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RESEARCH PAPER

Evaluating performance of a novel developed robotic catheter manipulating system

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Abstract Manual operation of the catheter is inaccurate in minimally invasive surgery, requires dexterous and efficient manipulation for the catheter and exposes the surgeons to intense radiation. A novel robotic catheter manipulating system has been developed with remote navigation to reduce the performance error and irradiation to surgeons. In addition, unlike the conventional technique which requires surgeons to manipulate the catheter using their hands, remote systems always have removed surgeons' hands and replaced from joystick and handle, thus withdrawing their unique skills and experience. The proposed novel robotic catheter manipulating system presented that surgeon could manipulate the catheter that is same to the surgeons' often use. The surgeon console (the master side) used to measure the axial and radial motions of input catheter transferred to the catheter manipulator (the slave side). Also, we designed the haptic device in the surgeon console and proximal measurement mechanism of resistance force in the catheter manipulator to provide the force feedback feeling and get the resistance force during input catheter. Performance evaluation of system was conducted to test both the dynamic and static performance of manipulation and synchronization between master and slave side. Finally, tele-operation has been done by endovascular evaluator (EVE) simulator. The experimental results showed the system has the ability to be a training system for neurosurgeons and to complete the clinical interventional surgery in the future.

Keywords Index terms · Minimally invasive surgery · Performance evaluation · Tele-operation · Catheter manipulating system · Surgical robotics

1 Introduction

Endovascular intervention is expected to become increasingly popular in medical practice, both for diagnosis and for surgery. However, as a new technology, it requires a lot of skills in operation. In addition, the operation is carried out inside the body, it is impossible to monitor it directly. Much more skills and experience are required for doctors to insert the catheter. In the operation, for example the catheter is inserted through patients' blood vessel. Any mistakes would hurt patients and cause damages. An experienced neurosurgery doctor can achieve a precision about 2 mm in the surgery. However, the contact force between the blood vessel and the catheter cannot be sensed. During the operation an X-ray camera is used, and long time operation will cause damage to the patient. Although doctors wear protecting suits, it is very difficult to protect doctors' hands and faces from the radiation of the X-ray. There are dangers of mingling or breaking the blood vessels. To overcome these challenges, we need better technique and mechanisms to help and train doctors. Robotic system takes many advantages of higher precision, can be controlled remotely etc. However, compared with hands of

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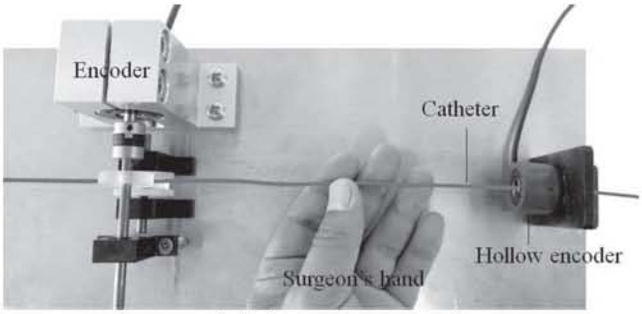
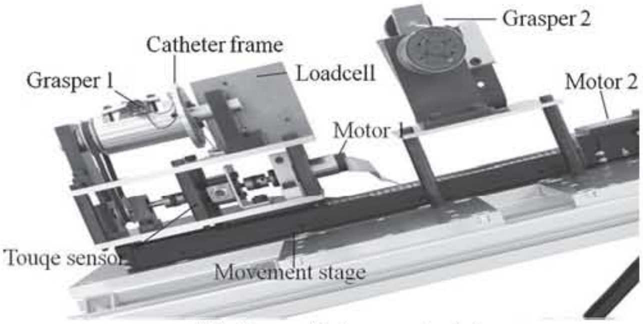


(a) The surgeon console



(b) The catheter manipulator

Fig. 1 The robotic catheter manipulating system

human being, none of a robotic system could satisfy all of the requirements of an endovascular intervention.

Not only because the machine is not as flexible as hands of human being but also lacks of touch. In any case, robotic catheter manipulating system could provide assistant to surgeons during the operation, but it has a long way to go to replace human being.

A lot of products and researches are reported in this area. One of the popular products is a robotic catheter placement system called Sensei Robotic Catheter System supplied by Hansen Medical [3, 6] (http://www.hansenmedical.com/home). The Sensei system provides the physician with more stability and more force in catheter placement with the Artisan sheath compared to manual techniques, allows for more precise manipulation with less radiation exposure to the doctor, and is commensurate with higher procedural complications to the patient. Because of the sheath's multiple degrees of freedom, force detection at the distal tip is very hard. Catheter Robotics Inc. has developed a remote catheter system called Amigo (http://catheterrobotics.com/CRUS-main.htm). This system has a robotic sheath to steer catheter which is controlled at a nearby work station, in a manner similar to the Sensei system. The first human trail of this system was in April 2010 in Leicester UK, where it was used to ablate atrial flutter. Magnetecs Inc produced their Catheter Guidance Control and Imaging' (CGCI) system (http://www.magnetecs.com/). This system has 4 large magnets placed around the table, with customised catheters containing magnets in the tip. The catheter is moved by the magnetic fields and is controlled at a nearby work station. The Stereotaxis Inc developed a magnetic navigation system: the Stereotaxis Niobe (http://www.stargen.eu/products/niobe/). The system facilitates precise vector based on navigation of magnetically-enabled guide wires for percutaneous coronary intervention (PCI) by using two permanent magnets located on opposite sides of the patient table to produce a controllable magnetic field. Yogesh Thakur et al. [26] developed a kind of remote catheter navigation system. This system allowed the user to operate a catheter manipulator with a real catheter. So surgeon's operative skills could be applied in this case. The disadvantage of this system is lack of mechanical feedback. T. Fukuda et al. [1] at Nagoya University proposed a custom linear stepping mechanism, which simulates the surgeon's hand movement. Regarding these products and researches, most concerns are still the safety. Force information of the catheter during the operation is very important to ensure the safety of the surgery. However, measurement of the force on catheters is very difficult to be solved in these systems. A potential problem with a remote catheter control system is the lack of mechanical feedback that one would receive from manually controlling a catheter [4, 5, 8, 10, 12, 14, 18, 20, 21].

