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A NOVEL CATHETER OPERATING SYSTEM WITH FORCE FEEDBACK FOR MEDICAL APPLICATIONS

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We developed a novel catheter operating system with an integrated force sensor for medical applications which included a highly precise master-slave remote control system. This paper explains the system design and control system in detail. As part of our research, we designed a micro force sensor and included it in the system to ensure safe operation in intravascular neurosurgery applications. We performed operation simulation experiments and analyzed the operating errors. The experimental results indicated that the proposed force sensor-based catheter operating system works well and can be controlled remotely, and the force feedback can effectively improve operability at an aneurysm.

Keywords: Catheter; mechanism; minimally invasive surgery (MIS); force sensor; medical application.

1. Introduction

Intracavity intervention is expected to become increasingly common in medical practice, both for diagnosis and for surgery. Minimally invasive surgery (MIS) frequently involves the use of an endoscope or a catheter, and this has a number of advantages, including reduction of intervention delay. However, it requires a great deal of skill to operate inside the body where direct observation is not possible.

The aim of this project was to develop a new catheter operating system for intravascular neurosurgery. Such surgery presents many challenges:

(1) Doctors must be very well trained and possess the skills and experience to insert catheters. Intravascular neurosurgery is much more difficult than traditional surgery and there are few skilled doctors who can perform this type of operation. To keep pace with the growing number of patients, a mechanism is required to allow the training of sufficient numbers of doctors.
(2) During the operation, doctors check the position of the catheter tip using the X-ray camera. Although they wear protective suits, it is very difficult to shield the doctor's hands and face from the effects of the X-ray radiation, which may result in radiation-related illness after long periods of exposure.
(3) In intravascular neurosurgery, catheters are inserted into the patient's blood vessels, which in the brain are very sensitive. When operating in this area, extreme care is required to avoid damaging the fragile vessels. An experienced neurosurgeon can achieve an accuracy of about 2 mm. However, as the force of contact between the blood vessel and the catheter cannot be judged accurately by the doctor, catheters are obviously not suited for this type of surgery.
(4) Sometimes doctors cannot be physically present to operate on patients. Therefore, Internet-based master-slave systems are required for such cases so the operation can proceed.

For these reasons, a remote-controlled catheter system is urgently required [Feng *et al.*, 2006; Guo *et al.*, 2007].

There has been considerable research into this type of master-slave system [Guo *et al.*, 1996; Fukuda *et al.*, 1994; Arai *et al.*, 1996]. A new prototype model of micro catheter incorporating an active guide wire with two bending degrees of freedom has been reported, which uses an ionic conducting polymer film (ICPF) device on the front end to act as the servo actuator [Tanimoto *et al.*, 1998; Preusche *et al.*, 2002; Ikeda *et al.*, 2005]. Arai *et al.* reported a catheter driving mechanism that uses linear stepping based on the principle of the mechanical pencil [Arai *et al.*, 2002]. Unfortunately the step size is not stable and varies between 0.3–1.9 mm, and therefore it must be improved before it can actually be used for surgery.

We designed a system to improve the precision to 0.015 mm to make it suitable for surgical applications. We attached a micro force sensor to the side of the catheter to detect the force when the catheter contacts a blood vessel [Peirs *et al.*, 2004; Sedaghati *et al.*, 2005; Negoro *et al.*, 1994]. In this paper, we show the structure, mechanism, and performance of our new catheter operating system.

2. Concept of the Medical Assistance System

We propose a new type of multifunctional intelligent medical assistance system (Fig. 1), concentrating on the micro active catheter system shown in Fig. 2.

In this paper, we report the structure, mechanism, and performance of a new catheter operating system with an integrated sensitive pressure force sensor (Fig. 3). This system has the potential for use inpatients as the slave device in a master-slave system. The aim of this project was to design a mechanism to replace manual operation.

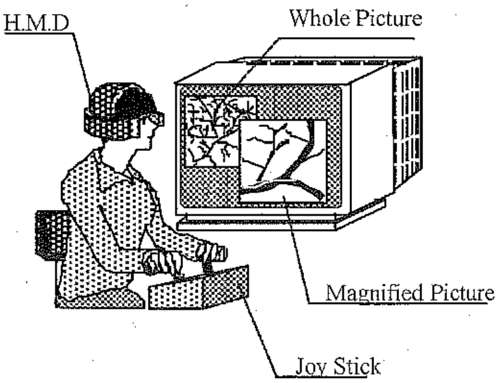


Fig. 1. Concept of the multifunctional intelligent medical assistance microsystems.

