Surgeons' Operation Skill-Based Control Strategy and Preliminary Evaluation for a Vascular Interventional Surgical Robot

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ORIGINAL ARTICLE

Surgeons' Operation Skill-Based Control Strategy and Preliminary Evaluation for a Vascular Interventional Surgical Robot

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Abstract

Background Remote vascular intervention surgery that employs surgical robot is an important research field. It is difficult to ensure that the surgical robot realize the surgeons' operation skills precisely.

Objective To solve this problem, surgical robot must be able to duplicate the surgeons' changeable operation, and guarantee accuracy of synchronous motion between the surgeon's unpredictable operation and robotic control of surgical tool.

Method In this research, the surgeons' operations were disassembled, eight basic actions were obtained. The surgical robot which can reproduce these basic actions is designed. Further, fuzzy control theory was applied to optimize the remote control and to guarantee the control precision of the synchronous operations.

Result Using an experiment, the surgical procedures and operations of interventional surgical robot were obtained and evaluated. The robot can duplicate the surgeons' operative skills when the control precision of the guidewire is guaranteed. And the axial displacement error of the surgical robot is limited to less than 2 mm.

Conclusion The new type of interventional surgical robot was designed and proved that the surgical robot can duplicate the operation skills of the surgeon. The control error of novel surgical robot reaches the accuracy required by the surgeon.

Keywords Master–Slave surgical robot · Catheterization · Control strategy · Surgeons' operation skill · Fuzzy controlling theory

1 Introduction

With the development of robotic technology, surgical robot have been an essential means for optimizing vascular interventional surgery. Interventional surgical robot solved some disadvantages of traditional interventional surgery, such as long-time exposure to x-rays, the lack of experienced surgeons, and large consumption of the surgeons' energy [1–8].

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Some types of surgical robots have been employed in clinical usge. The Amigo remote catheter system, invented by Catheter Robotic Inc., apply a rocker to manipulate rotation, insertion, and front bending of the catheter (Khan et al. [9]). Hansen Medical invented Sensei X Robotic Catheter System, which provides a key remote controller for surgeons to control the motion and deformation of the catheter [10]. The controlling side of these systems is set outside the operating room and the operating side is in the operating room, which prevents the exposure of surgeons to x-rays. However, these machines cannot manipulate the guidewire as flexibly as surgeons do. In these systems, the key remote controller or remote controlling rocker has been designed for the controlling side. The operating side only provides uniform motion with variable gears to control the guidewire. Such a mode differs from the conventional operation and creates conflicts with the surgeons' knowledge and experiences, which results in surgical error. To solve this problem, we have proposed a controlling mode in our previous research, which offers synchronous guide-wire controlling [11–14].

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Due to the several advantages of this synchronous operative controlling mode, the research in this field has attracted an increasing number of experts. Jian Guo designed a catheter guiding system based on this idea, together with following catheter testing experiment [15–18]. Catheter robot invented by Shuxiang Guo have been used in some method to improve the controlling precision of catheter [19–27]. However, the controlling method for the catheter and guidewire also differs from that of the surgeons' hands in the above research, which cannot replicate the surgical skills from the surgeons' training. Such skills are crucial to the success of the surgery. Therefore, to reproduce the surgeons' operation skills by surgical robot, the complete duplication of the surgeons' handling actions is needed. Furthermore, surgical operations are changeable and the operating procedure is unpredictable, which leads the degeneracy of the control accuracy. Such an issue would affect the success of the whole surgery. Overall, our research aims to enable surgical robot to reproduce the surgeons' operating procedure and to guarantee the controlling precision of the robotic operation.

To solve the problems, in our research, a bionic interventional surgical-robot control strategy based on duplicating the surgeons' surgical procedures was applied. The master side allows surgeons' control tools outside the operating room provide surgeons with a virtual operative environment and sent the information of surgical operation to the slave. The slave side performed operations according to information collected from the master side. After ensuring the complete reproduction of the surgeons' operations, the controlling precision of robotic surgery was analyzed. The fuzzy control algorithm was selected to improve the control accuracy of the surgical robot. Finally, the experiment which is similar to the surgical intervention teaching-training assessment was designed to evaluate the performance of this surgical robot. Section 2 describes the operation mode of the surgical robot and operation skills of surgeons in interventional surgery. Section 3 describe the Surgical Robot based on reproducing surgeons' operation actions. Section 4 describe the control algorithm for remote operation of the surgical robot. Section 4 describe the evaluation experiment of remote operation. Section 5 presents the concluding remarks.

2 Controlling Strategy for Reproduction of Surgeons' Operation Skills with Surgical Robot

2.1 Operation Mode of the Surgical Robot

The completion of the remote-control surgery by interventional surgical robot requires the coordination between the master side and slave side. Specifically, the master side is surgeon's control platform for adoption of surgical operation and the slave side is the manipulated structure for performing the surgical operation. Besides, the whole interventional surgical robot contains an image acquisition device, force feedback device, force acquisition device, human interface device and software. The structure and function of the designed interventional robotic surgery system are demonstrated in Fig. 1.

However, current researches have two shortcomings in the realization of surgical skills. First, the master side of the system is realized by a key-remote control or rocker controller. The second point is that the control on the catheter is mostly belt transmission. In such a situation, surgeons' manipulation and guidewire control are not synchronous, resulting in the problem that the surgical skills cannot be executed and that the actual feel would not be sensed by surgeons. Considering these conditions, our group adopted the bionic control strategy duplicated from the surgeons' hand actions. Only in this way, surgeons' clinical experience can make sense in remote-control surgery and the robot can offer real surgical feelings to surgeons. Hence, we disassembled the surgeons' hand operations and designed a virtual surgical environment and a linear-dragging guidewire manipulator to accomplish the controlling scheme for reproducing surgeons' operation.

The systematic design procedure includes five steps.

