Cloud Communication-Based Sensing Performance Evaluation of a Vascular Interventional Robot System

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Abstract—As an essential method for diagnosing and treating cardiovascular and cerebrovascular diseases, interventional surgery has always been a research hotspot in biomedical engineering research. The vascular interventional robot can improve the surgical environment of the surgeon and improve the safety and stability of the operation when assisting the surgeon to complete the surgical operation. In today's global pandemic phenomena, the study of operating vascular interventional robots in remote situations is of more significant value. Based on the previous animal experiments and clinical trials, this paper presents a preliminary study of the interventional robot to complete surgery operations under the condition of long-distance cloud communication. After analyzing the influence of time delay in remote operation, a control strategy for predicting time delay was proposed, and an evaluation experiment was conducted. Through the human model evaluation, the sensing performance of robotic



surgery under the condition of long-distance cloud communication is analyzed and compared with the experiments in previous studies. The experimental results show that the operator can remotely control the robot to complete the intubation operation, which is valuable for further study and animal experiments.

Index Terms—Cloud communication, interventional robot, remote control, robot sensing performance, time delay.

I. INTRODUCTION

INTERVENTIONAL operation is the major surgical method to treat cardiovascular and cerebrovascular diseases. The

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Fig. 1. The conventional procedure of interventional surgery [10]. The surgeon treats the target part in the heart or cerebrovascular by inserting a catheter and guidewire from the patient's groin or arm.

operation process of interventional surgery is shown in Fig. 1. During the operation, surgeons need to know the condition of the catheter and guidewire in real-time through X-ray. Although surgeons wear lead aprons, radiation can still affect their health under long-term and high-intensity work. Surgeons are standing for long periods and maintaining awkward, ergonomically unsound positions. According to a previous study, the high prevalence of neck and back pain among

1558-1748 © 2022 IEEE. Personal use is permitted, but republication/redistribution requires IEEE permission. See https://www.ieee.org/publications/rights/index.html for more information. interventional surgeons is likely due to the chronic effect of wearing protective garments [1]. In a survey on the health status of surgeons, 153 (49.4%) operators among 314 researched surgeons reported at least one orthopedic injury, including 24.7% of cervical spine disease, 34.4% of lumbar spine problems, and 19.6% of hip, knee, or ankle joint problems. Moreover, there is a small but substantial incidence of getting cancer [2].

To relieve surgeons' working pressure, interventional surgical robots are becoming an important study issue in biomedical engineering. Surgeons can be "liberated" from the operating room by controlling a robot to manipulate the catheter and guidewire. There are already many mature commercial products in this field, and some have been used in actual clinical interventional surgery. CorPath ®GRX Robotic System was reported performing the therapeutic neuroendovascular intervention in a human in 2020 [3]. This robot system allows manipulation of the guidewire, balloon, and stent catheter with one hand and operates the automatic contrast media injector with the other hand [4]. Another interventional robot commercialized by Stereotaxis named Niobe™ Magnetic Navigation System comprises two permanent magnets that generate static magnetic fields from 0.08 T to 0.1 T, which are moved around the patient to orientate and steer the catheter remotely [5]. The Sensei[™] Robotic Catheter System is an electromechanical system including an instinctive motion controller, a remote robotic arm, and an artisan sheath. The Intellisense[™] software provides contact force control with measurement of catheter forces, which is displayed at a physician workstation to assure ablation safety [6].

Additionally, studies of interventional robots have also been conducted in universities and other research institutions. In electrophysiological interventions, S. Ghazbi et al. developed a robot-assisted catheterization system named Althea I for semi-automatic navigation of catheters. Compared to the available technologies at the time, Althea I offers less complexity and cost with reasonable positioning accuracy [7]. M. Dalvand et al. developed a modular force feedback-enabled laparoscopic instrument. The device is used to restore the sense of touch in remote surgery, which is employed in Hero-Surg minimally invasive surgical system [8]. The modularity feature of the laparoscopic instrument makes it interchangeable between various tip types of different functionalities. D. Kundrat et al. proposed a novel endovascular robotic platform, which accommodates emerging non-ionizing magnetic resonance imaging (MRI). The research paved the way for clinical translation with device deployment to endovascular interventions using non-ionizing real-time 3D magnetic resonance (MR) guidance [9]. J. Guo et al. [11] presented a prediction-detection-combined tracking algorithm to automatically track the catheter tip for an interventional robot. The distal force can be simultaneously estimated due to the length variation of the passive marker and the sensed force can be fed back to a robotic catheterization system during intravascular interventions.