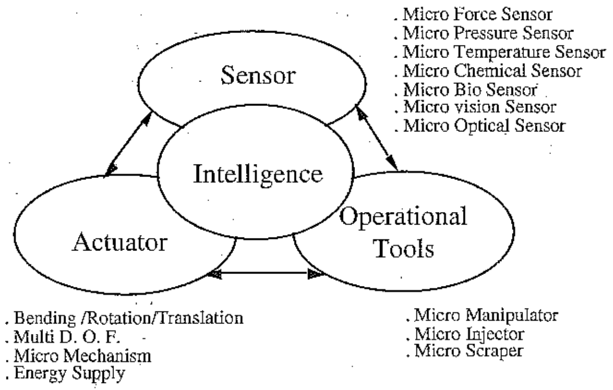


Fig. 2. Concept of the micro active catheter system.

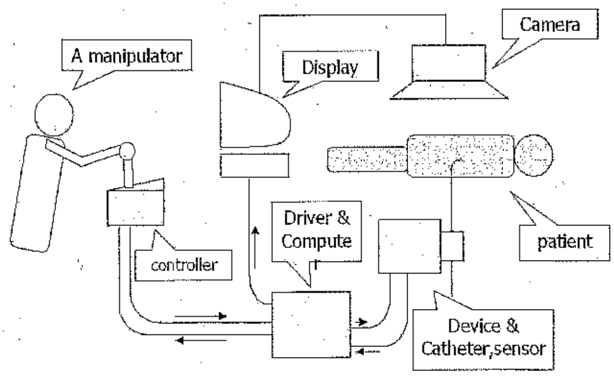


Fig. 3. Proposed new catheter operating system.

3. Structure and Mechanical Details

3.1. *Design concept and overall structure*

The points we considered in designing the system can be summarized as follows:

(1) Movement stability of the catheter in the virtual blood vessel.
(2) Simulation of system motion during surgery.
(3) Simulation of the system at a range of speeds with different step angles.
(4) Ease of sterilization.
(5) Safety.

The most important aspects of intravascular neurosurgery are precision and safety. The precision of experienced doctors navigating by X-ray monitor is not sufficient. As the previous slave device did not resolve this problem, we developed a new device with much better precision.

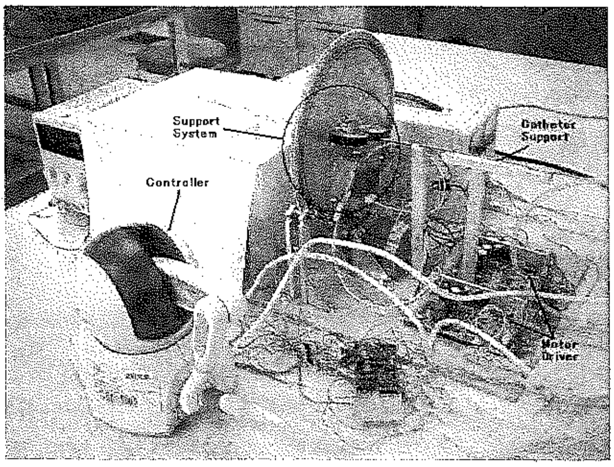


Fig. 4. Photograph of the system.

The highest degree of precision of our system is 0.015 mm, and is therefore more suitable for practical intravascular neurosurgery.

We placed a micro pressure force sensor on the side of catheter to detect the force when the catheter contacts the blood vessel.

The system and experimental instruments developed here are shown in Fig. 4. The whole system consists of three parts: The catheter and its support, the mechanism, and the control system.

For precision, we used a laser displacement sensor and camera to measure the distance and rotation angle of the mechanism. A camera may help doctors to observe the motion of the catheter.

The catheter has two movement modes: Axial (moving backward and forward) and radial (rotation). The catheter will usually move axially, but when it arrives at junction of blood vessels and encounters difficulty in moving, it must be able to rotate to enter a specific vessel or traverse a blockage.

