

The Design of Insertion Force Measurement Device for Catheter Operation Surgery System's Slave Side

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Abstract – In the endovascular surgery, the master and slave catheter operation system benefits surgeons for it prevents them from X-ray exposure. However, the separated positions prevent the surgeons feel the catheter insertion force as if he or she threads the catheter directly into the patients. Thus, it's important to measure the proximal force on the slave side in order to feedback to master side's haptic device. For above consideration, we proposed a strain-gauges-based force measurement device which is suitable for our team developed slave side. The newly designed device is not only able to measure the catheter's inserting force but also can cooperate with slave side rotation mechanism to be a grasper. To calibrate the device, we adopt the loadcell as reference to derive the relationship between the force and strain gauges deformation change. Finally, in the experiment, we testified the device's measurement maximal error and range. The results indicate that the performance of this newly designed device is in the acceptable range.

Index Terms –Minimally invasive surgery, Robotic catheter operating system, Inserting force measurement

I. INTRODUCTION

Since cardiovascular disease and cerebrovascular disease are big risks for mortality in the world, the minimally invasive surgery (MIS) is applied in vascular interventional therapy widely. The advantages of MIS, such as less pain and recovery time, make the MIS-related study drawing much attention both in commercial company and university research group.

The widely known products Sensi [1] and Anigo [2] are manufactured by Hansen Medical and Catheter Robotic Inc. respectively, which allow physicians to navigate the catheter with greater stability and accurate position. Meanwhile, the remoter controllers prevent physicians from exposure to the radiation. But with the consideration of ergonomics, the catheter controller's design of neither Senei nor Anigo is not similar to physicians' habits.

In order to reach good operability, our research group developed the master-slave robotic tele-operation catheter system [3][4][5][6][7] shown in Fig.1 and Fig.2. Such tele-operation system was designed to imitate surgeons' hand actions. Usually, the catheter moving to the destination is by

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hand's two motions: insertion and rotation. Inspired by this, our team developed system is able to realize the catheter's translation and rotation both on master and slave sides. On the master side, catheter is able to move forward or backward when a physician drags or pushes the handle. The handle connects with a force sensor to detect the physician's applying force on catheter and through admittance control algorithm to drive the slide moving by the step motor. In addition, the handle is coupled with a motor by pulleys and a belt, which results in the catheter rotation. In this way, the master side is not only capable to realize the catheter two motions but also suitable to surgeons' habits.

The slave side is located in the surgery operation room which is responsible for threading the catheter into the patient's target position. The catheter manipulator on the slave side is able to obey the commands from the master side. The two encodes mounted on master side can detect the catheter's translational distances and rotational angles which will transmit to the slave side by Internet. According to this information, the catheter clamped by grasper 1 is inserted or rotated. When the grasper 2 fixes the catheter and grasper 1 releases, the cylinder shaped clamping structure moves backward without any influence on catheter position. Except from the catheter motion, it's important to feedback the haptic force from the slave side to the master side. Such force sensation facilitates the surgeons to feel the resistance as if they beside the patient and thread the catheter in his/her vessels. Now our team has already utilized magnetorheological (MR) fluid to provide the haptic force. The haptic device is displayed in Fig.3 [8][9]. But in order to implement the sensation, the accurate force measurement on the slave side is essential. In the interaction of catheter and blood vessels, the force includes of contact friction force, collision force and viscous drag force showed in Fig.4. [10].