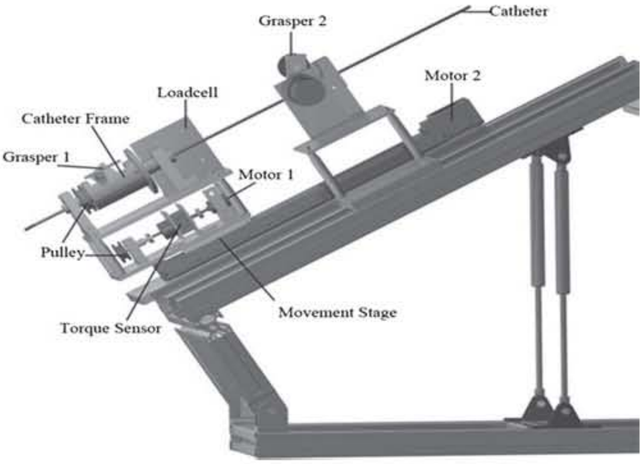


Fig. 3 The catheter manipulator

Fig. 2 The communication sketch map

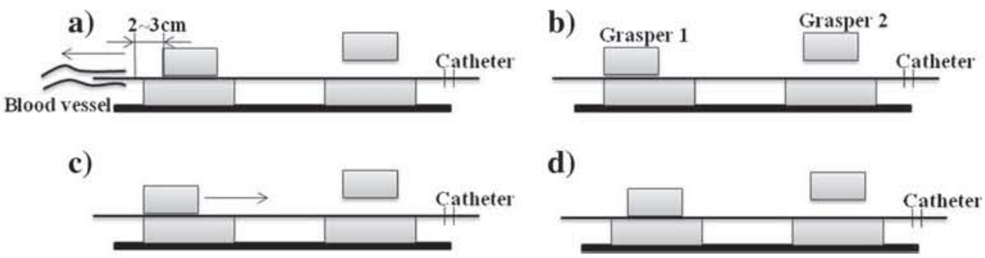


Fig. 4 The insertion motion

Unlike the conventional bedside technique, which requires surgeons to manipulate a catheter using their hands, employment of these remote manipulating systems removes the catheter from the surgeons' hands, thus removing his/her dexterous and intuitive skills from the procedure. Furthermore, the technological complexities of these systems may require long training times to ensure that the surgeons are skilled in their use. For example, a study conducted by Schiemann et al. [19] demonstrated that equivalent navigation efficacy was achieved when comparing conventional navigation to remote navigation using the Niobe system in a glass phantom, after 6 months of surgeon training on the system. Therefore, it should be beneficial if a catheter manipulating system incorporated the dexterous skill set of an experienced surgeon during the procedures.

In this paper, a new prototype robotic catheter manipulating system has been designed and constructed based on the requirements for the endovascular surgery. Compared with robots mentioned above, our system features a slave manipulator that consists of one movement stage and one rotation stage, allowing for steering and inserting the catheter simultaneously as Fig. 1(b) shown. Also, the slave has a new developed force feedback measurement mechanism to monitor the proximal force which has been generated during the inserting catheter and provide the force feedback to the surgeon. The robotic catheter manipulating system has a master controller called surgeon console in Fig. 1(a), using two motion-sensing devices via control unit DSP to communicate the position and rotation information with slave side. Also, we designed the haptic device to provide the feeling back to surgeons. The whole system was evaluated in aspect of dynamic and static performance of the axial and radial motions. The results of synchronization experiments had to evaluate the accuracy and precision of sensed and replicated motions. Finally, Tele-operation had been done by EVE simulator to provide the performance under the similar situations.

2 Robotic catheter manipulating system

The catheter manipulating system was designed with the structure of master and slave. The surgeon console of the system is the master side and the catheter manipulator is the slave side. Moving mode of the catheter manipulator is designed as well as the surgeon console. The movable parts of surgeon console and catheter manipulator keep the same displacement, speed and rotational angles, therefore, the surgeon would operate the system smoothly and easily. Each of surgeon console and catheter manipulator side employs a DSP (TI, TMS320F28335) as their control unit. An internet based communication was built between the surgeon console and the catheter manipulator, the sketch map of the communication is shown in Fig. 2. The surgeon console side sends axial displacement and rotational angle of the catheter to the catheter manipulator. At the same time, the catheter manipulator sends force information back to the surgeon console side. Serial communication is adopted between PC (HP Z400, Intel Xeon CUP 2.67 GHz speed with 3 GB RAM) and control unit of the mechanism. The baud rate of the serial is set to 19,200 [7, 9, 17, 19].