We used stepping motors as the actuators to drive the catheter. These motors control the catheter movement in different directions. To reduce weight, the whole mechanism was made of aluminium with a stainless steel base to increase stability. The large disk shown in Fig. 4 provides rotation for the catheter operating system. Figure 5 shows the mechanism for its insertion.

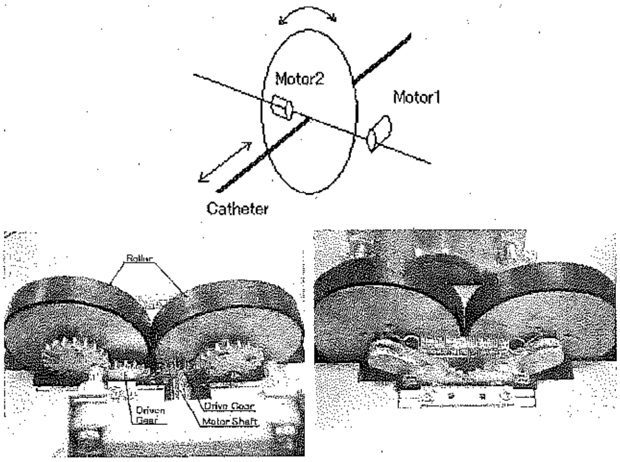


Fig. 5. Basic structure and mechanism of the system.

3.2. *Design of the control system*

To achieve the high precision required, we used highly precise stepping motors with a minimum stepping angle of 0.036° as the actuators. The whole mechanism works has two control modes, automatic and manual. We added a TCP/IP-based remote control to the system, and programmed the client to control it over the Internet. Using the client, a surgeon can control the catheter remotely as if he/she were standing beside the slave system. The system control chart is shown in Fig. 6.

The actuator mechanism is composed of two stepping motors, which represent the main control requirement. The two stepping motors are connected to stepping drivers, which receive power and square wave signals to drive the motors. We varied the angle of stepping motors to adjust the precision of the mechanism.

To make the mechanism more convenient to control, we used a PHANTOM® Omni™ haptic input device (SensAble Technologies, Woburn, MA) in the control system.

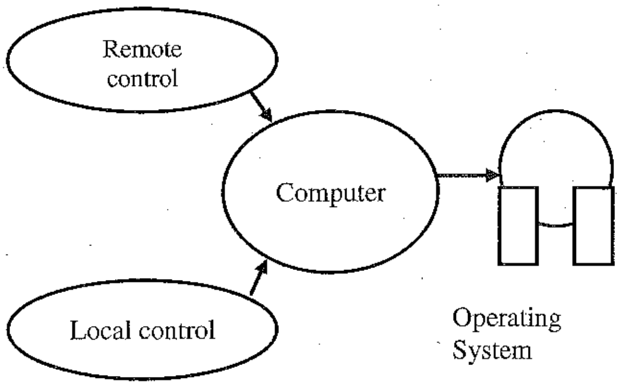


Fig. 6. Control system.

4. Characteristic Evaluation of System

To evaluate the performance of the system developed here, we performed experiments using the control input pulse signals, as shown in Fig. 7.

We recorded the motion and rotation characteristics as functions of input frequency. The experimental results shown in Figs. 8 and 9 indicated that the amount and speed of movement can be controlled. The experimental errors are shown in Figs. 10 and 11. The straight line collapsed for frequencies greater than 500 Hz, although the frequency and the speed were roughly proportional in the low-speed area. This error was most likely due to insertion and removal of the catheter and was influenced by the insertion speed because the degree of error was directly proportional to the speed of the motor.