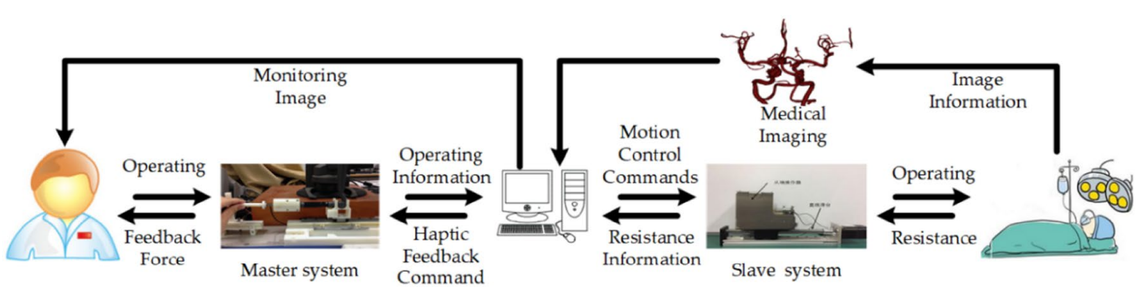

Fig. 1 Operation mode of the surgical robot

(1) Decomposition of Surgeon's operation in interventional surgery. In this step, operations which need to be detected by the surgeon control platform during surgery is examined.
(2) Design of the Master-side, surgeon control platform. In this step, a control platform that can accurately detect the operation determined in the first step was designed. And the platform must be consistent with the doctor's operating habits.

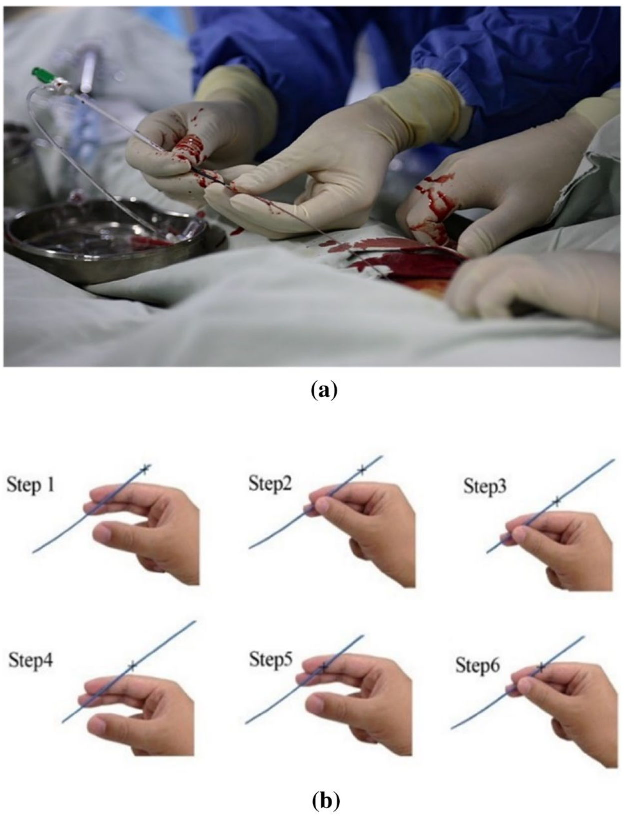

Fig. 2 Operation of surgeon in interventional surgery. **a** Clinical operation, **b** disassembled action

(3) Design of the slave-side, interventional surgical manipulator. In this step, a surgical manipulator that can accurately complete the operation detected by the master-side was designed.
(4) Design of the fuzzy controller for remote synchronization operation. In this step, the fuzzy controller that can improve the accuracy of remote synchronization operations between the master side and the slave side was designed.
(5) Performance evaluation of remote operation. In this step, an experiment that can evaluate the accuracy of remote synchronization operations was designed.

2.2 Research on Operation Skills of Surgeons in Interventional Surgery

To design an interventional surgical robot which can reproduce the surgeons' operation, the clinical surgical procedure and operation were analyzed and decomposed. The operation performed by surgeons in interventional surgery is illustrated in Fig. 2. Through the analysis of surgical imaging data, clinical assessment and discussion with surgeons, cardiovascular interventional surgical procedure was analyzed and decomposed.

The operation procedure of the surgeons is reciprocating, which include grasp, operate, relax, select operation location, and repetition. For eliminating the disturbances from the surgeons' personal habits, our research decomposes the surgeons' operations into basic actions based on changes of the guidewire and catheter state. The decomposition of the operation actions is illustrated in Fig. 3.

Although different surgeons have individual operating styles and different reciprocating cycles in surgical procedures, basic actions are eventually consistent. From the decomposition of surgical operation actions, the surgeons' operation procedure can be divided into eight basic actions, which are accomplished with fingers and arms independently.

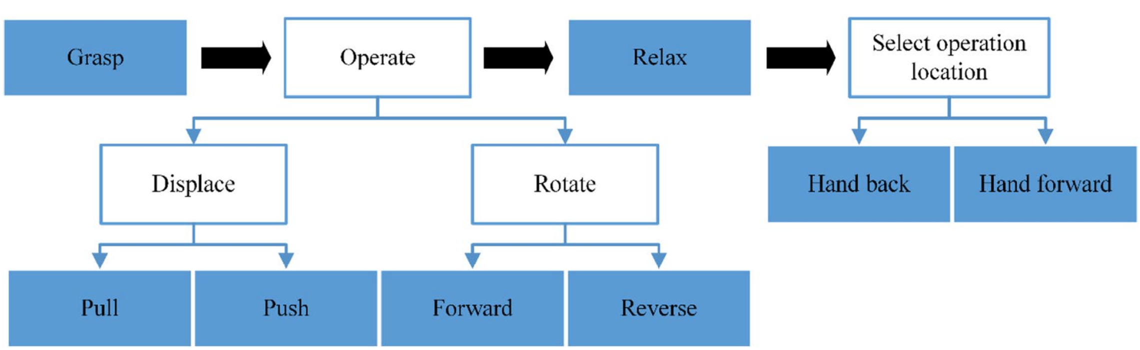

Fig. 3 Decomposition of the operation actions

Four actions for fingers: grasp, relax, rotate forward, and rotate reverse.

Four other actions for arms: pull and push to the guidewire, backward and forward to the hand.

Actions of the arms are divided into two groups, which are actually the same. The only difference between these groups is the state of the fingers when relaxing and grasping. Therefore, we can continue simplifying the operation into six basic actions.

According to such results, the control strategy for the interventional surgical robot for reproducing the surgeons' operation actions was designed. During the operation procedure, information of operation that must be measured in the master side are grasping, relaxing, rotating forward, rotating in reverse, hand forward, and hand back. The designed surgical robot can realized these basic actions independently as well as with coordination. According to these basic actions, the slave side can act like the surgeons' hands.