Although these proposed robots are able to complete part of interventional surgery diagnosis or treatment, they all have certain shortcomings. There are two specific challenges:

First, it is difficult for proposed interventional robots to realize the cooperative operation of the catheter and guidewire. Most of the robots use a single catheter or guidewire for surgery or switch between catheter and guidewire during the operation. This kind of control set is very different from the surgeon's traditional operation method, making it difficult for surgeons to quickly get underway. To overcome this defect, our previous research proposed an interventional robot that can conduct cooperative operation of catheter and guidewire [14]. The designed robot allows surgeons to operate the catheter and guidewire and perform angiography outside the operating room. In addition, the robot can detect force signals from the slave side and provide surgeons with tactile feedback during operation. The robot has implemented several animal experiments and clinical trials to verify the reliability and operating accuracy [12]-[16]. At the same time, based on the user feedback from surgeons, we are designing a master side controller that imitates the surgeon's surgical operation technique and replaces the currently used two identical haptic interaction devices (Geomagic® Touch, 3D Systems Corp, Rock Hill, SC, US).

Second, most of the remote operations using vascular interventional robots do not count for actual long-distance surgery. There are currently papers on robot operation experiments using the 5th generation mobile communication technology (5G) network, dedicated fiber line, or public networks for interventional surgery [17], but the relevant studies are lack of experimental data during surgery. A majority of the currently proposed robots are deployed in the corners of the operating room (using lead shields for radiation protection) or in places near the operating room when completing animal or human experiments. This kind of wired data communication method got great results in the past surgical environment. To a certain extent, the robots' assistance reduces the surgeons' burden and improves the operation accuracy and stability. However, under the impact of the coronavirus disease 2019 (COVID-19) epidemic, all front-line workers, especially those who have direct contact with patients, face major risks. Affected by the epidemic, patients' medical services have been severely restricted even including the cancellation of surgery, which has brought a heavy burden to patients and substantial economic losses to hospitals. At the same time, due to the restrictions of epidemic prevention measures, it is more difficult for patients to go to well-developed area hospitals for higher-level treatments and surgeries, and the possibility of delay in treatment may increase [18]. Under these circumstances, enabling surgeons to truly conduct interventional surgery over a long distance, or even across half of the earth while ensuring real-time accuracy and safety requires more experimental research.

Given the above-mentioned challenges in the research of robot-assisted systems for vascular interventional surgery, this paper aims to preliminary establish a cloud communicationbased robotic system, realize long-distance operations for the interventional robot. The statistical characteristics of operation time delay were analyzed to present a time delay prediction strategy for future cloud control. Finally, the sensing performance of the robot's cloud communication-based operation was evaluated. The discussion of operation safety and sensing accuracy was provided as a basis for future cloud control research.

The remainder of this paper is organized as follows. In Section II, we introduce the overall structure of the interventional robot and conduct a feasibility analysis of the cloud communication method. The analysis of the time delay characteristics under cloud communication and a time delay prediction method are presented in Section III. The effectiveness evaluation of the time delay prediction method and the robot operation sensing evaluation under long-distance cloud communication are described in Section IV. Discussion of the evaluation results is conducted in Section V. Finally, the conclusions are presented in Section VI.

II. SYSTEM DESCRIPTION

According to our communication with surgeons, the angiography operation of interventional surgery can be summarized in the following operation procedures:

- During the operation, a catheter is used to inject contrast medium or drugs for local therapy. The function of a guidewire is to gain access to narrow blood vessels using minimally invasive techniques.
- The surgeon needs to manipulate the catheter, guidewire to advance or retreat during surgery, and twist the catheter or guidewire when choosing the forward blood vessel branch.
- 3) The surgical skills of the surgeon have a significant influence on the operation. When using the robot, the familiar operation method allows the surgeon to enter the target lesion faster, reducing the catheter and guidewire operation time and the use of X-ray observations.
- The tactile information from force feedback and the visual feedback information from the X-ray are vital to the surgeon's surgical procedure.

Based on the above requirements, our lab developed an interventional robot that can realize the coordinated operation of a catheter and guidewire. This section will briefly introduce the structure of the robot and describe the construction of the cloud communication network for remote surgery.

A. Master-Slave Interventional Robot System Overview

The operation process of the interventional robot is shown in Fig. 2 (a). The robot consists of two parts: the master side and the slave side. The surgeon operates the master side controller outside the operating room, the robot slave side in the operating room receives the instructions and manipulates the catheter and guidewire to complete the surgery. During the operation, the surgeon will observe the surgery condition through digital subtraction angiography (DSA) image. The slave side of the robot detects the resistance encountered by the catheter and guidewire when performing linear movements, and passes it back to the master controller as force feedback, ensuring the operation safely. As shown in Fig. 2 (b), the master side of the robot system uses two haptic interactive devices (Geomagic®Touch, 3D Systems Corp, Rock Hill, SC, US) as the master controller. The surgeon performs the advance and retreat movement of the catheter and guidewire by operating

the control handle along the x-axis direction, and rotating the catheter and guidewire by rolling the control handle around the x-axis. By controlling the catheter controller with one hand and the guidewire controller with the other hand, the surgeon can use surgical skills and clinical experience to complete the operation.