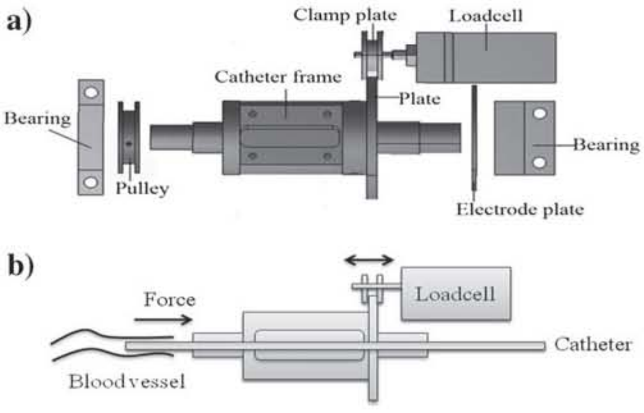


Fig. 5 The force measurement mechanism

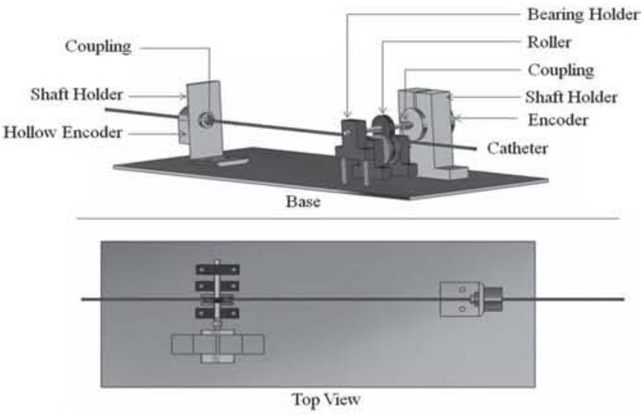


Fig. 6 The structure of the surgeon console

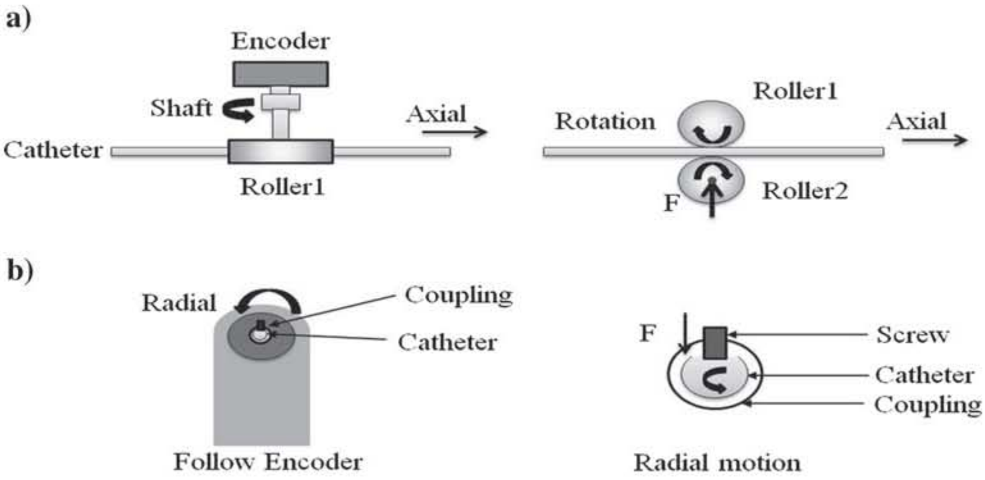


Fig. 7 The schematic diagram of surgeon console

To ensure remote operation using this system is appreciable with conventional bedside operation, the following criteria were used in the design process [6].

1) The system should be compatible with generic 6 7Fr (diameter: 2 2.3 mm) catheters, sizes common in interventional surgery.
2) Axial motion and radial motion should not be hindered by either the surgeon console and catheter manipulator.
3) Accuracy of axial movement: 1 mm for 1.5 m catheter
4) Accuracy of radial movement: below 3°
5) Synchronization performance between surgeon console and catheter manipulator

2.1 The catheter manipulator

Figure 3 shows the catheter manipulator. This mechanism is placed in the patient side. The catheter is inserted by using this mechanism. It could provide two DOFs, one is axial movement alone the frame, the other is radial one. Two graspers are placed on it. The surgeon can drive the catheter to move and rotate along both axial and radial direction only when the catheter is clamped by grasper 1 coupled with catheter frame. Because the stroke is limited, so we should withdraw the catheter by release the grasper 1 and keep the catheter at same place using grasper 2. Then, the catheter could be retreated for next insertion. Inserting motion of the catheter is described in Fig. 4. We could know that catheter insertion has been operated in the movement range of 2~3 cm every operating procedures shown in Fig. 4(a). For the clinical catheter, it is flexible. However, it has enough rigid to deliver the F/T in this short distance similar to the procedures of clinical surgery. Usually, the neurosurgeons operate the catheter within 2~3 cm movement range every operating procedures. The catheter manipulator was designed to imitate the operating procedures.

To realize axial movement, all catheter driven parts should be placed and fixed onto a movement stage (the plate under motor 1). The movement stage is driven by a screw which is actuated by a stepping motor (motor 2). On the other hand, one dc motor (motor 1) is employed to realize the radial movement of the catheter. It is coupled to the catheter frame by two pulleys connected with a belt together. The catheter is driven to rotate by motor 1 when the catheter is fixed on the frame by grasper1.

Torque sensor is applied in this system to measure the torque information during the operation. The torque data will be sent to the surgeon console. The torque sensor is linked to motor 1 and one shaft of the pulley below. The resistance torque on the catheter can be transferred to the torque sensor through coupled pulleys then measured by the torque sensor.

Resistance force acted on the catheter can be measured and it will be sent back to the surgeon console, then generate a haptic feedback to the surgeon. To measure the resistance force, a mechanism is designed as shown in Fig. 5(a) in details. A loadcell which is fixed on the movement stage is employed to measure the resistance force. A clamp plate fixed on the loadcell is linked to the catheter frame which is