3 Development of a Surgical Robot based on Reproducing Surgeons' Operation Actions

3.1 The Master-Side Surgeon Control Platform

According to Fig. 3, the data that the master-side surgeon control platform needs to detect is: to grasp, to relax, to rotate forward, to rotate reverse, moving forward, and moving backward. During surgery, the surgeon usually uses the guidewire torque to control the guidewire. Therefore, we designed a virtual surgical-operation environment that can provide surgeons with a handle whose diameter is the same as the diameter of guidewire torque. The handle achieves the authenticity of the surgeon's operating feel. As with actual surgery, the surgeon can manipulate the handle by push–pull and twist. To eliminate the impacts of excessive degrees of freedom and the quality of the device to the operating feel of the surgeon, the handle will be fixed on the sliding rails. This design not only eliminates the effect of gravity in the vertical direction but also limits the displacement of the guidewire to an axial direction. Moreover, because of the slide rail, the axial movement is not subjected to excessive friction. This design ensures that the surgeon's feeling accurate. Six basic actions which must to be measured will be detected by three sensors. The laser sensor (IL-300, KEYENCE, JP) measures the value of push and pull of the surgeon on the operating handle. The photoelectric encoder (E6H-C, OMRON, JP) detects the value of rotation of the operating handle. The piezoelectric rubber detects the grasping state of the guidewire. The operation detection method on the master side is illustrated in Fig. 4.

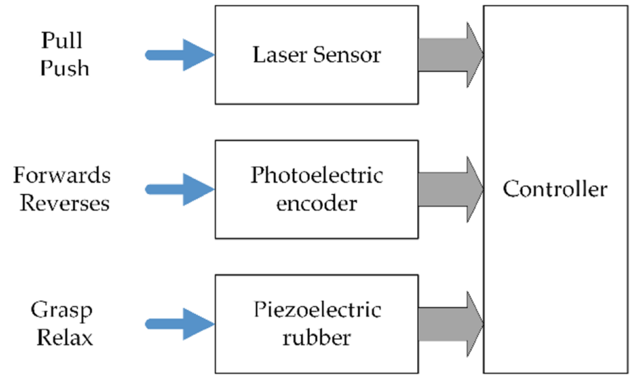

Fig. 4 Operation detection on the master side

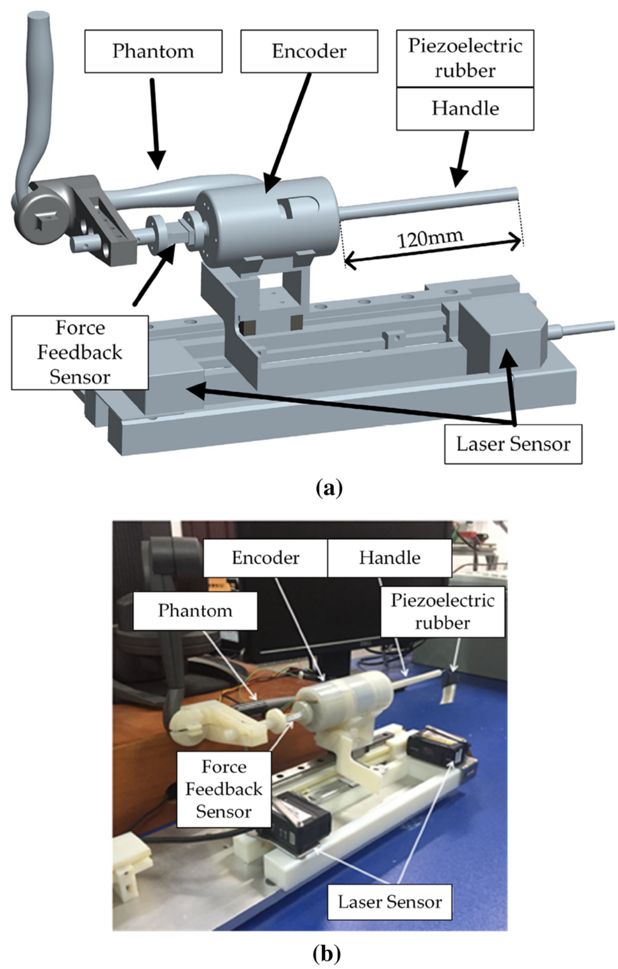

Fig. 5 The master-side surgeon control platform. **a** 3D model of the master side. **b** Prototype of the master side

Phantom (Desktop, Geomagic, US), a force feedback device, is connected to the end of the handle, so that the force feedback from the slave side can be given to the surgeon and measured by the force feedback sensor (LSB200,

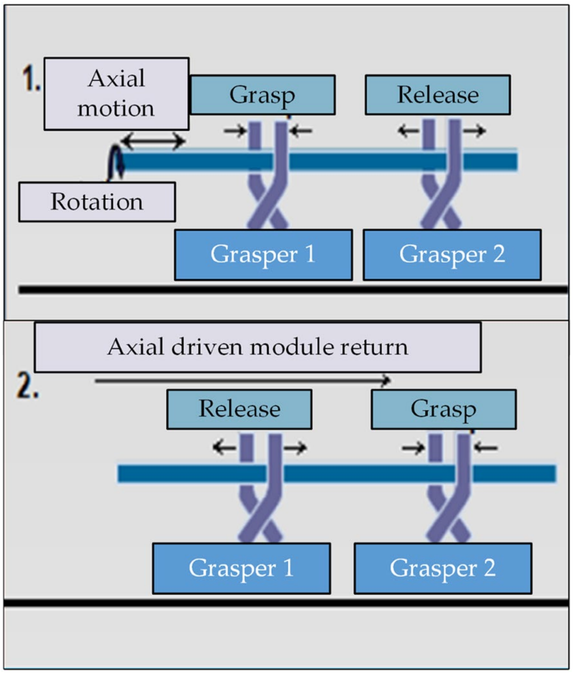

Fig. 6 Linearly towed catheter movement

Futek, US). While the procedure was detected, the surgeon also gained a realistic operation experience. The master-side surgeon control platform was designed as illustrated in Fig. 5.