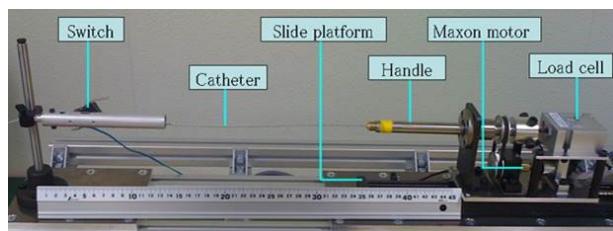


Fig.1. Master Side Physician Console [6]

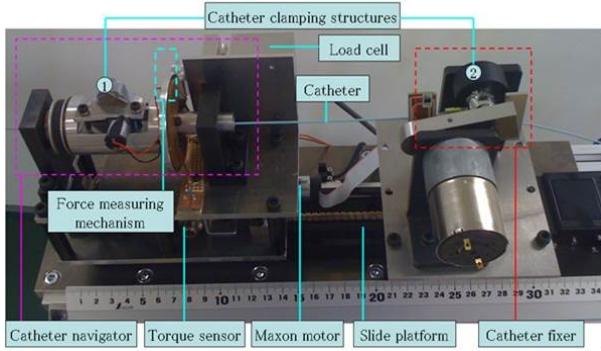


Fig.2. Slave Side Catheter Manipulator [6]

Therefore, the objective of this paper is to realize the proximal force measurement on the slave side without any impact of catheter's motion. The paper is organized into the following sections. Section II will introduce the design of force measurement device. How to integrate such device on the slave side will be explained in section III. The device performance evaluations are exhibited in section IV. Finally, the conclusion and future work are discussed in section V.

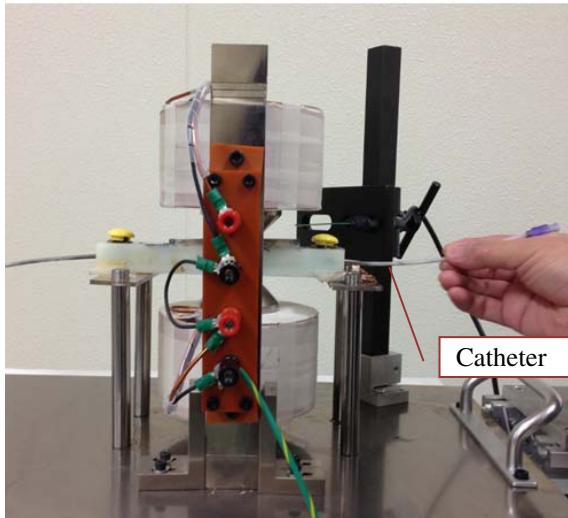


Fig.3 The MR fluids-based haptic device [7]

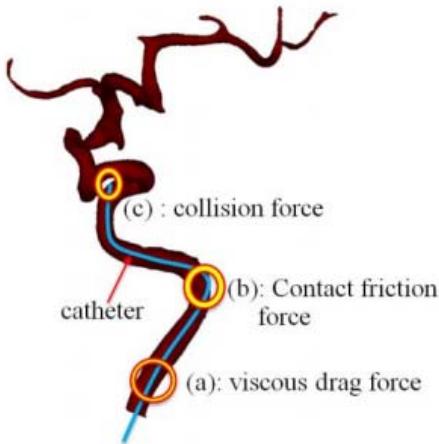


Fig.4 Force between the catheter and blood vessel.

II. THE MEASUREMENT DEVICE DESIGN

In this section, we will first introduce the force measurement principle and then analyze the strain and stress distribution on the device when exerting the force.

A. Force measurement principle

Our proposed force measurement device is based on the strain gauge load-cell working principle. Four strain gauges are stuck on a double bend beam shown in Fig.5. When threading into the vessel, the catheter will suffer from the resistant force as we mentioned before. The force will make the strain gauges deform and the deformation is as change in electrical resistance which is measured by Wheatstone bridge as shown in Fig.6. But the electrical signal output is extremely small which need an amplifier before it used in PC. Thus, through the mechanical perspective, the sensed force is proportional to the electrical signal. Such force measurement design is not only suitable for our slave side catheter motion but its structure is particularly stiff and tends to have long life cycle. Especially the four gauges are able to obtain the maximum sensibility and temperature compensation.