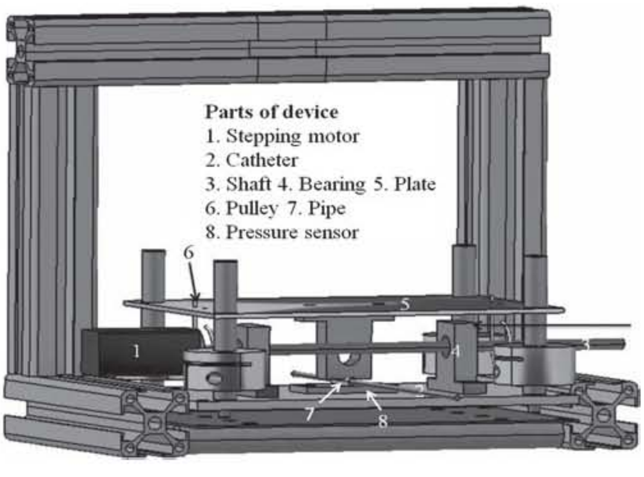


Fig. 8 Haptic device in the surgeon console

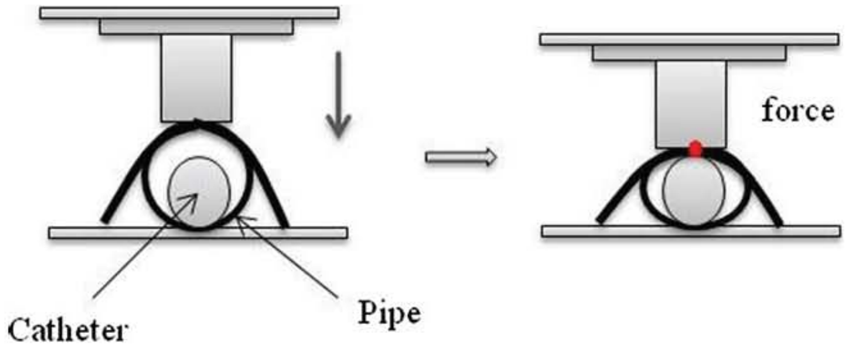


Fig. 9 Schematic diagram of haptic device

supported by two bearings. The resistance force acted on the catheter during the insertion can be detected by the loadcell. As the movement range of catheter operation is about 2~ 3 cm every operating procedures and the catheter is enough rigid in this range, therefore, it can guarantee that the generated resistance force could be transferred back and make the catheter frame have be a bit of movement. Then, this force could be measured by loadcell shown in Fig. 5(b). The clamp plate doesn't affect the rotation motion of the catheter frame [15, 24]. Although the designed measurement mechanism of resistance force could work, it also has some problems such as the sensitivity of the mechanism and so on need to be resolved.

2.2 The surgeon console

The prototype of surgeon console shown in Fig. 6 is an electromechanical device that measures the axial and radial motion of the input and output catheter using two mechanically independent passive sensors. Each sensor contains a 2,000 lines encoder, mechanically coupled to the catheter. Axial position of the catheter is measured using a mechanical structure that converts the axial motion of the catheter to a rotational motion of the shaft of an optical encoder (Rotary encoder, MES2000P, Japan) using two rollers which mechanically couple to the catheter described in Fig. 7(a). One of the rollers (the main roller1) is directly coupled to the encoder, while the second idler roller2 passively ensures continuous contact between the primary roller and catheter. The position of the second roller is adjustable to allow variable contact friction between the catheter and the primary roller. The rollers were manufactured from MISUMI Corporation to ensure dimensional stability and the material is rubber. The axial position of the input catheter's shaft is determined as the product of roller circumference (approximate 75 mm). In the current implementation, detection of a single-counter increment yields a motion sensitivity of about 0.04 mm/count in the axial direction.

To measure radial motion, the catheter is used as a shaft to be coupled with the radial encoder shown in Fig. 7(b). A kind of hollow encoder (Rotary encoder, UN2000C4, Japan) is constructed to house catheter and coupling, which housed one screw. We processed the circular catheter into a irregular shapes, then the screw (diameter 2 mm) can grip the catheter in the radial direction and holds it at the center of the encoder disk while allowing it to move freely in the axial direction; also, the screw which can be adjusted freely are loaded to ensure contact between the coupling and catheter. The outer edge of the coupling matching with hollow encoder enables the catheter to freely rotate the optical disk through the optical sensor. The radial position of the catheter can be measured directly by the encoder. In the current manipulation, detection of a single-counter increment yields a motion sensitivity of 0.18°/count in the radial direction.

Haptic devices in tele-operation systems have an important place because surgeons must have the same felling as a real surgery. We designed a new haptic device which can change the friction on the catheter and provide the feeling back to the surgeon as Fig. 8 shown. A plastic pipe is a bit bigger than the catheter can create friction on it as Fig. 9 described. If the catheter manipulator side detects resistance force, the haptic device will generate it as near as the real

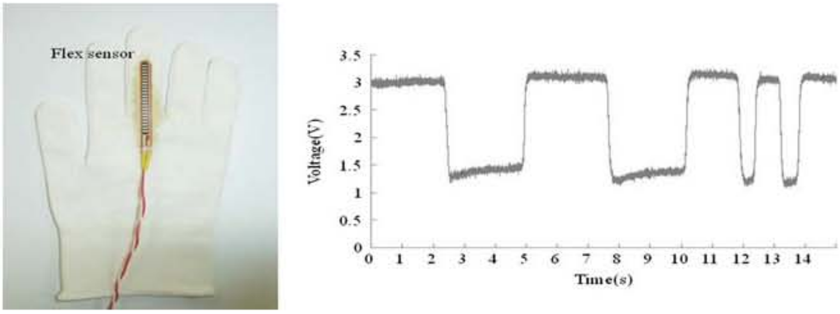


Fig. 10 Schematic diagram of the flex sensor

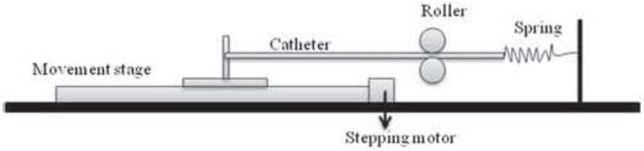


Fig. 11 Experimental setup of performance evaluation of axial motion

Table 1 Evaluation of the precision and accuracy

Catheter manipulator		Precision	Accuracy
	Axial (mm)	0.23	0.04
	Radial (deg)	2.2	3.0

one. We also used 4 springs for the system stability. In fact, when the catheter is totally stopped by the feedback pressure, we don't have any information about the force that the surgeon puts on the catheter. So, we will consider it and discuss the situation about the friction force measuring and force feedback providing in the future.