3.2 The Slave-Side Interventional Surgical Manipulator

To achieve the high-precision operation that duplicates the surgeon's actions, this study adopts linearly towed drive technology, rather than the traditional wheeled extrusion drive. The use of the reciprocating linear drive makes the action conformant with traditional operating habits. In this drive mode, the drive unit moves in the direction of travel of the guidewire. This is exactly the same as the surgeon's hand movement when pushing the guidewire, to achieve the existing clinical surgical skills of the surgeon. Fig 6 is a demonstration of the working mode of the reciprocating drag mechanism. When the Grasper 1 grasps the guidewire, the robot can push and rotate the guidewire. When the Grasper 1 releases the guidewire, the robot can move the manipulator to select the appropriate operating position. In the process of selecting the operation position, Grasper 2 can prevent unnecessary displacement of the guidewire due to frictional force. The design of Grasper 2 may not be discussed in the control strategy.

Because the diameter of the guidewire is extremely small, therefore the conventional grasping method can easily cause the guidewire to slip during the operation. Besides, it is extremely difficult to control the rotation of guidewire.

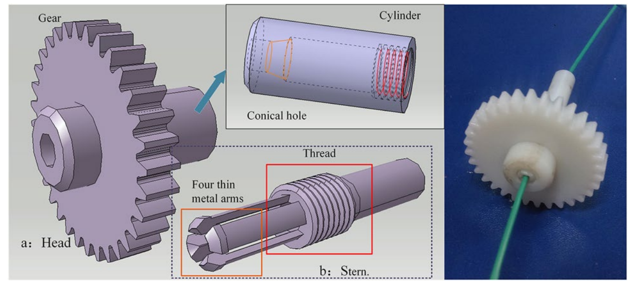

Fig. 7 Guidewire torque

Moreover, the guidewire may also be deformed when subjected to excessive pressure, thus affecting the operation. These are the problems that need to be solved in the research on guidewire operating mechanism.

In this study, inspired from traditional surgical instruments, a guidewire torque is designed to facilitate the mechanical operation. The structure is illustrated in Fig. 7. Part a and part b are connected through the thread, and the guidewire passes through the through-hole. In the front end of part a, the through-hole will gradually shrink. Rotate part a, and the front end of part b gradually comes into contact with the inner wall of the front part of part a. After being squeezed, the through-hole formed by the metal claw arm also gradually reduces the diameter of the inner tube, thereby tightening the guidewire. The main reason that the guidewire deforms during grasping is the uneven force from the holder. Therefore, to prevent the deformation of the guidewire, four metal claw arms are set at the front end of part b, and the four forces evenly act on the guidewire. The performance of this structure is verified during surgery. The structure can effectively prevent the slippage and deformation of the guidewire. Moreover, the rotational torque of the gear at the front end of part a is much larger than that of the guidewire. Therefore, rotation of the guidewire by the gear can significantly reduce the difficulty of rotation control of the guidewire.

Based on this guidewire grasping approach, there is a certain change in the operation of the guidewire.

Grasp the guidewire → tighten part b + rotate part a forward.

Release the guidewire → tighten part b + rotate part a reversely.

The rotation operation after tightening the guidewire:

Rotate the guidewire forward → loosen part b + rotate part a forward.

Rotate the guidewire in reverse → loosen part b + rotate part a reversely.

The grasp-and-release and rotation of the guidewire are converted into the grasp-and-release of the guidewire torque-part b and the rotation of the part a. The difficulties and possible mistakes in manipulating the guidewire are reduced.

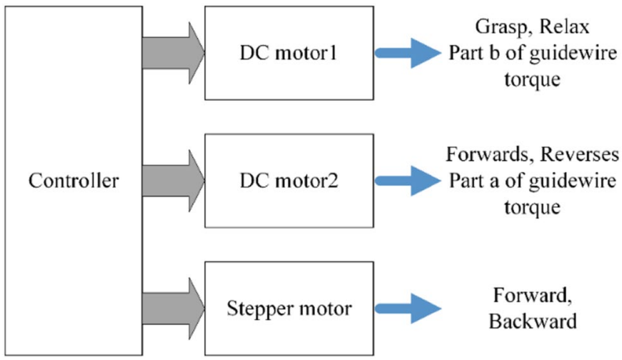

Fig. 8 Operation drive portion of the slave side

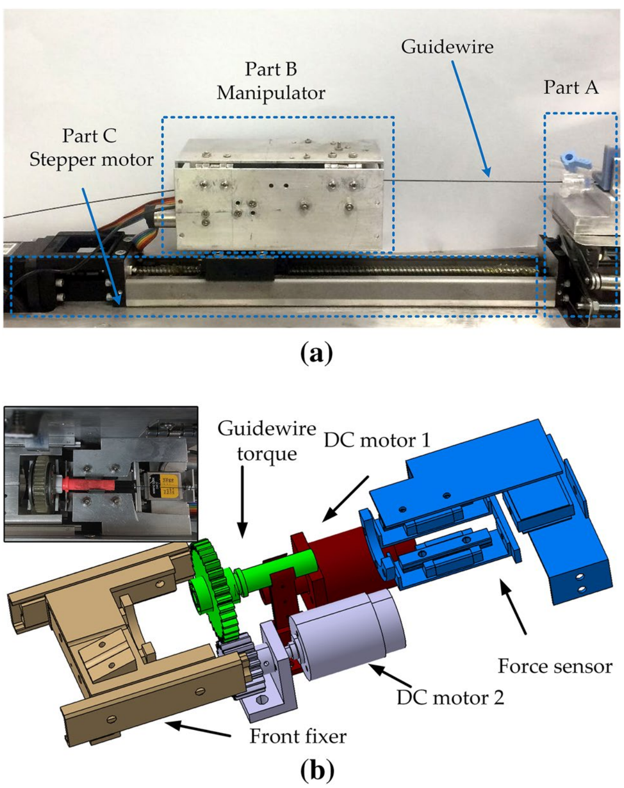

Fig. 9 The slave side interventional surgical manipulator. **a** Prototype of the slave side, **b** structure of manipulator

Therefore, the drive portion of the slave-side guidewire manipulator can be designed, as illustrated in Fig. 8.

The slave-side, designed based on the control strategy that duplicates the surgeon's hand action, is illustrated in Fig. 9a. The black line in the Figure represents the guidewire, and part A is the platform to fix the catheter sheath (grasper 2), which will contact the patient. Part B will be fixed on part C. It is the operation part that completes the function of the surgeon's hand, which controls the rotation and fixation of the guidewire. The torque, DC motor 1, and DC motor 2 (EC-max, Maxon, CH) are integrated in Part B, as illustrated in Fig. 9b. Part C is a fixed slide motor (SGMJV, YASKAWA, JP) that acts as the surgeon's arm. Its function is to drive the translation of Part B and to control the push of the guidewire.

