the slave side, the precision of axial direction is 0.23 mm, the rotation precision is 2.2° with a variance of 3.0°. From the evaluated results we can know that the precision in axial direction is better than the radial direction for both sides.

In this paper, we did not consider the time delay of the remote control. Figure 10 shows the evaluated results of synchronisation of axial direction. The master manipulator and slave manipulator are controlled by DSPs, DSPs communicate with each other with the serial peripheral interface (SPI) port and RS422. The distance between the master manipulator and slave manipulator is about 5 m. Based on the numbers of communication data and the distance, the SPI communication is fast enough to make the lag below 1 ms in theory. However, from Figure 10(a) we can know the movement curve of the master manipulator is fast than slave manipulator, it indicated that the lag exists. The lag time is going to be measured in the future. We repeated the procedure for four times, Figure 10(b) shows a statistic result, to evaluate the tracking precision, we have to align the data of two side. The peak values were aligned artificially to eliminate the effect of the lag. The movement value is about 20 ms. From the result in Figure 10(b), the axial error between master manipulator and slave manipulator are below 0.6 mm, and the standard deviation is below 1 mm. Figure 8 shows the rotation tracking error. As well as the master manipulator, lag could be found in Figure 11(a). Figure 11(b) shows the statistics of the evaluated results. Before getting the result, the data was aligned artificially. The mean error of the rotation is below 1.5°, but with a large standard deviation. It means a not stable radial motion. The mean overshoot mainly caused by the electromagnetic interface to the AD converter which is used to drive the motor. The control circuit should be redesigned. And with different operator the radial tracking error is different because of the different rotation speed.

In order to enhance the stability and consistency of the robotic catheter system, we used a PID control strategy. The experimental results indicate that the response and consistency of the system were good, enabling a surgeon to perform VIS. It can also be used to train surgeons to insert and rotate a catheter for VIS smoothly. Nevertheless, due to the accuracy of the measuring device, the robotic catheter system is not ideal. In the future, we will improve the system. In addition, in the simulation experiment we used distilled water with a lubricant to simulate blood. Since the viscosity of distilled water differs from that of blood, the experimental results will differ slightly from an actual operation. We plan to improve the system by conducting animal experiments.

7 Conclusions and future work

This paper proposed a novel master-slave robotic catheter operating system with force and visual feedback for VIS. The mechanisms on both the master and slave sides were constructed and a control system was built. We performed evaluated experiments and a simulation inserting experiment to validate the system. The evaluated and experimental results indicated that the system was reliable, and danger was avoided during VIS via force and visual feedback.

In the future work, we plan to test the system *in vivo* in animal experiments. Furthermore, we will extract operating data to establish a database for skilled surgeons that can be used to train novice surgeons.

Acknowledgments

This research is supported by Kagawa University Characteristic Prior Research Fund 2011.

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