

# Study on Slave Side of Interventional Surgery Robotic System Focused on the Feed-back Force Detection

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**Abstract - Minimally invasive interventional surgery shows its advantages compared to traditional operation. The master-slave robotic system technology can further significantly improve the accuracy, efficiency and safety of this complicated and high risk operation. However, one of the critical issues in the robotic system, guide wire force feed-back, needs more research. The mechanical structure of the slave robot is designed basing on modularizing design principle. Ball spline pair, guide pair and herringbone gear pair are adopted in the structure concept. The experimental equipment is developed and the verifying experiments are conducted. The guide wire detected feedback force matches well with the detected resistance force. It indicates that the designed slave part and design method is rational from the point of feedback force detection.**

**Index Terms - Minimally invasive interventional surgery, Surgery Robot, Master-Slave system, Feedback force detection**

## I. INTRODUCTION

Minimally invasive interventional surgery shows many advantages compared traditional surgery, such as less bleeding, fewer complications, small trauma, quick recovery, etc [1]. However, currently human intervention operations have its shortages. Firstly, because of long operation time, the doctor must be exposed to large dose of X-ray radiation, which will harm their health. Secondly, operation performance depends to large extent on doctor's priori knowledge of human anatomy and physiology and operating experience. Lastly, doctor's misoperation easily leads to failure of surgery and high risk of patient life. Recently, robotic assisted interventional surgery system is considered to be a promising and effective technology to improve this complex surgery by combining robot technology and the integration of vascular interventional technique [2].

Guide wire feedback force detection is one of the most important issue in the interventional surgery robotic system. Surgeons cannot directly contact with lesions during the endovascular intervention surgery. They feel the contact between the guide wire and the vessel wall by the resistance force on guide wire proximal end. So, it is necessary for the surgeon to feel the resistance force of the guide wire, which is a basic ensurence for successful interventional surgery. However, the guide wire force feedback has not been considered in most of the current interventional surgery robotic system. One of the most popular robot assistance systems is a robotic catheter placement system which is called

Sensei Robotic Catheter System supplied by Hansen Medical [3]. This System provides the surgeons with more stability in catheter placement with the Artisan sheath compared to manual techniques, so it can allows for more precise manipulation with less radiation exposure to the doctor. Catheter Robotic Inc. produced a remote catheter system called Amigo [4]. This system has a robotic sheath to steer catheter controlled at a nearby work station, and it is similar to Sensei system in manner. Magnatecs Inc. produced their 'Catheter Guidance Control and Imaging' (CGCI) system [5]. 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 called the Stereotaxis Niobe [6]. Yogesh Thakur et al. developed a kind of remote catheter navigation system [7]. This system allowed the user to operate a catheter manipulator just like operating a real catheter. So surgeon operative skill is able to be applied in this system.

In the previous research, there are many achievements. Shuxiang Guo put forward a new kind of pipe robot control system, the system uses a master-slave control mode and it achieves the remote operation [8]. Nan Xiao et al. [9] developed a robot-assisted catheterization system with which physician can feel the resistance on guidewire proximal end during the remote operation. Jian Guo et al. [10] detected the operating force of the slave manipulator adopting a load cell that fixed on the slide platform. Xuanchun Yin [11] et al. firstly introduced a human operator-centered haptic interface design concept into actuator choice and design. A semi-active haptic interface was designed and fabricated through taking full advantage of MR fluids and a mechanical model (force/torque model) was established. Jin Guo [12] presented a catheter-sensing unit (used to measure the motion of the catheter) and a force feedback unit (used to provide a sense of resistance force). A camera was used to allow a contactless measurement avoiding additional friction, and the force feedback in the axial direction was provided by the magnetic force generated between the permanent magnets and the powered coil. Weili Peng et al. [13] developed an interventional operation slave system and designed the force feedback detection structures adopting a FUTEK mechanical sensor. Xuanchun Yin et al. [14] proposed a haptic catheter operation system for teleoperation through exploiting