As we need to withdraw the catheter every operating procedures by controlling the grasper. The flex sensor was used by bending it to change its resistance then obtain the voltage variation data shown in Fig. 10. This voltage will be as the input signal transmitted to the DSP and control the grasper in the catheter manipulator side.

2.3 Control of the system

Control of the surgeon console and catheter manipulator is achieved through two DSPs (TI, TMS320F28335) via RS-232 serial communication. Control software was implemented using C language, to enable synchronized motion control in the axial and radial direction, device control was multithreaded. The axial and radial motions measured by two encoders in the surgeon console are represented for $P_{Surgeon}$ [X_M θ_M] and solved to determine the corresponding position $P_{Patient}$ [X_S θ_S] of the catheter manipulator in motor space. The position of each component of surgeon console is sampled at 1 ms intervals; the corresponding velocity and acceleration values are determined and commands are then transmitted to the catheter manipulator controllers at 10 ms intervals. In the catheter manipulator side, the PD control algorithm has been added to improve the tracking accuracy.

3 Evaluating methods

3.1 Evaluation of the surgeon console

To evaluate the performance of the surgeon console, two experiments were carried out. One is to evaluate the dynamic and static performance of axial motion and the other one for radial motion. Prior to evaluating the performance of the surgeon console, a series of experiments were performed to decrease the mechanical backlash. In the axial direction, mechanical backlash was measured by moving the catheter from 0 to 150 mm then back to 0 mm, ten times in succession. The difference between the start position and final position recorded by encoder, as reported by the surgeon console, was divided by the total number of iterations to determine error per direction change. The backlash error was then corrected. This process was repeated iteratively until the final error was below 1 mm. In the radial direction, the methodology to calculate the mechanical backlash was similar; rotating the catheter from 0° 180° and back to 0, ten times, and then adjusting the backlash constant until it was below 3°.

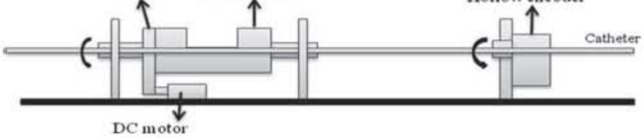


Fig. 12 Experimental setup of performance evaluation of radial motion

For the first experiment, we needed to evaluate dynamic and static performance of the axial motion. In terms of dynamic performance, we actuated movement stage as sinusoidal moving and change the moving frequency of movement stage from 0.1 Hz to 100 Hz. The catheter was coupled to the movement stage as Fig. 11 shown.

The catheter (6Fr) had been advanced and then retracted for 5 times at every frequency, then the axial displacement of movement stage that measured by an encoder inside the stepping motor was obtained. A DSP was applied to get the displacement data and sent it to the computer (HP, z400). These values were compared with the corresponding position reported by the catheter. At the same time, the measurement data by encoder of catheter was sent to the same computer by serial port, the sampling frequency of the controller was set to 1000 Hz. Baud rate of the serial port was set to 19,200. After comparing these two groups of

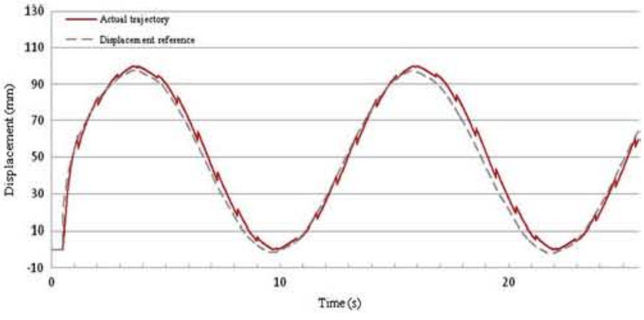


Fig. 13 Dynamic performance of axial motion at 0.1Hz

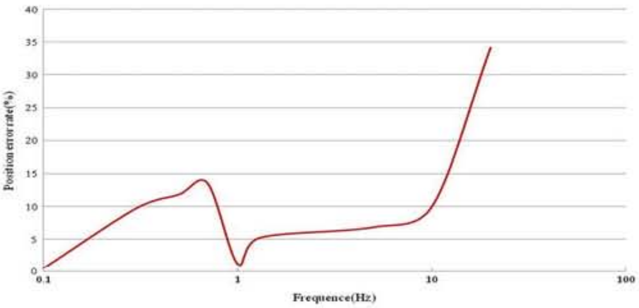


Fig. 14 Dynamic characterization of axial motion

data, the dynamic performance of axial motion could be evaluated. Next, we set the movement stage moving as the same velocity and direction to evaluate the static performance of axial direction. The catheter (6Fr) had been advanced for 5 times at certain velocity. We changed the velocity from 0.7 mm/s to 300 mm/s and measured the moving displacement of catheter and movement stage. Comparing with the two groups of date, we calculated the average error of displacement between catheter and movement stage. The static performance could be evaluated.

In the second experiment, only static performance of radial motion was evaluated using the 6 F catheter. As well as the first experiment, we actuated the catheter frame rotating as the same velocity and direction rotating and change the rotating velocity of catheter frame from 180°/s to 540°/s. The catheter was coupled to the movement stage as Fig. 12 shown. Comparing with the rotational degree between catheter and catheter frame, the static performance of radial motion could be evaluated.

3.2 Evaluation of the catheter manipulator

For the first experiment, we advanced and then retracted the catheter(6Fr) for about 2 min (approximate) in a 120 mm range, then the axial displacement were obtained that measured 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. These values were compared with the corresponding position reported by the catheter manipulator and accuracy was calculated as the average difference between laser sensor measurement and encoder measurement. At the same time, the measurement data of the catheter manipulator was sent 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 19,200. After comparing these two groups of data, the axial measurement precision could be evaluated [16, 23].