The slave side of the robot system consists of a catheter manipulator and a guidewire manipulator, as shown in Fig. 2 (b) and (d). Two manipulators are coaxially connected, imitating the clinical operating state of the catheter and guidewire during interventional surgery. Through the force sensor placed inside the manipulator, the bending and force information of the catheter and guidewire can be obtained [14].

So far, the reliability of the system has been verified through animal experiments and clinical trials. As shown in Fig. 2 (c) to (f), the surgeon performed an angiography by manipulating the catheter and guidewire into the aortic arch and right common carotid artery of a patient [15]. Under a wired communication, the average linear master-slave operation error of the catheter and guidewire is less than 0.2mm, and the average angle error of the rotary motion is less than 0.5° [16]. Therefore, the robot system has the potential to achieve longdistance interventional surgery operations.

B. Feasibility Analysis of Cloud Communication Method

The cloud communication method for long-distance robotic surgery needs to solve two problems: First is to determine the data transmission method, and the second is to consider the network time delay and packet loss rate under remote control.

In terms of data transmission, considering the robot operation flowchart shown in Fig. 2 (a), the master side controller (i.e., Geomagic® Touch force interaction device) should collect the surgeon's hand motion information and send them to the industrial computer of the system. After the industrial computer receives the signals, it sends them to the cloud server for further control. Only the controller's linear movement signal and rotation movement signal are used in actual operation. Therefore, to simplify the network data transmission, only the x-axis displacement data, roll angle data, and button state data of the controller are collected. Additionally, to record the time delay data of each operation in real-time for subsequent analysis, the data of the master side is added with a timestamp. Therefore, the packet sent to the cloud server from the master side contains a total of 56 bytes of data of 7 double types, as shown in Table I. After the cloud server receives the control data packet from the master side, it needs to forward it to the industrial computer at the slave side. As soon as the slave side parsed the data packet, the catheter manipulator and the guidewire manipulator will perform corresponding operations using the catheter and guidewire.

To ensure the closed-loop system stability, the slave side catheter and guidewire position, angle, and force information must be feedback to the master side in real-time. During the operation, the current positions are recorded by a grating ruler, the current angles are recorded by rotary encoders, and the force information is recorded by force sensors. The realtime data will first add a timestamp then send to the cloud server, which means the feedback signal data packet from



Fig. 2. Robot-assisted interventional surgery operation process, interventional surgery robot structure, and previous clinical trial results. (a) Robotassisted interventional surgery procedures. Surgeons perform operations outside the operating room to avoid radiation damage. During the surgery, visual feedback and tactile feedback are used to ensure the safety of the operation. (b) The structure and operation instructions of the master and slave sides of the robot. (c) Master side operating environment in previous clinical trial. (d) Slave side operating environment during in clinical trial. (e) Real-time record of previous clinical trial of interventional surgical robots. (f) Right common carotid artery and right subclavian artery angiography result.

the slave side also contains 56 bytes of data in 7 double types, as shown in Table I. After the cloud server receives the data packet from the slave side, it forwards the packet to the master side industrial computer. The master side controllers provide real-time force feedback signals to the surgeon based on the force information data. The entire transmission process is similar to the previous method shown in Fig. 2 (a).

There are many ways of data communication, including wireless networks, wired networks, 5G, and optical fiber communication. Each communication method contains various communication protocols. 5G as the fifth generation technology standard for broadband cellular networks, has greater bandwidth, giving a higher download speed up to 10 gigabits per second (Gbit/s) compared to 4G networks. However, surgical operations in long-distance require a constant, uninterrupted signal, which makes the Ethernet (wired network) a better choice in data communication. According to the

related research article, both wired and 5G-wireless networks can be used for remote surgery, but wired networks have a lower time delay, which can bring a more stable operation environment [19].

Considering the versatility, communication cost, and development complexity, wired Internet and socket are used for data communication based on the transmission control protocol and internet protocol address (TCP/IP protocol) in this preliminary exploration of cloud communication. The socket is used to describe the IP address and port number, and applications can send or respond at the request of the network. The socket is a basic operation unit of network communication that supports TCP/IP protocol. Users do not need to understand the underlying code of the protocol family when using it, which significantly improves the development efficiency.