5. Operating Experiments

5.1. *Micro force sensor*

Surgeons report some tactile feedback through the catheter from the blood vessels. Micro force sensors on the catheter tip have been used in previous studies [Feng *et al.*, 2006]. However, these could only detect the contact

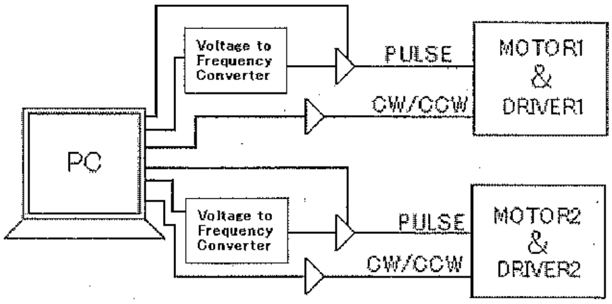
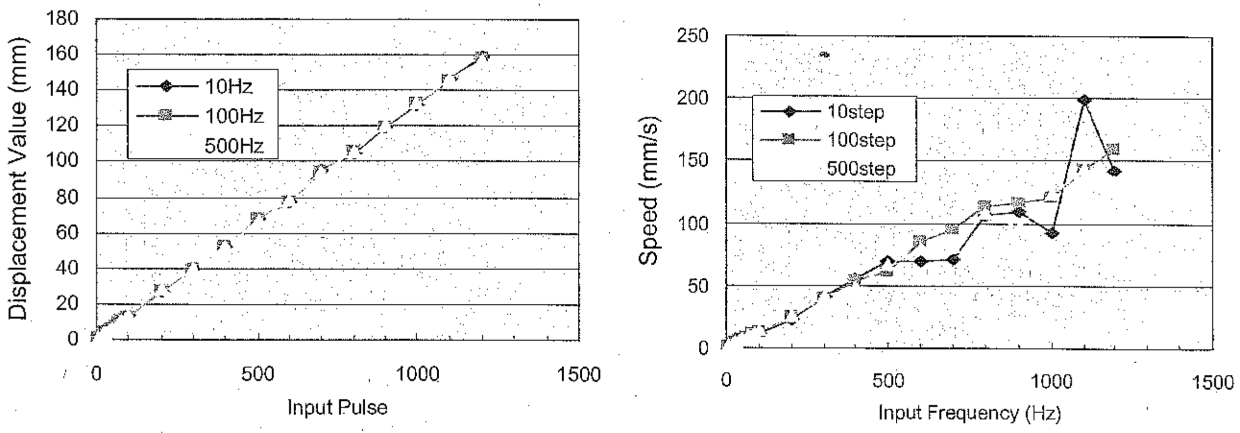
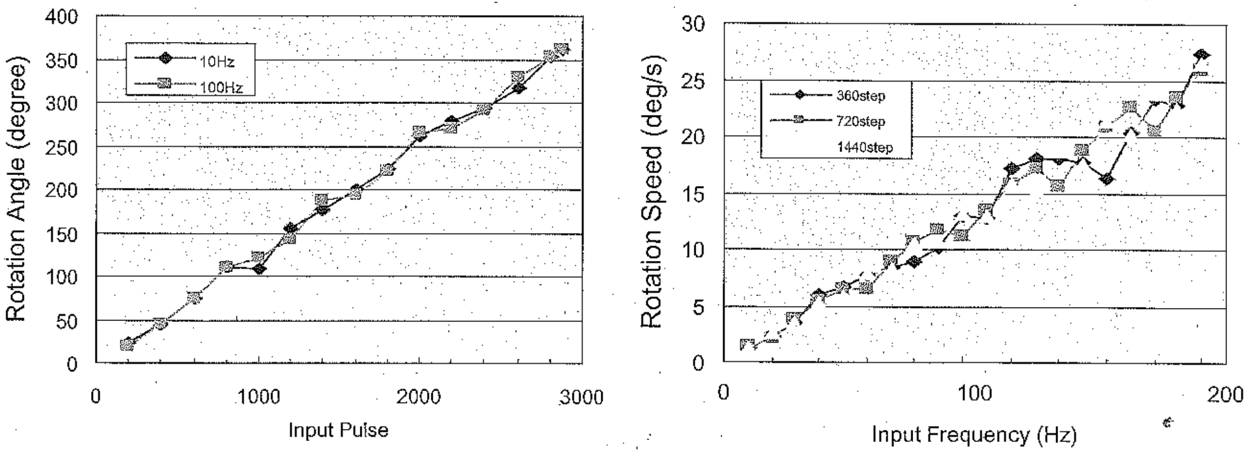


Fig. 7. Control system for stepping motors.