3.3 Synchronous Operation with the Surgeon

In this research, we have determined that the surgeon's operation is a reciprocating periodic operation, namely Grasp-Operate-Release-Select Operation Position-Grasp. The surgical robot also operated on the guidewire fully following this step, as given in Table 1.

To complete a cycle of operation on the guidewire, the action contrast between the cases with surgical robot and surgeon is illustrated in Fig. 10.

4 The Control Algorithm for Remote Operation

Because the surgeon's surgical operation is duplicated, the manipulation of the robot retains the variability of the surgeons' operating skills and the unpredictability in the operation procedure. This is a great challenge for robot control accuracy. The control of the system must ensure that the slave-side guidewire manipulator makes the same movements with the operating handle of the master side, to guarantee the highest possible follow-up. In the initial work, the traditional proportional–integral–derivative (PID) control method is used to realize the following movement between the master side and slave side through the upper

Table 1 Contrast between the cases with the surgical robot and surgeon

Step 1	Surgeon	Grasp guidewire
	Surgical robot	Grasp head of guidewire torque, forwards stem of guidewire torque
Step 2	Surgeon	Operate guidewire (pull)
	Surgical robot	Relax stem of guidewire torque, linear stepper motor to move forward
Step 3	Surgeon	Relax guidewire
	Surgical robot	Grasp stem of guidewire torque, reverses head of guidewire torque
Step 4	Surgeon	Select operation location (Hand back)—grasp guidewire
	Surgical robot	Linear stepper motor to move backward—grasp guidewire

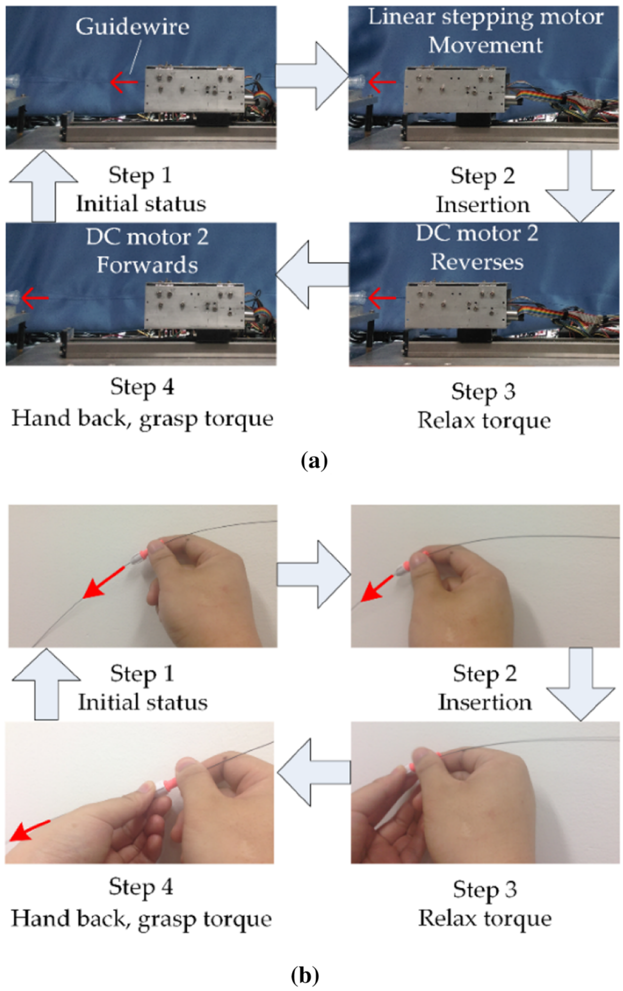

Fig. 10 Operations of the surgical robot and surgeon. **a** Operation of robot, **b** operation of surgeon

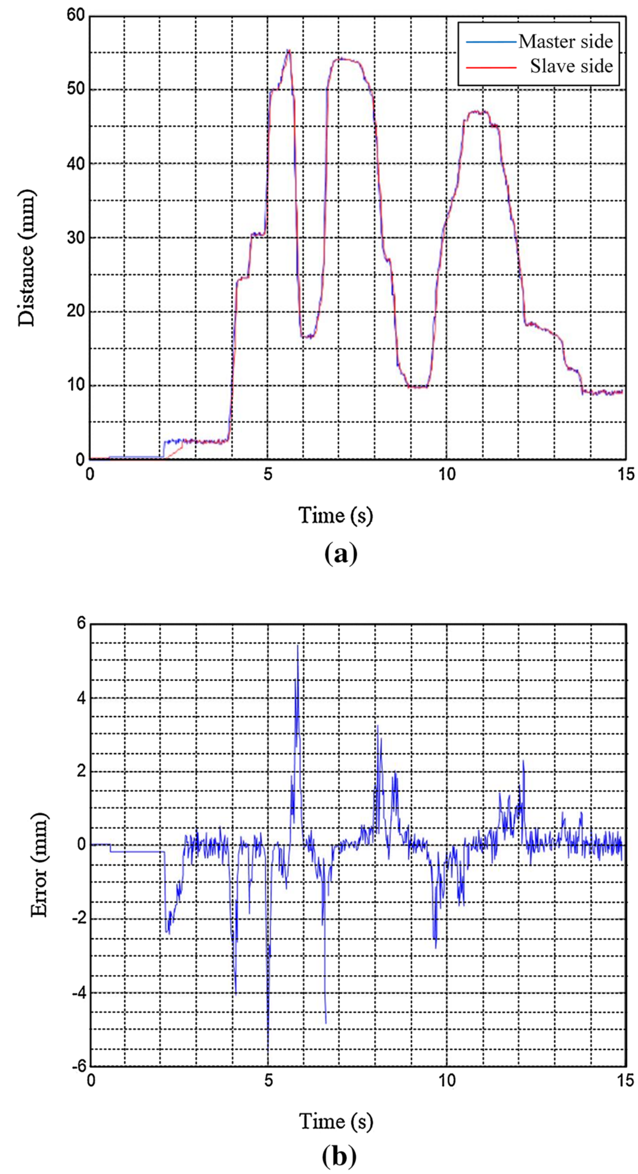

Fig. 11 Following movement between master side and slave side. **a** Position tracking, **b** Positioning error

computer. The effect of the following movement is illustrated in Fig. 11.