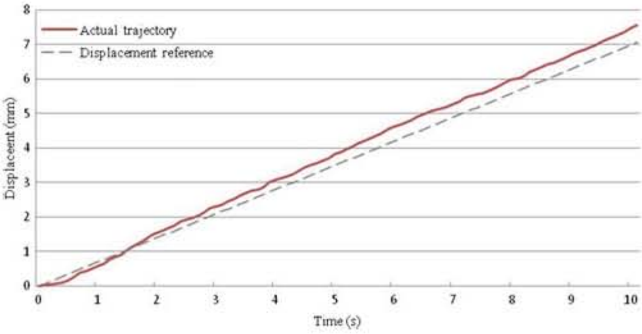


Fig. 15 Static perfomance of axial motion at 0.7 mm/s

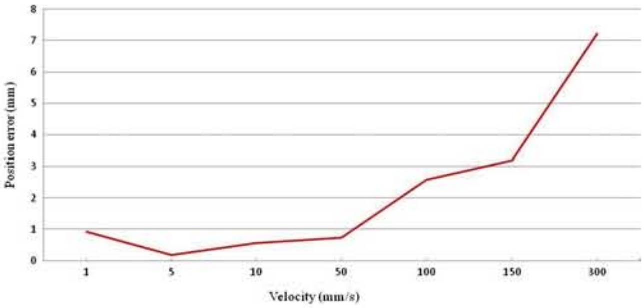


Fig. 16 Static characterization of axial motion

In the second experiment, the accuracy and precision of radial position measurements were evaluated using the 6 F catheter. As well as the first experiment, we rotated the catheter in clockwise and anticlockwise for 2 min. Accuracy was evaluated by obtaining measurements at −180° and 180°, then calculating the mean error in the measurement. Radial measurement precision was evaluated by rotating the rod by 360° and then calculating the standard deviation. Then measure the rotation angle by a 3-axis inertial sensor (Xsens Inc. MTx, resolution 0.1 deg) fixed on the catheter. The sampling frequency of the inertial sensor is set to 100 Hz as the same as the controller. Sampling data of the controller was send to the computer by serial port [13, 22, 25].

3.3 Evaluation of the synchronization performance

The synchronization experiments were carried out and we did not consider the lag. We just evaluated the tracking performance of the axial and radial displacement. Firstly, we advanced and retreated the catheter many times. Then,

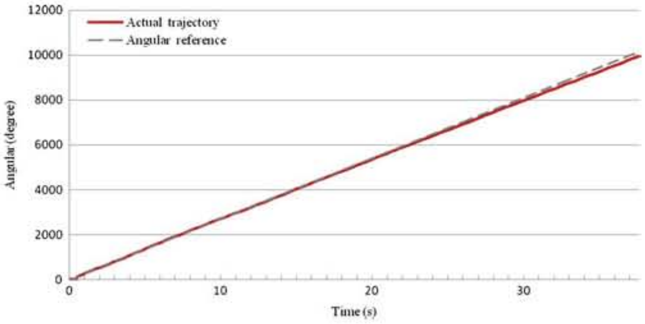


Fig. 17 Static perfomance of radial motion at 270°/s

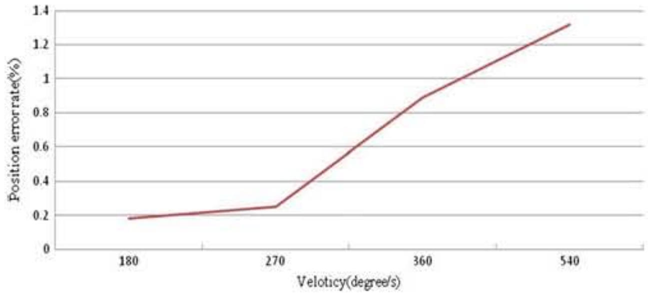


Fig. 18 Static characterization of radial motion

we got the axial displacement by encoders both in surgeon console side and catheter manipulator side. This procedure was carried out for four times. Similarly, the synchronization of rotation could be obtained.

4 Experimental results

4.1 Evaluation of surgeon console and catheter manipulator

The dynamic and static performance of surgeon console was evaluated described in Figs. 14, 16 and 18, and accuracy and precision of the catheter manipulator were listed in the Table 1. All of the evaluation had been measured after backlash correction and calibration. Figures 14 and 16 shows the dynamic and static performance of axial motion. In the Fig. 14, position error described the difference of catheter moving distance (actual output) and movement stage moving distance (ideal output). Vertical axis (position error rate) meant the ratio of position error and ideal position. Horizontal axis meant the moving frequency of movement stage and catheter from 0.1 Hz to 100 Hz. The surgeon console worked well between 1 Hz and 10 Hz. From 0.1 Hz to 1 Hz, the position error was much bigger, that because the backlash was generated. Although we corrected the backlash before, it was still generated during the test. In the Fig. 16, position error described the difference of moving distance of catheter and movement stage. Horizontal axis meant the moving velocity of catheter and movement stage from 0.7 mm/s to 300 mm/s. The surgeon console worked well in static characterization. The Figs. 13, 15 and 17 described the dynamic and static performance of surgeon console side in detail. (Figs. 14, 15, 16, 17 and 18)