magnetorheological fluids. The haptic sensation is provided by varying the viscosity of the magnetorheological fluids by adjusting the magnetic field, which is dependent on the force measured in the slave manipulator. The haptic interface consists of three parts: magnetic field, magnetorheological fluids container and haptic performance calibration mechanism. Shuxiang Guo [15] et al. designs a catheter grasper adopting a common structure like the pliers, which can guarantee that the catheter can be clamped on the same axes with other via hole. The clamping force can be adjusted by the screw through changing the entered length of the screw to change the compression length of the spring. The graspers clamp the catheter just like the surgeon's hand and the clamping method of the grasper imitates the surgeon's operation. Jin Guo [16] et al. studied the force feedback in vascular interventional surgery assistance robotic system. In order to realize the force feedback, a damper is used based on the intelligent fluid magnetorheological fluid. The damper is a piston structure with MR fluid. It can transmit the force feedback to surgeon's hand through the operating catheter from the control of master controller, which seems that the surgeon operates the catheter beside the patient. Xu Ma [17] et al. proposed a novel robotic catheter manipulating system to reduce the performance error and irradiation to surgeons. The surgeon console (the master side) used to measure the axial and radial motions of input catheter and the catheter manipulator (the slave side) used to implement to patients. Yu Wang [18] et al. introduces standard linear solid model to formulate the vascular physical model and determine this model's parameters based on vascular wall elasticity analysis in the virtual-reality simulator of the robotic catheter operating system. Yuan Wang [19] et al. introduces a haptic feedback function in the developed interventional surgical robot system. This robot system could simulate the procedure of the doctor's hand to operate the guide wire, and providing haptic feedback to the doctor. However, the guide wire force feed-back detection structure needs more research to improve the force detection accuracy.

In this paper, the slave part of interventional surgery robotic system is studied from the point of feedback force detection. In section II, the mechanical structure of slave robot is designed to realize the accuracy detection of feedback force, meanwhile, realizing nondestructive clamping of guide wire, pushing-pulling and reversing of guide wire. In section III, the prototype of slave robot and experimental system is developed. Corresponding experiments are conducted to verify the detective precision of feedback force. In section IV, the research work in this paper is concluded and the future work is pointed out.

## II. KINEMATIC ANALYSIS AND MECHANICAL DESIGNING

Interventional surgery robot system assists the physicians operates the surgery basing on master-slave control principle, which consists of master robot and slave robot. As shown in Fig. 1, the physician manipulates the master robot to do all kinds of surgical operations to implement vascular interventional surgery. Meanwhile, the master robot detects

the surgical operations and sends synchronically the action instructions to the slave robot. The slave robot operates the guide wire and catheter to accomplish this complecited surgery under the controlling of master robot. At the same time, the slave robot detects the feedback force and torque of the guide wire and catheter applying on the clamp holder and sends the feedback force and torque signal to the master robot. The master robot provides force and torque feedback to the physicion based on feedback signal and force repetition techniques. Therefore, the detective precision of feedback force of guide wire is significant issues in intervention operation robotic system. In this section, the kinematic mechanism of slave robot is analysed. Then, the mechanical structure of slave robot is designed.

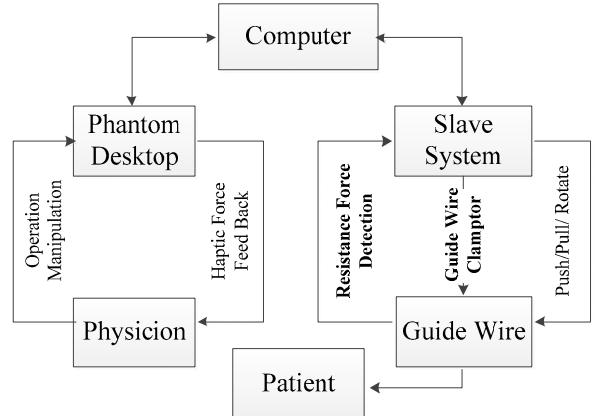


Fig. 1 Schematic diagram of the interventional assistance robotic system

As shown in Fig. 2, the mechanical structure of the slave robot consists mainly of the guide wire clamping device, gear pair, locking device of the clamping part, motor. When the locking device locks the one side of the clamping part, the motor drives the gear pair to rotate. The gear rotates the other side of the clamping part. The two side of the clamping part is connected with each other by screw pair. So, the two side of the clamping part get close with each other because of the screw pair and relative rotation. Then, the guide wire could be clamped with the clamping device.