After using and testing the traditional PID algorithm, the maximum error is 5.903 mm, which means that the result is not satisfactory. The system has a large error when the speed changes too fast. In this study, the problem is analyzed. The reason why that the error cannot be reduced are described as follows:

1. The master–slave motion control of remote surgery cannot use the detailed internal structure to obtain the accurate mathematical model.
2. The process of operation relies on the experience of surgeons, which means that the operation is variable and unpredictable.
3. The surgeons are non-professional engineers, for whom the process of human–computer interaction is comparatively complicated.
4. The remote surgery has high requirements of accuracy, stability, fault tolerance, and adaptability.

The remote-control system is a type of non-linear, time-varying, lagged, and incomplete model system. It needs a nonlinear controller with better robustness, adaptability, and fault tolerance. Therefore, the fuzzy control algorithm is used when designing the controller of the interventional surgical robot. Fuzzy control can effectively solve the above problems. Firstly, the control system of the robot is identified through system identification, and the fuzzy rules are designed through the experience of surgeons. Then the controller is designed by the fuzzy rules.

4.1 System Identification

Under the guidance of the surgeon's experience, the controlling situation is divided into 12 intervals according to the speed. These 12 speeds are the comparatively common propulsion speeds of the guidewire selected by surgeons in surgical operations. To experiment by putting the step response within one cycle (5 ms) into the system identification box in MATLAB. The transfer function of the second-order system is known, as given by Eq. (1), and the results are calculated according to the least squares method.

$$G(s) = \frac{Kp1}{(1+Tp1*s)(1+Tp2*s)}$$
$$Tp1 + Tp2 = 2\left(\frac{\zeta}{\omega_0}\right), Tp1 * Tp2 = \frac{1}{\omega_0^2} \quad (1)$$

where $Kp1$ is the magnification of the second-order system. $Tp1$ and $Tp2$ are simplified second-order system transfer parameters recognized by MATLAB, ζ is the damping ratio of the second-order system, ω_0 is the natural angular frequency of the second-order system.

Since this function is a transfer function under continuous time, it is necessary to obtain the transfer function in discrete time by transforming the operators of Laplace transform into Z transform operators. The step response is illustrated in Fig. 12. As given in Table 2, the parameters of the second-order system identification are obtained through the results of the step responses at different speeds. Combining Eq. (1), 12 different reference models $G(s)$ can be obtained. The rotary control solution is the same as the linear motion solution exactly.

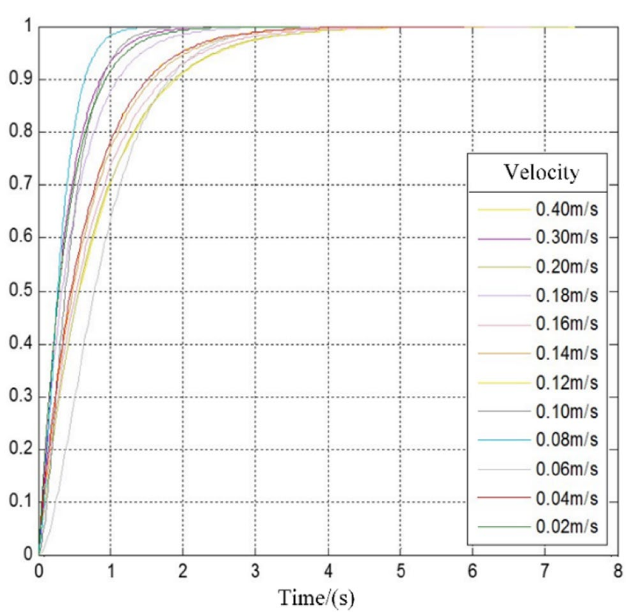

Fig. 12 Step response of the second-order system

Table 2 The parameters of the second-order system

Velocity (m/s)	$Kp1$	$Tp1$	$Tp2$
0.00–0.03 (0.02)	0.99975	4.0256e-4	1.2885e-7
0.03–0.05 (0.04)	0.99975	6.5648e-4	1.4139e-7
0.05–0.07 (0.06)	1	4.6478e-4	4.6471e-4
0.07–0.09 (0.08)	1.0001	1.3045e-4	1.9962e-4
0.09–0.11 (0.10)	1	2.2652e-4	2.2652e-4
0.11–0.13 (0.12)	1	6.5708e-4	1.2317e-7
0.13–0.15 (0.14)	1.0001	6.8668e-4	4.1175e-9
0.15–0.17 (0.16)	1	7.5635e-4	1.2678e-7
0.17–0.19 (0.18)	1	1.0000e-6	4.7815e-4
0.19–0.25 (0.20)	1	8.1585e-4	1.5281e-9
0.25–0.35 (0.30)	1	3.6079e-4	3.0608e-5
0.35–0.45 (0.40)	0.99997	8.2633e-4	1.1075e-8

4.2 The Design of the Fuzzy Controller

According to the results of system identification, the parameters of the fuzzy control are identified, and the algorithm designed will be verified in the following section.

To simplify the controller, according to 12 different speeds in Table 2, 5 different error intervals are set for control. They are Small (S), Medium-Small (MS), Medium (M), Medium–Large (ML), Large (L). At the same time, according to different errors, Δe is set to five different intervals. The setting of interval for Δe and e is the same. There are 25 different model choices in this method. In the case of more complex operations, the classification process need to be refined.

According to the characteristics of the interventional robotic system, the model in this study chosen refers to adaptive fuzzy PID control. The system is synchronized between the slave side and the master side. Hence the desired output is the input $x(T_n)$. According to the current speed $v(T_n)$, the operation is judged to locate in which kind of interval. And the appropriate control model $G(s)$ is selected. The $v(T_n)$ is role of the e in Table 3. Then, the error $e(T_n)$ between the reference model output $ym(T_n)$ and the actual output $y(T_n)$ is calculated, and the error $e1(T_n)$ between the reference model output $ym(T_n)$

Table 3 Fuzzy control rules

	Δe				
	S	MS	M	ML	L
e					
S	u11	u12	u13	u14	u15
MS	u21	u22	u23	u24	u25
M	u31	u32	u33	u34	u35
ML	u41	u42	u43	u44	u45
L	u51	u52	u53	u54	u55

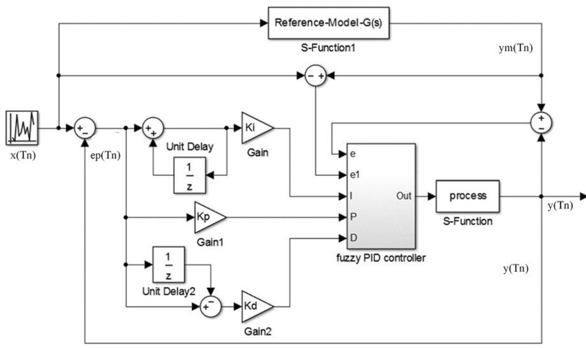

Fig. 13 MRAC fuzzy PID control flowchart

and the input $x(T_n)$ is calculated. In addition to using the speed to change the PID parameters of the fuzzy PID controller, the error $e1(T_n)$ is role of Δe in Table 3. And $e1(T_n)$ will also affect the judgment of the fuzzy PID controller parameters Ke.