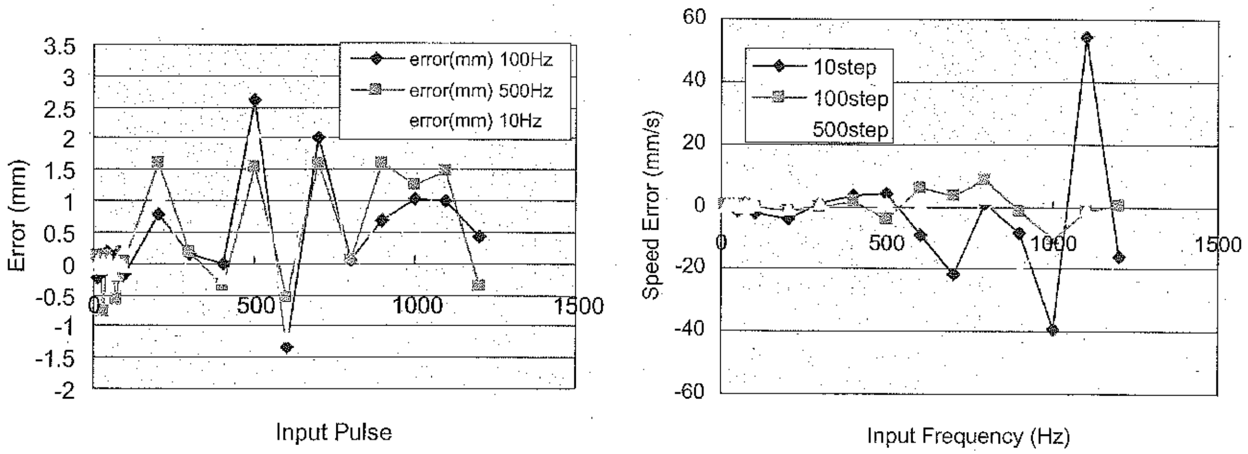
(a) Moving displacement (b) Moving speed

Fig. 8. Motion characteristics as a function of input frequency.



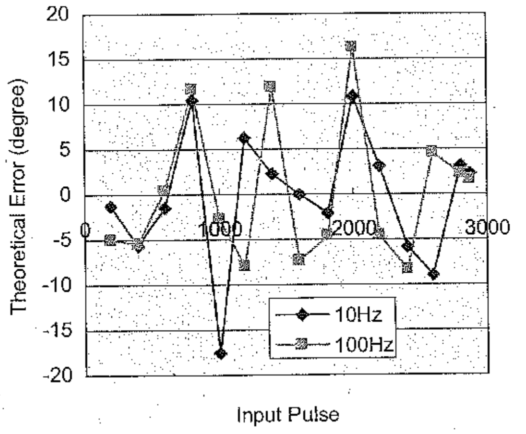
(a) Rotation angle (b) Rotation speed

Fig. 9. Rotation characteristics as a function of input frequency.

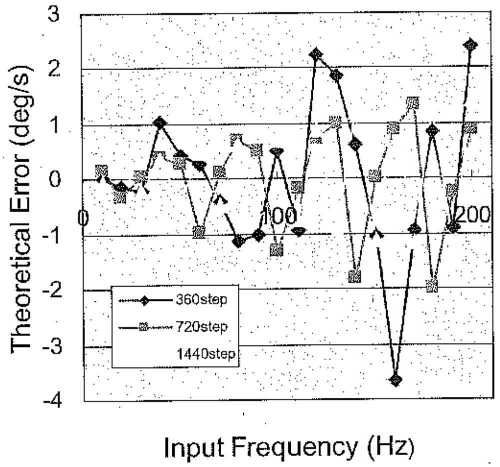


(a) Insertion displacement errors (b) Insertion speed errors

Fig. 10. Insertion motion errors.



(a) Rotation angle errors



(b) Rotation speed errors

Fig. 11. Rotation motion errors.

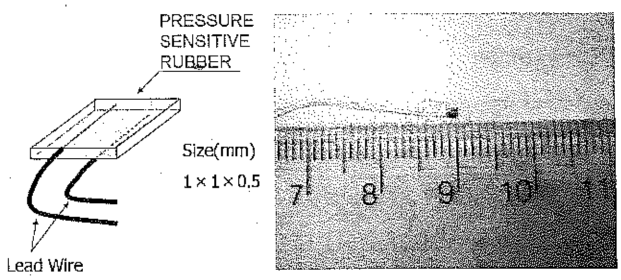


Fig. 12. Micro force sensor.