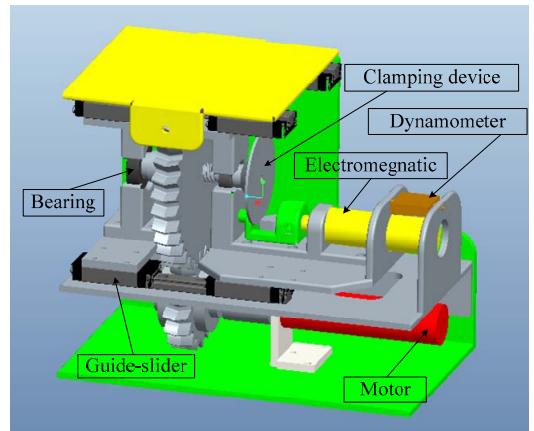


Fig. 2 The mechanical structure of the slave part of the robot system

#### A. Designing method of guide wire clamping device

As is analyzed above, the slave robot is designed to clamp the guide wire and realize three-kind movements of guide wire, push, pull and torque. At the same time, the feedback force should be detected accurately.

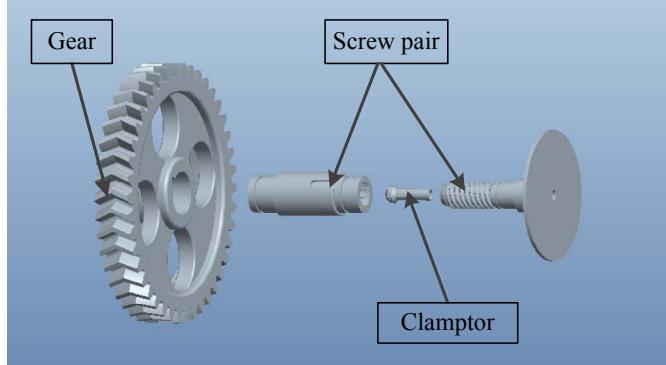


Fig. 3 Mechanical structure of guide wire clamping device

Firstly, the guide-wire-clamping device is designed basing on medical grade guide wire rotator. As shown in Fig. 3, the guide wire clamping device consists a screw pair and a clamping part. The screw pair can achieve self-locking after the guide wire is clamped. One part of the screw pair provides a conical surface to the clamping part, which is defined as part P. The other part of the screw acts as a limit sleeve, which is defined as part Q. The schematic diagram of guide wire clamping part, as shown in Fig. 4. The clamping part and conical surface are coaxial. There axis is defined as x axis. y axis is perpendicular to the x axis. The original point is defined as intersection of the conical surface and x axis. C is one of the generatrixes of this conical surface.  $\alpha$  is defined as the included angel of line C and x axis. Point A is the intersection point of line C and the guide wire clamping part, when the clamping part just contacts with the guide wire.  $r_1$  is defined as the radius of the cross section of the conical surface at point A. Point B represents the clamping point, which is the contact point between clamping part and guide wire. It is assumed that the conical surface is rigid and the clamping part is elastomer. When the clamping part moves along the x axis to the positive direction, the clamping point B moves down until the guide wire is completely clamped. When it achieves this state, the moving distance of clamping part is defined as clamping distance  $d_c$ , the intersection point between clamping part and line C is defined as A', and the radius of the cross section of the conical surface at point A' is defined as  $r_1'$ . Basing on the geometrical principle, clamping distance  $d_c$  can be expressed in Eq. (1):

$$d_c = (r_1 - r_2) \cdot \cos \alpha \quad (1)$$

Where  $(r_1 - r_2)$  is considered approximately equal to the ordinate value of point B when the clamping part just contacts with the guide wire, which is depend on designing size of clamping part and the radius of guide wire.