The block diagram of the fuzzy controller is illustrated in Fig. 13. The control method is as below. First, according to the input $x(T_n)$ and the sampling time, the velocity and the angular velocity $v(T_n)$ can be calculated. The Eq. (2) reveals this relationship. This is a judgment factor for the fuzzy PID controller and identifying the reference model $G(s)$. The reference model $G(s)$ is the Eq. (1). The parameters of the model are in the Table 2.

$$\begin{aligned} v(T_n) &= x(T_n)/T \\ v(T_n) &\rightarrow G(s) \end{aligned} \tag{2}$$

After obtained the model $G(s)$ in Eq. (1), the reference output $ym(T_n)$ is calculated by Eq. (3).

$$ym(T_n) = (Kp1)x(T_n) - (Tp1 + Tp2)y(T_{n-1}) - (Tp1 * Tp2)y(T_{n-2}) \tag{3}$$

Then the error $ep(T_n)$, $e1(T_n)$, $e(T_n)$ are calculated by the Eq. (4).

$$\begin{aligned} ep(T_n) &= y(T_n) - x(T_n) \\ e1(T_n) &= ym(T_n) - x(T_n) \\ e(T_n) &= ym(T_n) - y(T_n) \end{aligned} \tag{4}$$

where the error $ep(T_n)$ is the actual error which need to be controlled and reduced. The Eq. (4) is changed into the Eq. (5).

$$ep(T_n) = e1(T_n) - e(T_n) \tag{5}$$

To get the final output $y(T_n)$, backward difference has been done to the error $e1(T_n)$, $e(T_n)$. In the expectation state, the error is as small as possible, so error $e1(T_n)$, $e(T_n)$ are considered to be the same. The backward difference equation is Eq. (6).

$$y(T_n) = x(T_n) + y(T_{n-1}) - x(T_{n-1}) - e1(T_{n-1}) + e(T_{n-1}) \tag{6}$$

This equation is enough for the closed-loop, for except the output $y(T_n)$, each item is known. However, there is a fuzzy controller for this system, so we need to find the error $ep(T_n)$ in this equation. Where the Ke is controls parameter of $e1(T_n)$.The Eq. (6) is changed into Eq. (7).

$$\begin{aligned} y(T_n) = x(T_n) + y(T_{n-1}) - x(T_{n-1}) - Ke * (e(T_n) \\ + ep(T_n)) + e(T_{n-1}) e1(T_{n-1}) = Ke * e1(T_n) \end{aligned} \tag{7}$$

As mentioned before, the error $e1(T_n)$, $e(T_n)$ are considered to be the same, so the Eq. (7) could be the Eq. (8).

$$\begin{aligned} y(T_n) = x(T_n) + y(T_{n-1}) - x(T_{n-1}) - Ke * (e1(T_n) \\ + ep(T_n)) + e(T_{n-1}) \end{aligned} \tag{8}$$

The items after the input $x(T_n)$ Eq. (8) can be converged as the Eq. (9).

$$(1 + Ke) * ep(T_n) = ep(T_{n-1}) + e(T_{n-1}) - e1(T_{n-1}) = 0 \tag{9}$$

Obviously, this formula conforms to the goals that make the error $ep(T_n)$ approach to zero, so this control method is considered convergent.

5 The Evaluation Experiment of Remote Operation

After achieving the control strategy based on the duplication of the surgeon's operation procedure, we designed the experiment to verify the actual operation performance and control precision of the robot. The experiment validated surgical robot using the teaching-training assessment for medical students. The experiment used a simulation vascular model as the experimental environment. The vascular model, named endovascular evaluator, is illustrated in Fig. 14e. The vascular model can be highly realistic in simulating the blood vessel environment in the body, including blood pressure and heart rhythm. Meanwhile, enough lubricant is added to the blood vessel model to simulate the real friction of a blood vessel wall. Therefore, it can provide a more authentic verification effect for the surgical robot. The process of simulated surgery is illustrated in Fig. 14. Surgeon operate the master-side surgeon control platform. The master sends the detected action to the controller. With this information, the controller controls the slave side to operate the guidewire. The catheter is inserted from the leg blood vessel and pushed to the brain blood vessel. The partial data of the operation

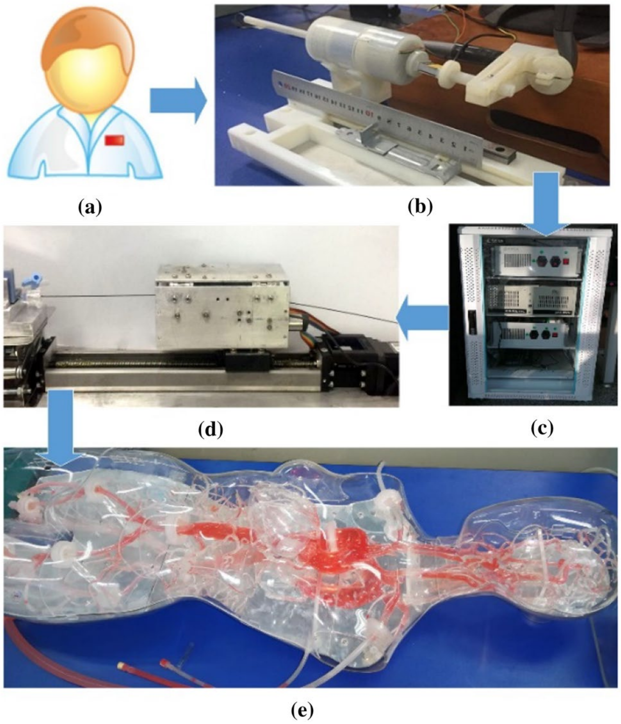

Fig. 14 Process of simulated surgery. **a** Surgeon, **b** master side, **c** slave side, **d** controller, **e** endovascular evaluator