Based on the determined data transmission method, the robot system uses Tencent Cloud to build the cloud

Data packet format sent by the master side			Data packet format sent by the slave side			
Byte number	type of data	Data content	Byte number	type of data	Data content	
0	double	Timestamp	0	double	Timestamp	
1	double	Catheter linear movement	1	double	Catheter linear position	
2	double	Catheter rotational movement	2	double	Catheter rotational position	
3	double	Catheter handle button state	3	double	Guidewire linear position	
4	double	Guidewire linear movement	4	double	Guidewire rotational position	
5	double	Guidewire rotational movement	5	double	Catheter force feedback	
6	double	Guidewire handle button state	6	double	Guidewire force feedback	

TABLE I CLOUD COMMUNICATION DATA FORMAT

communication platform. The configuration of the platform server is 1 core central processing unit, 2 GB random access memory, 50 GB disk, 3 Mbps public network bandwidth cap, and running a Windows Server 2012 R2 system.

Two indicators are used to determine the location of the cloud server: the time delay and packet loss rate. Time delay refers to the time it takes for server A to send data to server B. In a realistic scenario, data needs to pass through a series of routing nodes to reach B from A, and each routing node will affect the total transmission time, thereby causing the delay. In the case that the operating location of the master side is not determined, we first study the time delay between the local operating computer and the cloud server. Under the condition of cloud communication, the time delay is defined as $T_2 - T_1$, where T_1 represents the time when the master side information is sent, and T2 represents when the master side receives the operation information from the cloud server. To avoid errors caused by clock synchronization between different servers, both T_1 and T_2 use the synchronize internet time after the industrial computers are connected to the network.

The packet loss rate refers to the ratio of the number of lost packets compared to the total number of packets. The main reason for packet loss is that the router cannot accommodate all the packets, only to discard some of them. The packet loss rate is 0% when there is no network congestion, 1%-4% when the network is lightly congested, and 5%-15% when the network is severely blocked. Networks with large delays and high packet loss rates will significantly increase the operating risk and cannot be used in clinical surgery.

This study used the ping command to test the delay and packet loss rate. Five thousand data packets were sent each



Fig. 3. The network performance test results of servers in different locations. (a) The test result of the server in Beijing. (b) The test result of the server in Shanghai. (c) The test result of the server in silicon valley.

time, and each data packet was 56 bytes. For comparison, Tencent Cloud servers with identical configurations in Beijing, Shanghai, and Silicon Valley in the United States were selected for testing. The test was carried out at different periods of one day. The results of this network performance are shown in Fig. 3, and the data of this network performance test experiment is shown in Table II.

The test may have certain differences compared to the realtime surgical operation. However, the results showed that when the cloud server is located in mainland China, the time delay of the executed ping command does not exceed 100ms on most occasions. Even during the heavy traffic period of network usage, the packet loss rate did not exceed 1%. The delay between Beijing and Shanghai didn't reach 30ms during peak network usage hours, and the packet loss rate was less than 0.5%. When the distance between the cloud servers is too long, the delay will greatly increase, so as the packet loss rate. During the peak hours of network usage, the average delay between Beijing and Silicon Valley in the United States reached 226.573ms, and the packet loss rate reached 20.34%. This has over exceeded the tolerable range of long-distance operation. According to the experimental results, in order to

Time period	Server location	Minimum time delay (ms)	Maximum time delay (ms)	Average time delay (ms)	Delay variance	Packet loss rate (%)
00:30~02:00	Beijing	6	48	6.809	3.895	0.06
	Shanghai	27	78	27.676	5.012	0.10
	Silicon Valley	159	267	183.345	584.914	10.08
02:30~04:00	Beijing	6	32	6.389	0.524	0.00
	Shanghai	27	91	27.055	0.955	0.00
	Silicon Valley	159	178	159.517	4.535	0.02
05:00~06:30	Beijing	6	29	6.588	0.516	0.00
	Shanghai	27	29	27.123	0.108	0.00
	Silicon Valley	159	172	159.090	0.384	0.00
	Beijing	5	120	5.630	22.726	0.06
07:30~09:00	Shanghai	27	171	27.751	22.204	0.08
	Silicon Valley	159	370	164.818	67.039	0.60
	Beijing	6	91	8.192	31.518	0.12
09:30~11:00	Shanghai	27	132	29.832	31.742	0.22
	Silicon Valley	154	240	167.973	69.351	1.70
	Beijing	6	101	8.576	37.601	0.18
11:30~13:00	Shanghai	27	123	29.733	40.025	0.48
	Silicon Valley	159	240	169.175	78.113	3.24
13:30~15:00	Beijing	6	71	8.077	22.169	0.08
	Shanghai	27	102	28.946	22.991	0.12
	Silicon Valley	159	241	172.318	125.391	6.90
	Beijing	6	116	8.696	26.304	0.08
15:30~17:00	Shanghai	27	117	29.423	21.714	0.24
	Silicon Valley	159	282	174.665	296.705	3.46
17:30~19:00	Beijing	6	69	7.899	18.119	0.10
	Shanghai	27	93	28.647	15.110	0.10
	Silicon Valley	159	232	166.372	105.575	0.40
19:30~21:00	Beijing	6	73	8.686	24.091	0.26
	Shanghai	27	80	29.549	19.662	0.28
	Silicon Valley	159	350	173.052	225.449	4.60
21:30~23:30	Beijing	6	53	8.334	11.653	0.18
	Shanghai	27	71	29.360	14.311	0.08
	Silicon Valley	174	386	226.573	345.604	20.34

TABLE II CLOUD SERVER NETWORK PERFORMANCE TEST DATA

select a different location from the robot slave side in Beijing, the robot system uses the cloud server located in Shanghai to build the communication platform.