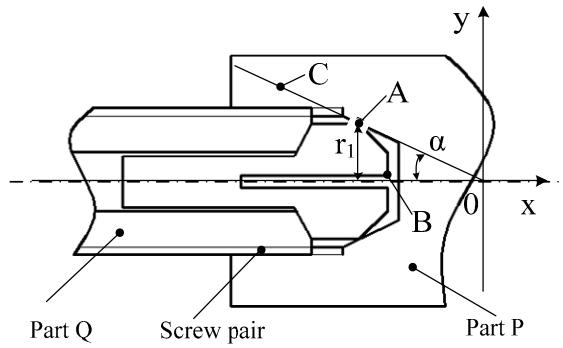


Fig. 4 Schematic diagram of guide wire clamping part

In this research, the positive and negative motion of clamping part relative to conical surface is driven by the screw pair. The relationship between the angular displacement  $\Delta\theta$  between the clamping part and conical surface, helical pitch  $S$  of screw pair and clamping distance  $d_c$  can be expressed in Eq. (2):

$$\Delta\theta = \frac{d_c \cdot \pi}{S \cdot 360^\circ} \quad (2)$$

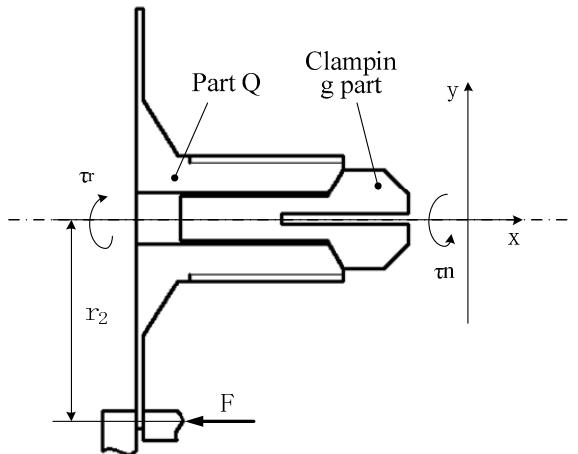


Fig. 5 Schematic diagram of locking of Part Q of clamping device

The reliable and fast clamping of guide wire depends on locking efficiency of part Q of screw pair at a certain extent. To reduce the angle displacement error of guide wire generated during clamping and unclamping process, friction braking method is adopted in this work to lock the part Q of screw pair, as shown in Fig. 5.  $\tau_n$  is defined as the torque needed to completely clamping the guide wire by rotating the screw pair. To enlarge the force arm, the end side of part Q is designed to be disc shape with radius of  $r_2$ . A slider provide the normal pressure to produce friction force  $F_f$  at the contact surface between the end side of part Q and itself, which further generates friction resistance moment  $\tau_r$ . If  $\tau_r$  is bigger than  $\tau_n$ , the guide wire can be completely clamped. The safety factor of guide wire clamping is defined as  $\zeta$ , which is the ratio of  $\tau_r$  and  $\tau_n$ .  $\zeta$  can be given in Eq. (3), (4) and (5):

$$\xi = \frac{\tau_r}{\tau_n} \quad (3)$$

$$\tau_r = F_f \cdot r_2 \quad (4)$$

$$F_f = F \cdot \mu \quad (5)$$

Where  $\mu$  is the frictional coefficient between the slider and the end side of part Q.