B. Stress and strain analysis

In order to test the deformation existence on the double bend beam, we have done the stress analysis. The beam is 9mm in length, 3mm in width and 0.2 mm in thickness, which is made of aluminum. There is 1N force applied on the top the beam because the maximum force in catheter insertion is around 1N. The stress and displacement results are displayed in Fig.7 and Fig.8. The stress is mainly concentrated in the force applied area and fixed mechanism area and the maximal displacement is nearly 0.112mm. These are exactly the places

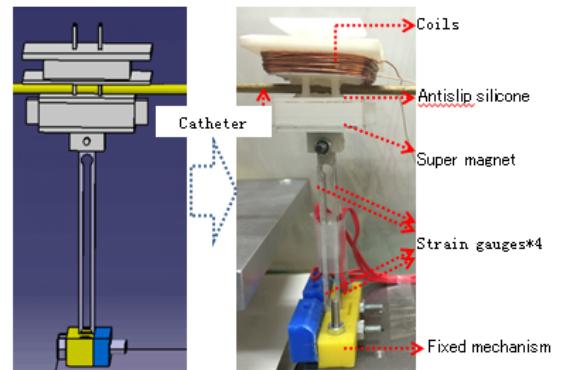


Fig. 5 Strain gauges-based force measurement device

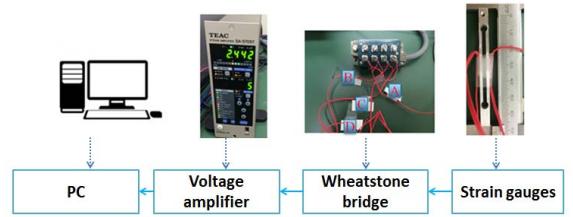


Fig. 6 Force measurement flow chart

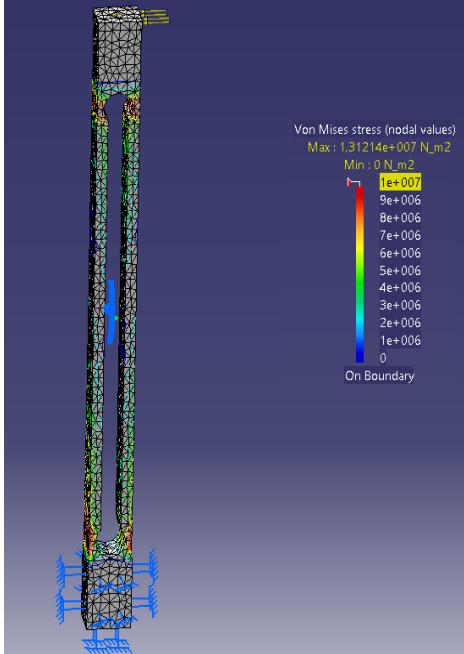


Fig. 7 Stress distribution on beam

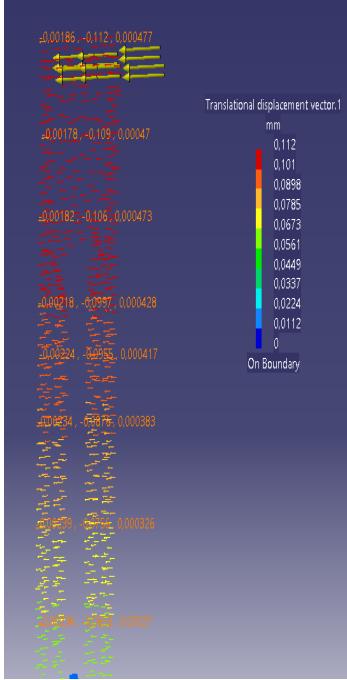


Fig. 8 Displacement vector on beam

where we attach the strain gauges. Meanwhile, strain gauges deform as the beam and the changes in resistance converts into voltage for calibration the load.

III. MEASUREMENT DEVICE AND SLAVE SIDE

In order to realize the catheter two kinds of motions in surgery, the grasper 1 and grasper 2 in Fig.9 are necessary.