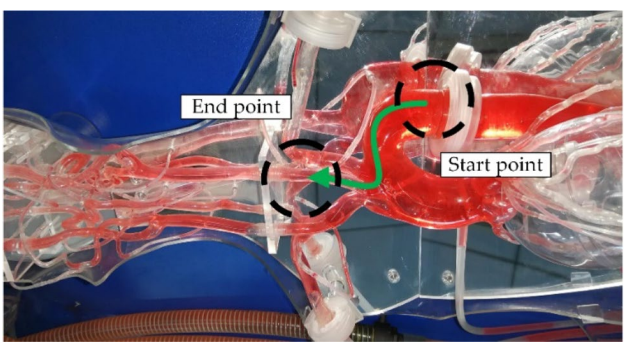

Fig. 15 The guidewire through the aortic arch and into the carotid artery

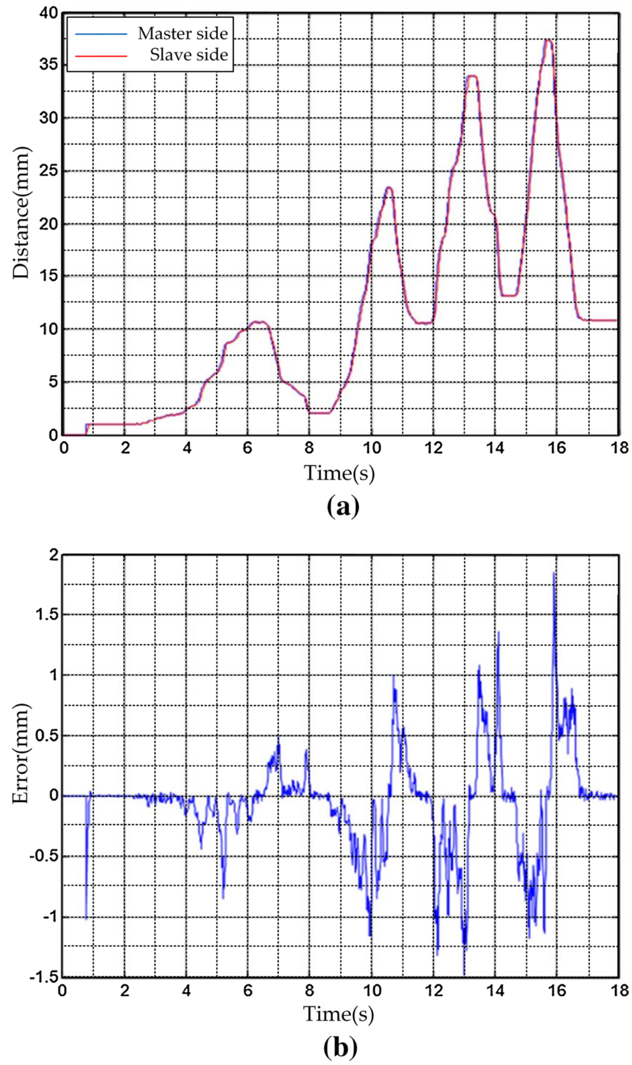

Fig. 16 Following movement with fuzzy PID control. **a** Position tracking, **b** positioning error

was analyzed. The selected representative date is collected from the process of the guidewire inserting the aortic arch into the carotid artery. The route of the guidewire during this process is illustrated in Fig. 15.

The experiment is to use robot to make the guidewire pass through the aortic arch. Because the entire operation involves many repeated operations, there are redundant data in the experimental results. The complete data is not conducive to clearly demonstrate and discuss the performance of the system. A part of important and representative operating was used to analyze. The operation was that the guidewire inserted the aortic arch into the carotid artery. In this operation, the guide wire insertion distance is approximately 40 mm and the operating time is approximately 20 s. This experiment validates the feasibility of using a robot for vascular intervention and verifies the control accuracy of the linear push of the guidewire by using experimental data. To ensure repeatability, five volunteers took part in the experiment and each one completed 10 times operations.

Figure 16 illustrates the results of master–slave motion following of the overall experiment process. Based on these results, it can be found that the dynamic performance of the system is stable. The errors of dynamic tracking performance are between − 1.5 and 2 mm at the appropriate speed. When the system has an appropriate fuzzy-control system parameter, the controller selects the appropriate policy and reduces the error. As is reflected from the error data, the dynamic tracking performance of the system has been greatly improved compared with the previous experiment. The method used in this study is more compatible with the control of surgical robot than the traditional PID.

To enhance the reliability and safety of surgical robot further, the research team analyzed the results of the study. The error is closely related to the speed. Through calculation, it can be seen that a large proportion of the error is caused by the time delay in the master–slave control system. At presently a no-real-time operating system is being used for the surgical robot. Hence, this part of the error cannot be eliminated temporarily. In future research, a digital signal processor (DSP) will be used as a processor, which can effectively eliminate the error caused by time delay. However, from the results of this experiment, the remote surgical control precision of the surgical robot has been greatly improved and has reached the surgeons' request of 2 mm.

6 Conclusions

This study focused on improving the accuracy of the skilled surgical operation by robot. This difficulty is divided into two key points: the duplication of the surgeon's operating procedures and the synchronized motion accuracy of surgeons and surgical robot. First, through the decomposition and analysis of the surgeon's operation procedures, a new remote operation detection environment for the surgeon is designed. The environment enables that surgeons perform remote surgery with familiar feel and experience. The master side detect the surgeons' surgical procedures. The slave side, which is synchronized with the surgeon's operation, is designed by the linearly towed catheter drive technology. This device is used to complete the operation of the surgeon. Then, the remote control of the surgical robot is optimized by the fuzzy control method to ensure the control accuracy of synchronous operation. Finally, the new type of interventional surgical robot is verified and proved that the surgical robot can duplicate the operation skills of the surgeon. The control error is limited to less than 2 mm, which reaches the accuracy required by the surgeon. The cause of residual error is the time delay of the operating system. Future work will include the use of DSPs instead of industrial computers to reduce motion errors caused by the delay.

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