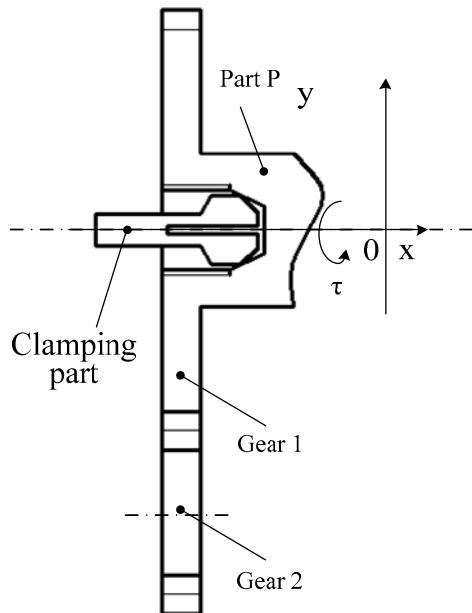


Fig. 6 Schematic diagram of part P

The part P of the screw pair provides a driving torque, which realizes the relation rotation between part P and part Q to achieve the clamping distance. To realize accurately the guide wire clamping and guide wire rotation, part P is designed with a gear structure. The part be is driven by gear 2, as shown in Fig. 6. The transmission ratio of the gear set is defined as  $i$ . The guide wire clamping period is defined as  $t_c$ , which can be given in Eq. (6):

$$t_c = \frac{\Delta\theta \cdot i}{360^\circ \cdot n_2} \quad (6)$$

To completely clamp the guide wire and prevent angle error due to guide wire clamping process,  $\tau$ ,  $\tau_n$  and  $\tau_r$  should meet the relationship in Eq. (7):

$$\tau_n < \tau_r < \tau \quad (7)$$

#### B. Designing method of feed-back force detection structure

Feed-back force detection is a critical issue for interventional surgery robotic system. Basing on feed-back force signal and force telepresence, the robot system can provide the manipulator with the fell of resistance of guide wire, which is necessary for physician to do this operation safely and efficient. As shown in Fig. 7, the structure principle of feed-back force detection.

A commercialized high-precision Dynamometer is adopted to detect the feedback force of guide wire. An

electromagnetic could be adopted to provide the tensile force to the slider to generate the normal force to the part Q in clamping device. The clamping device is assembled to four set slide block, which is assembled on four set of liner guide. To reduce the error generated due to friction force, the dynamometer is assembled between the liner guide and the clamping device. When the gear 1 moves with a tiny distance, gear 2 should moves with gear 1 to prevent the friction between them. So, herringbone gear pair is adopted in clamping device. It can transfer the axial force between the gears, while it transfers torque. In addition, ball spline pair is adopted as the joint between gear 2 with the motor shaft. During the operation process, the guide wire applies the feed-back force onto the clamping device, which leads to tiny deformation of the Dynamometer. In this way, the feed-back force is detected. Because of the use of bearing structure and guide-sliding structure, effect of the friction force on accuracy of feed-back force detection is reduced.