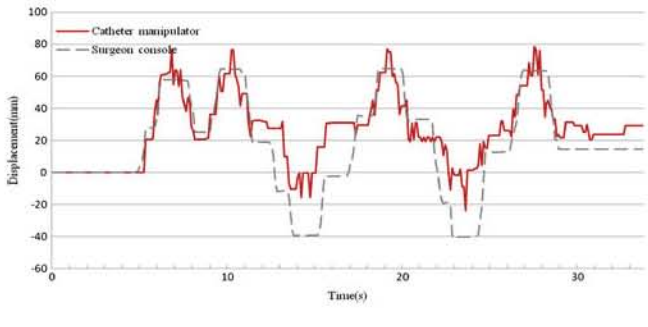


Fig. 19 The tracking curve of axial motion

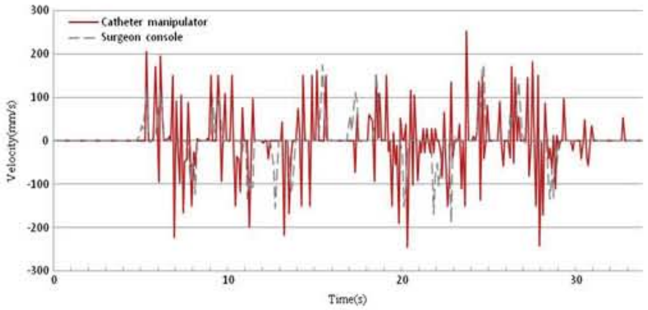


Fig. 20 The inserting velocity in both sides

4.2 Evaluation of the synchronization performance

In this experiment, we implemented synchronization experiment between the surgeon console and catheter manipulator. The axial and radial displacement both of surgeon console and catheter manipulator was compared. Figures 19 and 20 showed the axial tracking experimental results. Similarly, Figs. 21 and 22 showed the radial tracking experimental results.

4.3 Tele-operation

The tele-operation experiments were carried out with LAN and the lag was above 300 ms, especially much larger when started the operation. Figure 23 shows the configuration for this case, an EVE simulator which consisted of a fluid control unit and blood pressure monitoring instrument was employed. The properties of the EVE simulator are similar to the blood vessels of human body. In order to keep the blood pressure of the EVE simulator similar to human body, the fluid control unit was used to adjust it every time.

The server of communication was built in the surgeon console side. The surgeons would see the position of the catheter from the screen. In this experiment, our target was to insert the catheter to reach a goal position. The

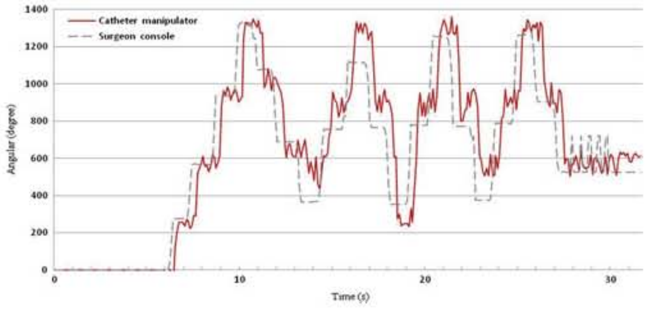


Fig. 21 The tracking curve of radial motion

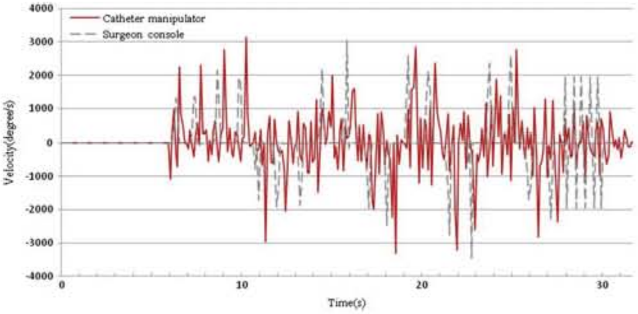
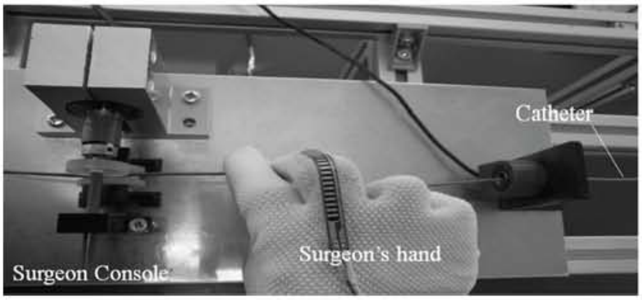


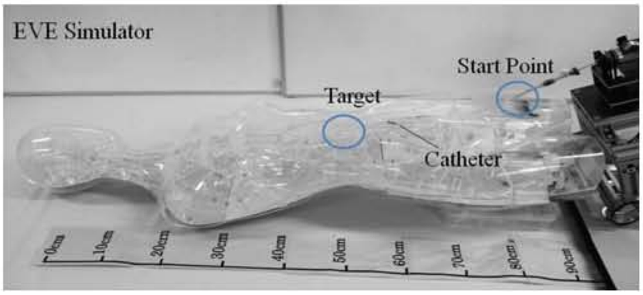
Fig. 22 The rotational velocity in both sides

displacement of the surgeon console and the catheter manipulator are kept same. Figure 24 shows the position tracking trajectory of the axial direction.

At beginning, we moved the catheter forward in the surgeon console, the catheter manipulator inserted the catheter suddenly after kept the stationary state in 3 s because of the time delay. In consequence, the LAN was not stable at anytime. Then, we performed the experiments from the start point to the target in two times. Due to the inserting route was not straight route, it has one branch after the start point. When the catheter went through the branch at the second time, the tip of it touched onto the wall of blood vessel. The fiber optic pressure sensor was used to measure the contact force in Fig. 25 described. The measured contact force was about 15 mN. In the future, we will test the performance under the real situations like animal organs or clinical surgery.