III. SYSTEM CONTROL STRATEGY

For the cloud communication-based interventional robot system, an unknown and variable time delay can cause instability to the closed-loop control system and hinder the surgery process. According to the surgery safety requirements, predicting time delay in advance can provide performance improvements for the system. In this section, based on statistical properties of the time delay, we constructed a sparse multivariate linear regressive (SMLR) model, which can predict the coming time delay for the remote operation system.

A. System Time Delay Analysis

According to Table II, we have some noticeable time delays and packet loss from Beijing to the Shanghai server during periods like 09:30-11:00 and 11:00-13: 00. Take the data packets collected in 09:30-11:00 shown in Fig. 4 (a) as an example. The histogram of the probability of time delay in this period is shown in Fig. 4 (b). This "skewed right" characteristic indicates a lower bound for the propagation delay (in our test result, the lower bound is around 20ms). The data can be fitted by a shifted gamma distribution, as discovered by [20]–[22]. The probability density function of shifted Gamma is as follows [23]:

$$f(x) = \frac{\left(\frac{x-\gamma}{\beta}\right)^{\alpha-1} \cdot \exp(-\frac{x-\gamma}{\beta})}{\beta \cdot \Gamma(\alpha)} \tag{1}$$

where α is defined as the shape parameter, β is the scale parameter, while γ is the location parameter. To verify whether the probability density of the delay follows several shifted Gamma distributions with different parameters. We use autocorrelation to check the randomness of the data set. The randomness is determined by calculating the autocorrelation of data values with different time lags. If it is random, this autocorrelation



Fig. 4. Communication time delay analysis of network performance test.(a) Time delay from beijing to the shanghai server during 09:30-11:00.(b) Time delay histogram of the probability.

should be close to zero for all the time delay separations. If it is not random, one or more autocorrelations will be significantly non-zero. Given time series x_1, x_2, \ldots, x_N at time lag 1, 2, ..., N, the autocorrelation at time delay τ is defined as

$$C(\tau) = \frac{\sum_{i=1}^{N-\tau} (x_i - \overline{x})(x_{i+\tau} - \overline{x})}{\sum_{i=1}^{N-\tau} (x_i - \overline{x})^2}$$
(2)

where \overline{x} is the average of x_1, x_2, \ldots, x_N . The autocorrelation result is shown in Fig. 5. The result is with a high autocorrelation of about 0.782 at start, then gradually decreases. Such a pattern is the autocorrelation plot signature of "high autocorrelation" with some noise, which in turn provides high predictability if modeled properly, indicates the time delay series is strongly one-step ahead predictable [24].

B. Time Delay Prediction Strategy

Through the above analysis, elements in the sliding window with a strong correlation with the current packet array will be selected and used in a sparse multivariate linear regression (SMLR) algorithm to perform predictions on the time delay of communication [25]. The related prediction strategy diagram is shown in Fig. 6.

The establishment of the prediction model first requires the accumulation of time delay data. Set sampling time k (k = 1, 2, ..., N); time delay data set Y; sliding window size m. Through the network communication experiment in section II.B, the real-time delay value dt_k at



Fig. 5. The autocorrelation result of the time delay from beijing to the shanghai server during 09:30-11:00.

each sampling time t_k is collected to form the set $Y = \{dt_1, dt_2, \ldots, dt_k\}$. The data accumulation process needs to go through two sliding windows. Given the knowledge of time series $\{dt_k, k = 1, 2, \ldots, N\}$ and the size of slip window *m*, take consecutive m (m < N) elements as an array:

$$X_{i} = \left[dt_{k-2m+i}, dt_{k+1-2m+i}, \dots, dt_{k+m-1-2m+i} \right]^{I}$$

(*i* = 1, 2, ..., *m* + 1)

and composed the arrays to a matrix $X = [X_1, X_2, ..., X_{m+1}]$. By calculating the autocorrelation coefficient:

$$\delta_{X_i X_{m+1}} = Corr [X_i, X_{m+1}] \quad (i = 1, 2, ..., m+1),$$

select arrays in X which strongly correlated with X_{m+1} as the regressive variables and grouped them into a matrix:

$$\delta = \left[\delta_{X_p X_{m+1}}, \dots, \delta_{X_q X_{m+1}}, \dots, \delta_{X_r X_{m+1}}\right]$$

(1 \le p < q < r \le m)

Construct regression matrix $R = [H, X_p, ..., X_q, ..., X_r]$, which $H = [1, 1, ..., 1]^T$. The time delay y can be modeled as

$$y = R \cdot B = b_0 H + b_1 X_p + \dots + b_n X_r \tag{3}$$

where $B = [b_0, b_1, \dots, b_n]^T$ is called the regression coefficients.