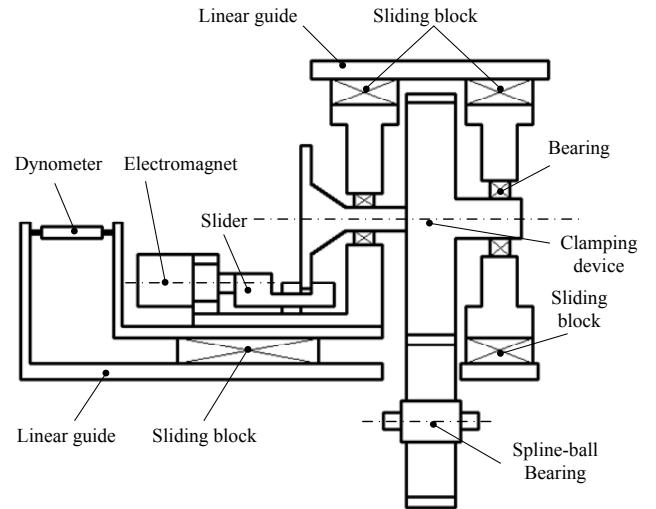


Fig. 7 Sketch of the feed-back force detection structure

### III. EXPERIMENTAL DETAILS AND RESULTS

#### A. Experimental equipment and experimental process

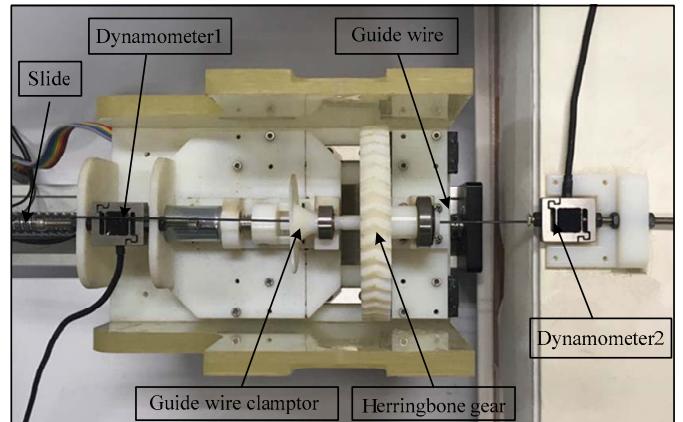


Fig. 8 Prototype of the slave robot and the resistance force Dynamometer

To verify the rationality of the designed slave robot and the accuracy the feedback force detection, the experimental equipment is developed. Firstly, the slave part is designed based on the designing method illustrated in section 2. According to the radius of guide wire, the clamping part is designed. Then, the clamping device is designed basing on Eq. (1~7). A commercialized motor and a special designed electromagnet is adopted, according to the parameters of which the mechanical structure of the slave robot is designed, as shown in Fig. 8. The designed slave robot is processed and assembled. Integrating the designed slave robot and a commercialized phantom as the master robot, the experimental interventional surgery system is developed, as shown in Fig. 9.

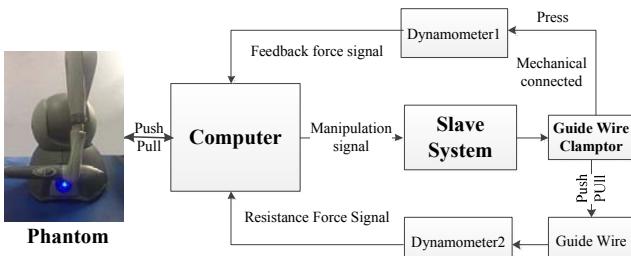


Fig. 9 Schematic plot of the overall experimental system

In the verifying experiments, the slave part is controlled in two ways: one of them is to manipulate the phantom by moving the handle along horizontal straightness, simulating the operation of the physician, the other one is to moving the slave part by program to realizing uniform motion of the slave part. The slave robot pushes or pulls the guide wire to press the Dynamometer 2. The Dynamometer 2 detects the pressing force of the guide wire. At the same time, the Dynamometer 1 assembled on slave robot detected the resistance force of guide wire, which contains the error due to the mechanical structure between the clamping part and the Dynamometer 1. The difference of these detected two force value is defined as the detection error of the feedback force detection.

#### B. The results and discussion

Three volunteer are employed to conduct the verifying experiments. Every volunteer operates five sets of experiments in two experimental methods respectively. The most two representative experiment results of each volunteer are adopted and averaged to obtain the final results, as shown in Fig. 10 and Fig. 11. The red curve characterizes the detected resistance force and the blue curve represents the detected feedback force. The black curve indicates the difference between the resistance force and feedback force, which is defined as the detection error in this work.

The force detection results of the experiments controlling the slave part by Phantom manipulated by a volunteer are shown in Fig. 10. It can be seen that the feedback force detected by Dynamometer 1 matches well with the resistance force detected by Dynamometer 2. At the beginning, the guide wire tip does not contact with the Dynamometer 2, there is no pressure on the two Dynamometers, so the two force value

keep zero. When the guide wire tip presses on the Dynamometer 2, the absolute values of the resistance force and feedback force increase. Since the volunteers are cautious when the guide wire tip is close to the Dynamometer 2, so they push the guide wire slowly. In addition, the experimental method that manipulating the Phantom by human hand leads to instability of the forward velocity of the slave side. As a result, the resistance force and feedback force experience irregular fluctuation and overall increase. When the volunteer pulls back the Phantom, the guide wire gets away from the Dynamometer 2 with the slave side, which leads to the rapid reduce of the resistance force and the feedback force. The biggest force in the experiments achieves about 0.85 N. The biggest detection error between resistance force and feedback force is about 0.16 N. The biggest relative detection error rate is about 18.8%.