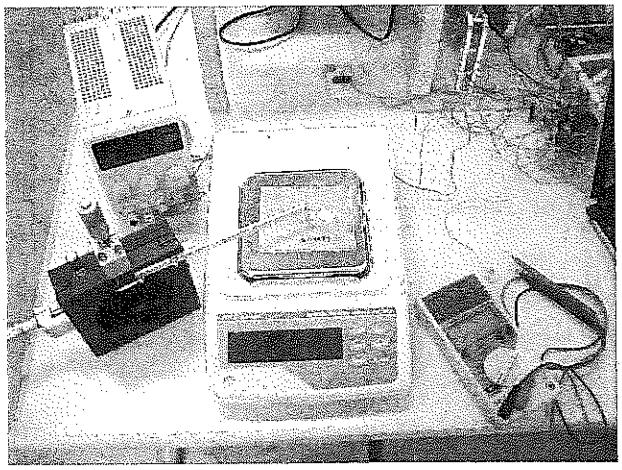


Fig. 13. Sensor calibration system.

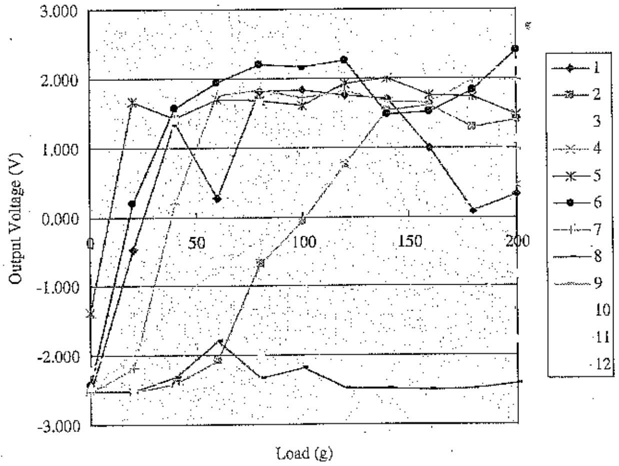


Fig. 14. Relationship between load and output voltages.

force between the catheter head and the blood vessels. We developed a new micro force sensor as sufficient attention has not been paid to the frictional force between blood vessels and the whole of the catheter tube.

We used a tactile sensor to detect the contact force between the side wall of the catheter and the blood vessel, which is an important safety concern during surgery. As shown in Fig. 12, the sensor, which is made of pressure-sensitive rubber, measures 1.0 × 1.0 × 0.5 mm and is fixed to the side wall of the catheter.

The measurement system for sensor calibration, which consists of an electrical balance, a single bridge electrical circuit, and a multimeter, is shown in Fig. 13. The experimental results are shown in Fig. 14.

The motor pull power can be controlled easily based on the output of the sensor, as shown in Fig. 15.

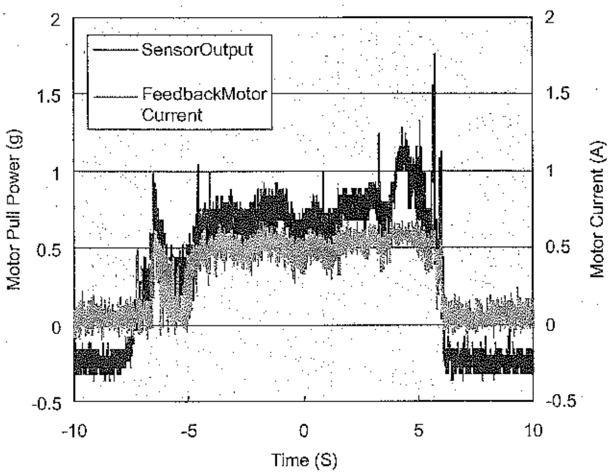


Fig. 15. Relationship between motor pull power and sensor output.