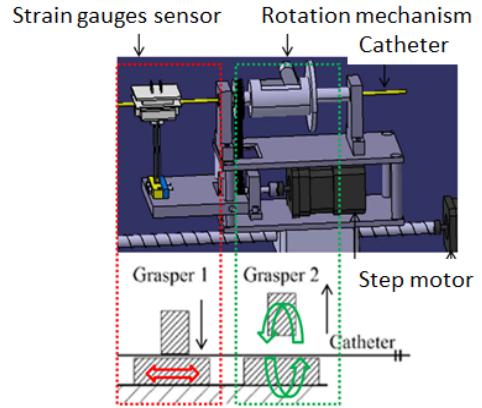


Fig. 9 Structure of Master and Slave System

When inserting into the patient's vessel, the catheter is clamped by grasper 1 tightly until the slide moving to the limit position. So as to back to initial position, the grasper 1 loose and grasper 2 clips. The graspers' states are same when the catheter need rotate.

In order to implement two catheter motions in slave side, the force measurement device has to cooperate with catheter manipulator. Except for force measurement, our designed structure is a good clip as grasper 1. When the catheter is inserted, the coils are charged with current and become an electromagnet shown in Fig.10. Sealed permanent super magnet attracts the electromagnet and clamps the catheter firmly. Meanwhile, the anti-slip silicone with big coefficient ensures that there's no any slide between catheter and grasper. On the contrary, the coils are charged with opposite current and the grasper release the catheter because of inverse magnet field. When the catheter is prepared to rotate, the electromagnet grasper releases the catheter and the rotational mechanism completes the rotation motion. The catheter's motions are summarized in Fig.11.

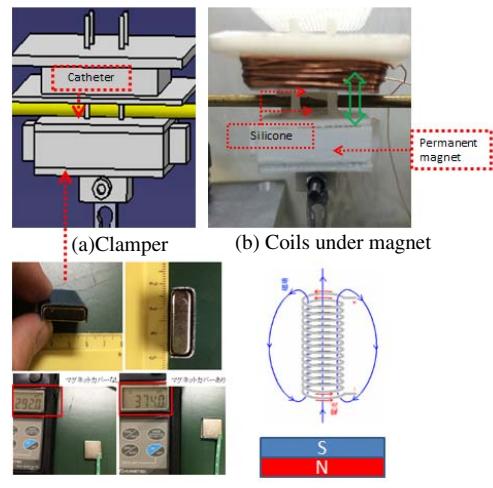


Fig.10 Grasper structure and working principle

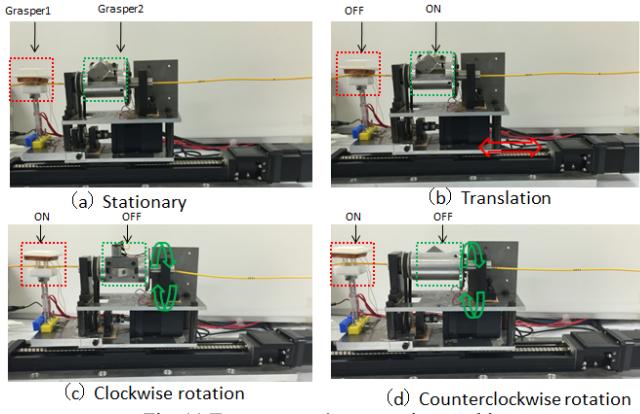


Fig. 11 Two graspers' cooperation working

IV. DEVICE PERFORMANCE EVALUATIONS

In this section, we are going to use above introduced strain-gauge based force sensor to measure the proximal force. As the strain gauges deformation is related with the Wheatstone bridge output voltage, it is necessary to get the corresponding relationship between the applied force and voltage. The experimental setup is displayed in Fig.12 where a loadcell outputs is fixed on the slide driving forward and backward by step motor. The loadcell detected value will be treated as standard force to weigh the strain gauges' voltage change. Both loadcell and strain gauges' value will sampled by 16-bits AD board. The sample data will be fitted by linear curve and the relationship between voltage and force is express as:

$$\text{Force(N)} = \text{Voltage(V)} \times 0.5792 - 0.003859 \quad (1)$$

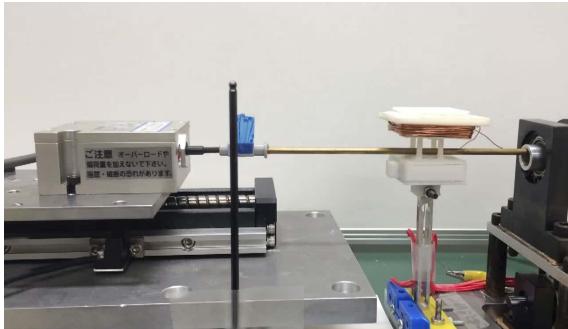


Fig. 12 The force and voltage relationship determination experimental setup

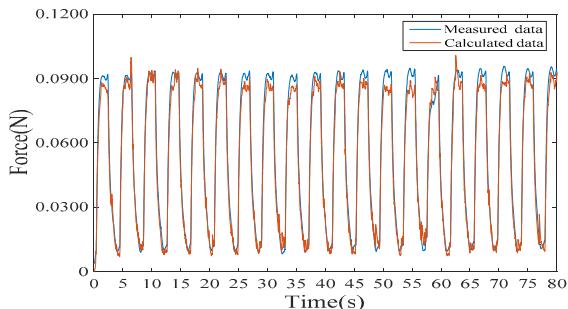


Fig.13 The comparison between the measured force and calculated force

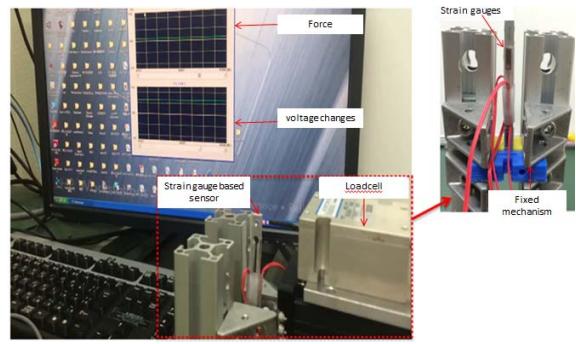


Fig. 14 Sensor measure limit experimental setup

Fig.13 exhibits and compares the loadcell measured force and linear curve calculated force. If the loadcell measured data are treated as reference, the strain-gauge based sensor is very close to these data. Due to the fact that the linear relationship of strain gauges' stress and strain is limited in a deformation range, it is necessary to testify the maximum of the sensor. The experimental setup is shown in Fig.14. The results imply that once the loadcell detected force is bigger than 0.925N, above derived linear relationship is not suitable to measure the catheter proximal force.

At last, we use our designed strain-gauges force sensor to measure the proximal force when forward or backward the catheter in the artificial blood vessel.

At last, we use our designed strain-gauges force sensor to measure the proximal force when forward or backward the catheter in the artificial blood vessel repeatedly. The experimental setup is displayed in Fig.15. To compare our designed sensor's results with the reference values measured by loadcell, we did the same experiment like Fig.16.