Using least-squares estimation, the optimum parameter of B can be obtained as:

$$\stackrel{\wedge}{B} = \begin{bmatrix} \stackrel{\wedge}{b_0}, \stackrel{\wedge}{b_1}, \dots \stackrel{\wedge}{b_n} \end{bmatrix}^T = \begin{pmatrix} R^T R \end{pmatrix}^{-1} R^T y \tag{4}$$

Renew regression matrix $R_{new} = [H, X_{p+1}, \dots, X_{q+1}, \dots, X_{r+1}]$, the next value of time delay can be predicted as

$$\stackrel{\wedge}{y} = R_{new} \cdot \stackrel{\wedge}{B} = \begin{bmatrix} \stackrel{\wedge}{d} t_{k+1}, \stackrel{\wedge}{d} t_k, \dots, \stackrel{\wedge}{d} t_{k-n+1} \end{bmatrix}$$
(5)

When the next time delay is observed, the sliding window slips ahead one step, renewing B based on the above sparse multivariate linear regression (SMLR) algorithm.

It should be emphasized that during previous communication with surgeons in animal and clinical experiments,



Fig. 6. The prediction strategy diagram of the sparse multivariate linear regression (SMLR) algorithm.

surgeons hoped that the remote operation of the interventional robot could be developed one step at a time. So we maintained the previous control strategy in consideration of the robot stability after adjusting from a wired connection to remote operation. Therefore, in this preliminary evaluation experiment of the cloud communication operation, the time delay prediction is only used as an evaluation criterion for the safety of remote operations and an accumulation of data for long-distance operations. At present, control strategy of the interventional robot is the fuzzy PID control method, which has been proven effective in previous animal and clinical experiments [15].

IV. EVALUATION EXPERIMENTS AND RESULTS A. System Time Delay Prediction Efficiency Evaluation

To verify the effectiveness of the prediction method, the network performance evaluation from Beijing (local host) to Shanghai (cloud server) was being conducted for another time. The experiment was conducted in three periods: 00:30-02:00, 07:30-09:00, and 11:30-13:00. Based on previous data collection experience, these three periods represent three different but typical network states: During 00:30-02:00, the time delay is relatively stable. During 07:30-09:00, the time delay variation range is relatively low, and the variance result is negligible. During the 11:30-13:00, the time delay changes drastically, and the variance result is enormous. The experimental results are shown in Fig. 7.

During the period of 00:30-02:00, the maximum error between the predicted result and the actual delay is 44.2ms. Due to the stable network status, the average error of the predicted value is 0.175ms. During the period of 07:30-09:00, the maximum error between the predicted result and the actual delay is 51.3ms. In this slight fluctuations state of network communication, the average error of the predicted value is 1.667ms. During the period of 11:30-13:00, the maximum error between the predicted result and the actual delay is 45.4ms. In this state of severe network fluctuations, the average error of the predicted value is 45.4ms. In this state of severe network fluctuations, the average error of the predicted value is 4.407ms.

It can be seen from the experimental results that under different network conditions, the maximum error between the predicted result and the actual time delay does not have an increasing linear trend. Under the condition of severe fluctuations in network delay, the prediction error is under 4.5ms. Therefore, the SMLR algorithm can be used to predict the time delay stably under various network conditions.

B. Sensing Performance Evaluation and Result on Vascular Model

To verify the system sensing accuracy of the vascular interventional robot based on cloud communication, a human blood vessel model was used to perform surgery under the condition of a long distance. As shown in Fig. 8, a silicone artificial vessel model EndoVascular Evaluator (EVE: FAIN-Biomedical, Nagoya, Japan) consists of the brain, trunk, heart, and peripheral extremity parts. The transparent silicone tubes can mimic the complete cardiovascular system from the femoral artery to the carotid artery. Artery pulsation can be simulated using a fluid control unit. The fluid will swirl inside the models as blood does in human vasculature and dynamically reproduces the systemic circulation [26].

The linear and rotational movement accuracy of the catheter and guidewire are vital references to determine the real-time sensing performance of the interventional robot based on cloud communication. As shown in Fig. 8, the femoral artery of the human blood vessel model was selected as the starting point, and the left subclavian artery was chosen as the target point. To measure the following error during the experiment, the master controller records the linear and rotational data of the operator in real-time, and the grating ruler and rotary encoder in the slave robot record the moving distance and rotational angle of the catheter and guidewire manipulator, respectively.