a) The surgeon console



b) The catheter manipulator and the EVE simulator

Fig. 23 Experimental system

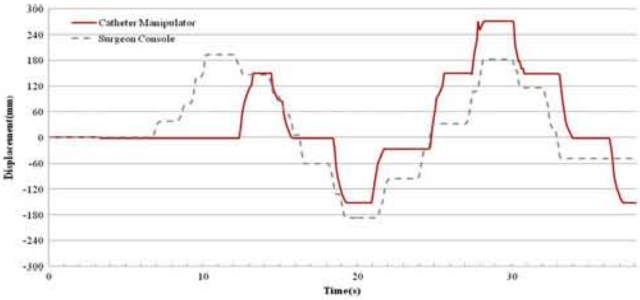


Fig. 24 Tracking trajectory of the axial direction

5 Discussion

The novel catheter manipulating system described in this paper uses a novel method to control the catheter for remote operation. This operation method promises to enable surgeon to use their highly dexterous skills to remotely manipulate the catheter, potentially reducing radiation exposure and physical stress during long procedures. The current implementation of the system was designed for use with 6 7Fr catheters, commonly used in minimally invasive surgery procedures, but is easily adaptable for catheters of different sizes. The performance evaluation demonstrated the system's ability to measure and implement catheter motion within good specifications. The reported dynamic and static performance of surgeon console and accuracy and precision in motion implementing of catheter manipulator were good. In addition, to use the dexterous skills possessed by the surgeon should enable rapid acceptance of this technology while maintaining the remarkable success of conventional intervention.

The presented catheter manipulating system has many potential advantages over commercially available systems. Unlike magnetic catheter navigation, where large permanent magnets are used to locate the catheter, thereby requiring specialized catheters, the presented system can be easily integrated into existing fluoroscopic suites. The current system also uses generic catheters, with performance characteristics known to the surgeon, during remote operation. Most other commercially available remote navigation

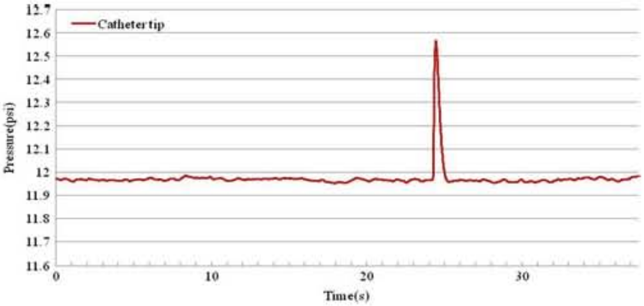


Fig. 25 Contact force signal described as pressure

systems utilize joystick input devices to operate the remote catheter without providing tactile feedback to the surgeon. Because of the flexible nature of catheters, external forces applied to the catheter during catheter guidance occur when the tip of the catheter pushes directly into tissue or when twisting the catheter pushes its body against the vascular wall. In both situations, the external forces applied to the catheter are not fully transferred to the surgeon but instead result in catheter deformation. The operator uses these visual cues during catheter guidance, and we expect that the ability to exploit prior dexterous skills during remote catheter operation, as provided by our system, may provide additional benefit over remote operation systems employing joysticks or other non-intuitive master devices.

Experiments are carried out to evaluate the performance of the robotic catheter manipulating system. The first experimental results described from Figs. 13, 14, 15, 16, 17 and 18 showed the dynamic and static characterization of the surgeon console. The surgeon console works well regardless of insertion or rotation the catheter as different frequency or the same velocity. In the catheter manipulator side, the precision of axial direction is 0.23 mm, the rotation precision is 2.2° with a accuracy of 3.0°. From the results we can find that the precision and accuracy in axial direction is better than the radial direction for both sides.

Figure 19 shows the evaluation of the synchronization of axial direction. In this pate, we did not consider the time delay during the performance evaluation. But for the tele-operation experiments, there has big lag at beginning operation. Maybe the tele-operation is difficult in the unstable and uncertainty network environment. The surgeon console and the catheter manipulator were controlled by DSP, DSP communicates with each other by the serial port and LAN network. Based on the numbers of communication data and the distance, the local network communication was fast enough to make the lag below 1 ms in theory. However, from Fig. 19 we could understand the movement curve of the surgeon console was faster than the catheter manipulator. It means that the lag existed. The lag time will be measured in the future. We repeated the procedures for 4 times. The manipulation time was about 30s. The axial average error between the surgeon console and the catheter manipulator was big that because of time delay and serial communication problem. Figure 20 shows the rotation tracking error. As well as the surgeon console side, lag could be found in Fig. 21. The mean error of the rotation is below 15°. It means a not stable radial motion. The Large overshoot mainly caused by the electromagnetic interference to the AD convertor 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 velocity [2, 11]. Finally, the fiber optic pressure sensor used to detect the contact force on tip of catheter was useful during the tele-operation. The surgeon could understand the situation about the catheter tip and know that how to avoid the damage to the patient as well as how to continue the next insertion.

6 Conclusions

In this paper, a novel robotic catheter manipulating system was proposed. We developed a high precision mechanical system to assist surgeon to complete the surgical procedures during the operation. The real catheter was used in the surgeon console side and the haptic device was designed to provide the force feedback to the surgeons. In addition, the catheter manipulator has been developed to realize the insertion and rotation catheter. The measurement mechanism of resistance force also has been proposed to detect the force information although it was not so sensitive. Moreover, in this presented system, we employed DSP which has highly precision and processing speed as a control unit both in the surgeon console and catheter manipulator side. The loadcell and torque sensor were utilized to measure the value of force and rotation torque in the catheter manipulator side.

The presented system is a unique platform that provides the surgeon with the ability to use their dexterous skills to perform catheter interventions from a location remote to the patient. The presented experiments have demonstrated the system's ability to measure and drive catheter in axial and radial motions. Combining the remote navigation on EVE simulator, implementation with the surgeon's skill verifies this system as an effective approach to reduce surgeon's radiation exposure and physical discomfort. In the future, the performance of the measurement mechanism of resistance force and the haptic device will be discussed. Moreover, utilizing this system to perform a range of interventional surgery in vivo is required to the clinical practice.

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