5.2. *Operation simulation experiments*

We conducted operation simulation experiments using the blood vessel simulator shown in Fig. 16. The simulator was made of soft rubber material, and it presented conditions similar to those of a blood vessel in the human brain. We measured the contact force between the blood vessel and the catheter, as shown in Fig. 17. The experimental results are shown in Fig. 18 and the operating states are shown in Fig. 19. The experimental results indicated that the proposed catheter operating system works well and can be remotely controlled, and that the force feedback improves the operability at an aneurysm.

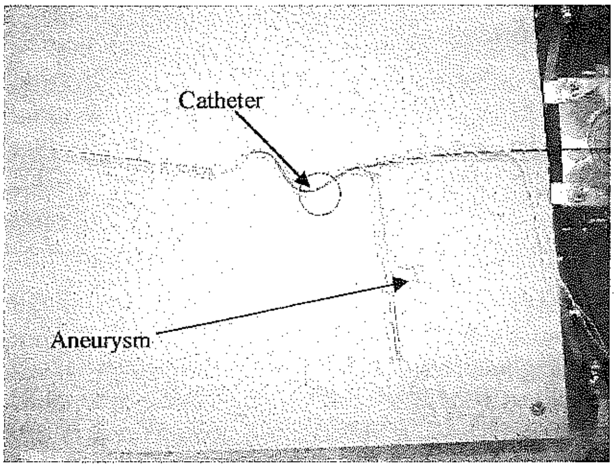


Fig. 16. Operation simulation system.

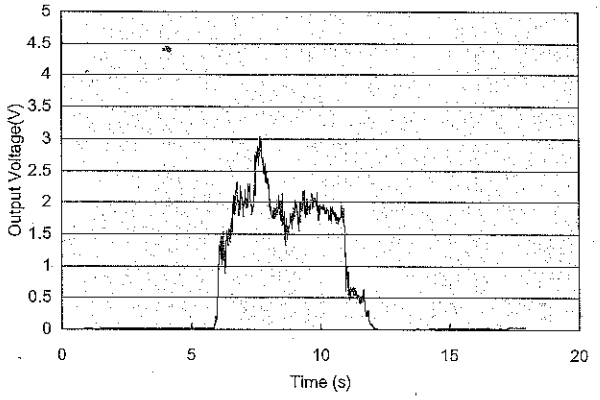
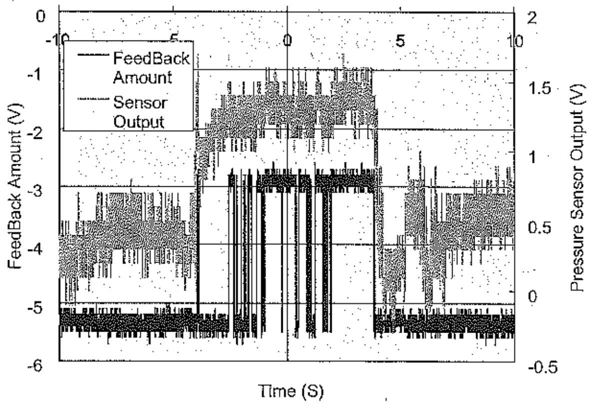
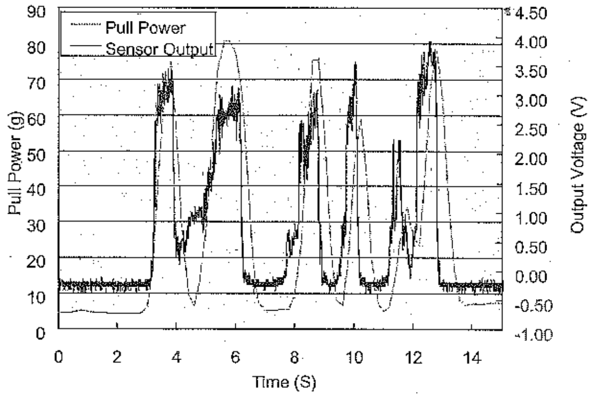


Fig. 17. Sensor contact force output.



(a) Feedback driving voltage using phantom



(b) Feedback force using phantom

Fig. 18. Experimental feedback results with force sensor.