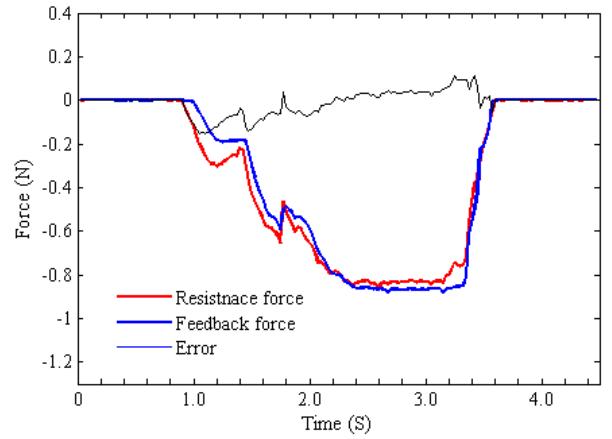


Fig. 10 Experimental results of controlling the slave part by Phantom

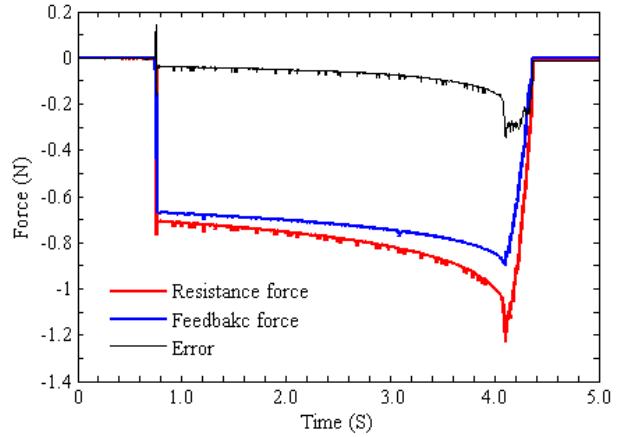


Fig. 11 Experimental results of controlling the slave part by control program

The force detection results of the experiments controlling the slave part by control program are shown in Fig. 11. In this experimental method, the slave part gets close to the Dynamometer under a small and uniform speed. So, when the guide wire contacts with the Dynamometer 2, the resistance force and the feedback force increase rapidly to a certain value. With the guide wire continuously increasing the pressure on

the Dynamometer 2 and the guide wire clampor, the detected two forces increase slowly. When the slave part deviates from the Dynamometer 2, the two detected force decrease quickly. The detected resistance force matches well with the feedback force. The biggest force detected by Dynamometer achieves about 1.25 N. The biggest detection error is about 0.3 N. The biggest relative detection error rate is about 0.24%.

In conclusion, the detected resistance force matches well with the detected feedback force. It indicates that the designed slave part and design method are rational from the point of feedback force detection. However, there is still detection error between those two forces. On the one hand, it can be seen from Fig10 and Fig.11 that the biggest detection error generates when the resistance force and feedback force vary rapidly. The reason of this part of detection error is considered to be on account of the inertia force of those mechanical parts between the guide wire clampor and the Dynamometer 1 in the structure of slave side. On the other hand, when the detected force is relatively stable or vary slightly, the detection error keeps relatively to be a lower level. The reason of these part of detection error is considered to be the friction force between the motion components of the slave side. It needs more research to reduce the friction and the inertia force of the parts in the slave side structure to improve the feedback force detection accuracy.

#### IV. CONCLUSIONS

In this paper, the slave part of interventional surgery robotic system is described from the point of feedback force detection. First of all, a novel design method and mechanical structure of the slave side of minimally invasive interventional surgery assistance robot system are proposed. Ball spline pair, guide pair and herringbone gear pair are adopted in the proposed structure to improve the feedback force detection accuracy. Then, the experiment equipment is developed by integrating the designed slave part and a commercialized phantom as the master side. The verifying experiments are conducted. The detected resistance force matches well with the detected feedback force. It indicates that the designed slave part and design method are rational from the point of feedback force detection. However, the proposed mechanical structure of slave part needs improvement to reduce the effect of the friction and inertia force between the Dynamometer 1 and guide wire clampor to reduce the feedback force detection error.

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