The experimental environment of the sensing performance evaluation is shown in Fig. 9. The master side is located in Harbin, China (45.81°N, 126.51°E), about 1676 km away from the system cloud server (Shanghai, China). The slave side is located in Beijing, China (39.96°N, 116.32°E), about 1068 km away from the system cloud server (Shanghai, China). To ensure the safety of the experiment, monitoring devices were set up at the slave side to visual feedback on both the status of the slave robot and the blood vessel model. This is also the only direct data exchange between the master and slave sides. During the experiment, the master side sends the operation data packets to the cloud server, and the cloud server forwards the packets to the slave robot. The slave robot feeds back the data of the grating ruler and encoder as the linear movement and rotation data of the catheter and the guidewire to the cloud server. Also, it sends the force signal data collected by the force sensor. After the cloud server receives the data packets, it forwards the packets to the master side to complete the PID control of the system and real-time force feedback. A total of ten successful remote operation experiments were carried out. Each experiment's completion



Fig. 7. The experimental results of the time delay prediction efficiency evaluation. (a) The time delay prediction result from 00:30 to 02:00. (b) The time delay prediction result from 07:30 to 09:00. (c) The time delay prediction result from 11:30 to 13:00.

signal was that the catheter entered the position of the left subclavian artery of the blood vessel model. The result data of one of the experiments is shown in Fig. 10.

Among the entire ten experiments, the minimum time delay is 47ms, the maximum time delay is 242ms, and the average time delay is 99.13ms. Take the experiment process shown in Fig. 10 as an example: In 0-6s, the catheter and guidewire mainly performed linear movements, moving from the femoral artery to the position of the abdominal artery; 6-15s, the angle of the catheter and guidewire changed rapidly, mainly due to adjusting the catheter tip to align with the entrance of the aortic



Fig. 8. Experiment setup of the vascular model. Including the starting point (the femoral artery) and the target point (the left subclavian aorta).

arch; 15-20s, the catheter and guidewire passed through the thoracic aorta into the aortic arch; 20-32s, the operator adjusts the angle of the catheter and guidewire to achieve the insertion of the left subclavian artery; 32-40s, at this time the guidewire has entered the entrance of the left subclavian artery. After slightly adjusting the catheter and guidewire back and forth, the guidewire formally led the catheter into the left clavicle Inferior artery.

The following error of catheter linear movement is between -14.3mm-25mm. The average following error is 2.23mm. The following error of guidewire linear movement is between -5.9mm-26.3mm. The average following error is 2.16mm. Compared to linear movement, rotational movement are more affected during operation: the following error of catheter rotational movement is between $-160.3^{\circ}-120^{\circ}$, the average following error is 9.8° ; the following error of guidewire rotational movement is between $-124.9^{\circ}-67.8^{\circ}$, the average following error is 5.87° . According to the experimental results, the robot can complete the intubation operation, but the robot sensing accuracy is affected under remote conditions.

V. DISCUSSION

To ensure a low time delay during the operation, the experiment was set to be carried out at nine o'clock in the morning Beijing time (May 2, 2021, BJT). In the experiment, the "voov meeting" software was used to observe the slave side in real-time. The operator did not encounter any obvious delay of the video signal or asynchrony between the video signal and the operation action according to video monitoring results. The number of data packets sent and received was recorded at both the master and slave sides during the experiments. The results show that experiments have no packet loss, thus the following error is not related to the packet loss rate. Studies have revealed that the operator will notice a delay of 250ms, and the control performance becomes degraded rapidly for higher values [25]. Although the time delay of the experiment was under 250ms, the operator was still able to sense the lag of the operation. In the process of remote operation, the operator's sense of hysteresis for the linear movement was lower than rotational movement in the same experimental environment. It can also be seen from the experimental results in Fig. 10 that the following error of the rotational movement is greater than that of the linear movement. Through the experiments,



Fig. 9. Experiment setup of the cloud communication-based interventional robot system. The master side of the operating system was located in Harbin (CN), the slave side was located in Beijing (CN), and the cloud server was located in Shanghai (CN). Other than the real-time visual signal of the monitor, all sensor data was transmitted between the master and the slave side through the server.



Fig. 10. The sensing performance result of the robot linear, rotational movement, and following error. Operation was affected by the same time delay during the experiment. (a) Linear movement result and the following error of the catheter. (b) Linear movement result and the following error of the guidewire. (c) Rotational movement result and the following error of the catheter. (d) Rotational motion result and the following error of the guidewire.

we believe that the following error of the operation under remote control is mainly affected by two factors: the time delay and the operation speed. We take the catheter operation result of the experiment described in Fig. 10 as an example to study the connections between the following error, time delay, and operating speed.