6. Conclusions

We developed a highly precise remote catheter operating system with an integrated force sensor to help doctors perform intravascular neurosurgery. With the motors designed here, the

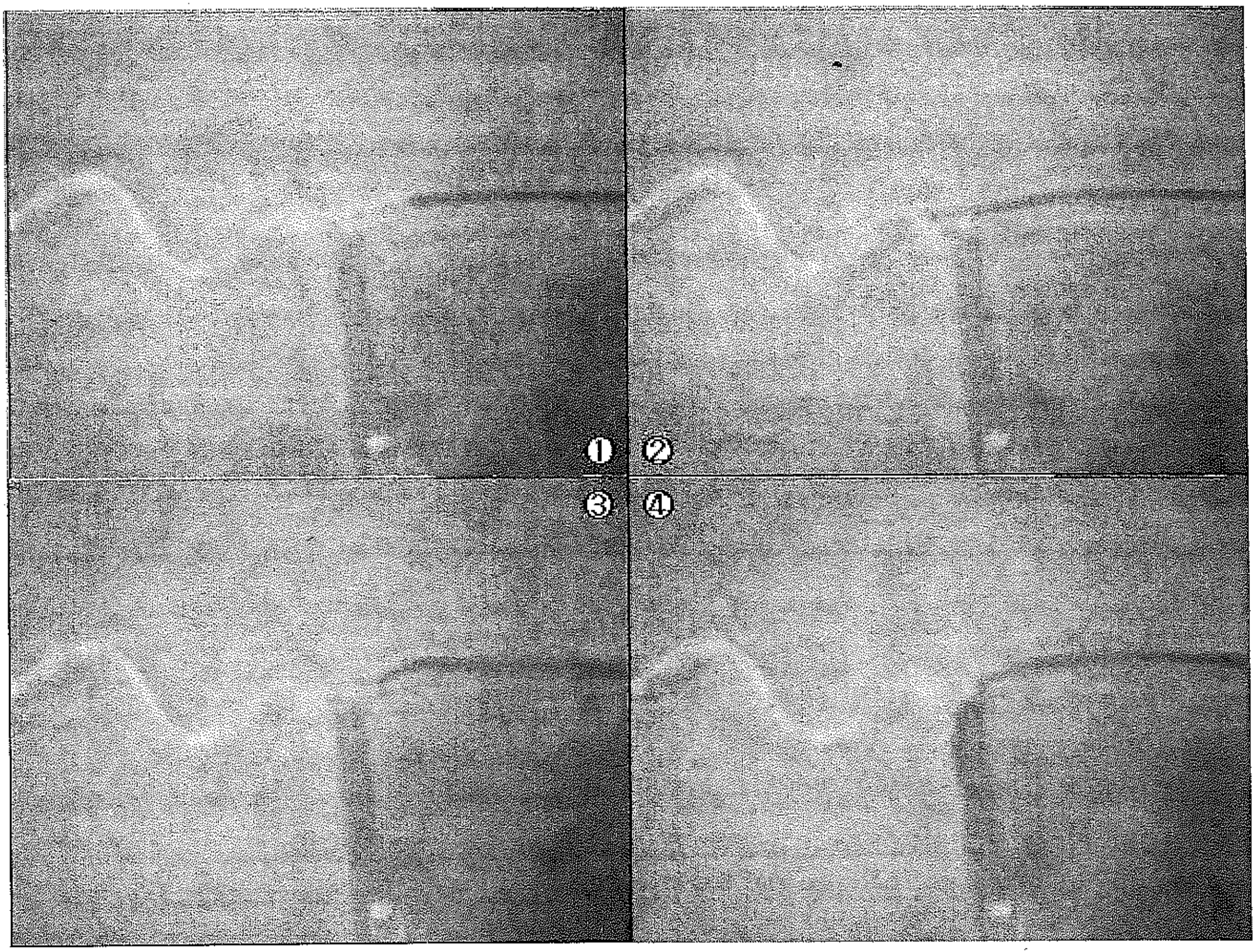


Fig. 19. Operation simulation experiments.

distance of catheter movement can be easily set using different stepping angles and step sizes.

We also carried out operation simulation experiments to evaluate the performance of the catheter operating system, and measured forward distances, rotation angles, and synthetic motions. The experimental results showed that the developed system has a precision of 0.015 mm. The catheter operating system works well and can be remotely controlled, and the force feedback effectively improved the operability for intravascular neurosurgery.

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