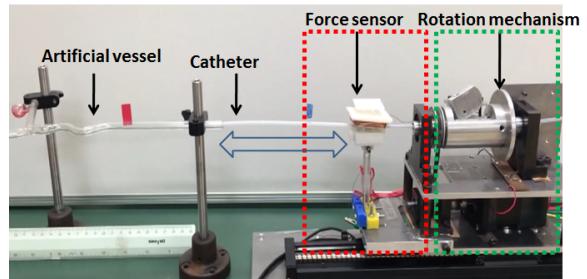


Fig.15 Catheter inserting into artifical blood vessel by strain-gauges sensor

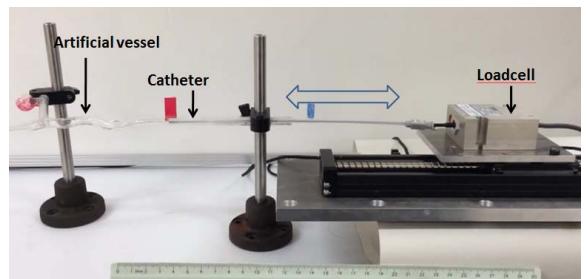


Fig. 16 Catheter inserting into artifical blood vessel by loadcell

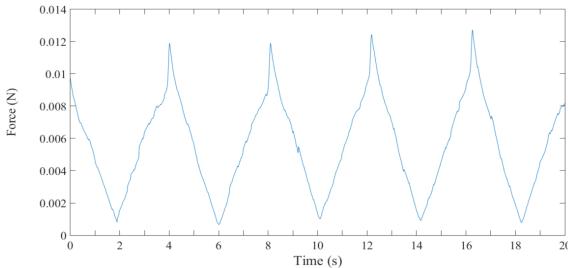


Fig.17 The strain-gauges sensor measure force data

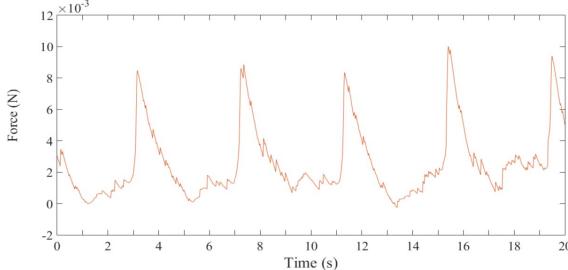


Fig.18 The loadcell measured force data

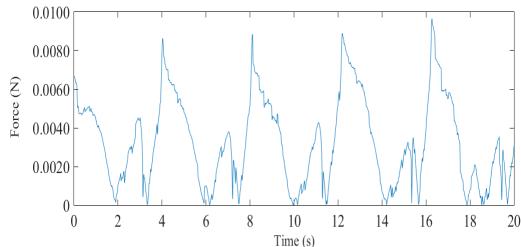


Fig.19 The errors between the strain-gauges sensor and loadcell

The experimental results are displayed in Fig. 17 and Fig.18. It is obvious that our designed sensor is less likely to be free from the outside interference than the loadcell measured data. Besides the force, we calculated the error between these two groups' data and the outcomes indicate that the maximal error is less than 0.01N which is acceptable.

V. CONCLUSION AND FUTURE WORK

The tele-operation system is a hot topic in endovascular surgery, which makes the surgeon and patients in isolated position and prevent surgeon from X-ray exposure. However, on contrary to the traditional surgery, master and slave sides keeps the surgeon feeling the catheter insertion sensation. Therefore, it is important to equip a proximal force measurement device on the slave side and feedback to the master side. The master side haptic mechanism can provide the fore sensation for surgeon according to the slave side measured force. The objective of this paper is to design a strain-gauges-based force measurement device. This novel designed force device can not only measure the proximal force but also be a grasper when inserting or retreating the catheter. To accurate calculate the force, we calibrated the strain gauges' output voltage by the loadcell and derived the linear relationship between the force and voltage. Then in the experimental part, we evaluate the maximum limit and error of our proposed force measurement device. The results showed

that the strain-gauges based device is very suitable for catheter slave side equipment and the measurement range and error are in the acceptable level.

Possible future work can be done in following parts. First, the slave side measured force will be feedback to the master side by the Internet. Then, the master side's MR-fluids based haptic device will provide corresponding sensation according such data. In this way, the surgeon can get more realistic feeling through this master-slave side catheter operation system.

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