Fig. 11. The influencing factors study of following error in sensing performance. (a) The relation between the following error, time delay, and linear movement velocity of catheter linear movement. (b) The relation between the following error, time delay, and rotational velocity of catheter rotational movement.

TABLE III COMPARISON OF EXPERIMENTAL RESULTS OF ROBOTIC INTERVENTIONAL SURGERY

Experimental setup	Average time delay (ms)	Average operation time (s)	Average following error (C;L) (mm)	Average following error (G;L) (mm)	Average following error (C;R) (°)	Average following error (G;R) (°)
Evaluation experiment in model (cloud communication, long-distance remote operation)	99.13	54.9	2.23	2.16	9.8	5.87
Evaluation experiment in model [13] (wired, short-distance remote operation)	10.85	55.8	0.11	0.14	0.24	0.29
Animal experiment [15] (wired, short-distance remote operation)	11.31	56.3	0.18	0.11	0.17	0.23
Clinical experiment [16] (wired, short-distance remote operation)	9.57	53.5	0.13	0.12	0.21	0.25

In the line of the corresponding data name, "C" represents the catheter, and "G" represents the guidewire, "L" represents linear movement, and "R" represents rotational movement.

As shown in Fig. 11, the following error, time delay, and operating speed of the catheter's linear and rotational movement have different features on the three-dimensional surface plot. It can be seen from Fig. 11 (a) that linear movement was simultaneously affected by two factors: the time delay and operating speed. When the time delay increased or the operating speed was too fast, the following error increased. In contrast, the rotational movement is mainly only affected by the operating speed. The experimental results show that the time delay has a much smaller effect on the following error of the rotation movement than the rotation speed, as shown in Fig. 11 (b). We believe that the different characteristics of this following error are related to the surgical actions of the interventional surgical intubation operation.

During the entire surgical experiment, the operator's linear movement duration was longer than the rotational movement, which was more affected by the time delay. In all ten experiments, the operation time with a linear velocity above 16.6 mm/s accounted for 30% of the remote operation time in a single experiment on average. At the same time, the operation time with a rotation velocity above 40 °/s accounted for 21% of the remote operation time in a single experiment on average (The number of pulses that need to be sent to the slave motor for these two speeds was the same: 20,000 counts). Meanwhile, the average maximum velocity of linear motion in each of the ten experiments is only 57% of the average maximum velocity of rotational movement, which leads to a more significant following error for the rotational movement in the experiment. This is because rotational movement is less likely to cause danger in interventional surgery experiments, so the operator was bolder when rotating the catheter and guidewire.

In order to evaluate the cloud communication impact on the sensing performance, compare the operation accuracy of the above-mentioned experiments with the short-distance human model experiment, animal experiment, and clinical trial completed in the previous studies [13], [15], [16]. The results are shown in Table III. Although the average time delay under remote operation conditions is ten times that of the previous studies' experiments, it can be seen from the average operation time that the operation process was not affected by the long-distance operation environment, which is consistent with the operator's feedback after the experiment. In terms of operating accuracy, the following error of linear movement at long-distance is 20 times that of short-distance experiments on average. The following error of the rotational movement is also 20-40 times that of wired conditions. Although the error did not greatly affect the operation like selecting blood vessels during experiments, it is necessary to upgrade control methods, collect more operation data and consult surgeons for the operation safety under this error.

VI. CONCLUSION

In this paper, we conducted a preliminary evaluation of cloud -communication-based interventional robot system sensing performance. Two aspects were addressed based on this research purpose: "long-distance cloud communication" and "sensing performance evaluation".

In terms of "long-distance cloud communication", this paper analyzed the feasibility of cloud communication, established the cloud server, and proposed a prediction method for the time delay during operation. The method of time delay prediction under cloud communication can estimate the coming time delay during operation in advance and provide a basis for the subsequent upgrade of the cloud control method.

In terms of "sensing performance evaluation", this paper conducted remote surgery experiments with a total communication distance of 2744km (Harbin to Shanghai 1676 km, Shanghai to Beijing 1068 km). The experiment results verified the feasibility of completing the interventional surgery under the condition that the master and slave sides are separated. The effects of time delay and sensing accuracy under different surgical actions are analyzed. The results show that the linear movement of the operator is more affected by the time delay, and the rotational movement will create a larger following error due to the faster operating speed than the linear movement. The data accumulated on the time delay and sensing accuracy of the masterslave operation provided a basis for further discussion with surgeons.

In future research, we will build a more comprehensive cloud data interaction system based on the existing method. The time delay prediction strategy proposed in this paper will be used to design an event-based path governor, which selects online reference parameter to further cloud control and improve the system's sensing accuracy.

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