A Proximal Push Force-based Force Feedback Algorithm for Robot-assisted Vascular Intervention Surgery

Mingyang Qin\textsuperscript{1,2}, Nan Xiao\textsuperscript{1,2}, Shuxiang Guo\textsuperscript{1,2,3}, Ping Guo\textsuperscript{1,2}, Yuan Wang\textsuperscript{1,2}

\textsuperscript{1}The Institute of Advanced Biomedical Engineering System, School of Life Science, Beijing Institute of Technology, No.5, Zhongguancun South Street, Haidian District, Beijing 100081, China; \textsuperscript{2}Key Laboratory of Convergence Medical Engineering System and Healthcare Technology, the Ministry of Industry and Information Technology, Beijing Institute of Technology, No.5, Zhongguancun South Street, Haidian District, Beijing 100081, China; \textsuperscript{3}Faculty of Engineering, Kagawa University, 2217-20 Hayashi-cho, Takamatsu, Kagawa 760-8521, Japan

E-Mails: 237221222@qq.com; xiaonan@bit.edu.cn; guoshuxiang@bit.edu.cn

Abstract - The accuracy control of force feedback is an important factor to improve the real-time and accuracy of the vascular interventional master-slave robot manipulation, it plays a more and more important role in the aspect of strengthening the doctor operation sense of reality and the operation efficiency. In this paper, according to the lack of precision problem of the force feedback, we construct the master-slave robot force feedback closed-loop control system. We put forward the real-time force feedback control strategy. And a new handle structure used on the Phantom has been designed. By measuring the proximal guide wire force and the force between the surgeon’s hand and the handle used on the Phantom, the force feedback closed-loop control can effectively eliminate the loss of mechanical impedance of force feedback information. By simulating the insertion of the guide wire, the real values of the force feedback from the slave are compared with the actual values of the force feedback in the master. And the simulant vascular insertion operation experiments have confirmed the advantages of the accuracy control of force feedback. The experimental results show that the accuracy control of force feedback is greatly enhanced in the aspect of reality and the operation efficiency during the doctor operation process.

Index Terms: A master-slave robot, force feedback, PID control

I. INTRODUCTION

In recent years, vascular interventional surgery with the advantages of minimally invasive, low risk, and less complication has been widely used in clinic [1]-[3]. It is considered to be the most valuable clinical medical technology at present, but due to the high skills, complex operation, long operation time and X-ray radiation injury problems, they restricted the further development of vascular interventional surgery [4]. Now, the organic combination of robotic technology and vascular interventional technology can not only effectively solve the problems, but can effectively combine the advantages of professional experiences and robot technology [5].

In the traditional vascular interventional surgery, the doctor with the help of flat DSA image position and the contact guidance of force feedback can quickly and safely feed the guide wire to the target position, but due to the limit of the imaging resolution of image equipment and two dimensional imaging, the doctor will rely more on haptic guidance during the operation [6]-[8]. In the use of master-slave robots system, the catheter is hold by the slave and the doctor will lack of the accuracy guidance of force feedback, which not only affects the surgeon’s hand and eyes coordination, but limits many operational experiences. Meanwhile, it increases the operation time and risk. The precision of force guidance can directly influence the doctor operation efficiency and success rate. Therefore, the vascular interventional surgical robot system must reconstruct the force feedback system.

In the vascular interventional surgery procedures, the feedback force can’t be just seen as a contact force between the guide wire and the vessel wall, the doctor need to adjust the action of guide wire according to the strengths of the contact force, such as whether to increase the holding power to make a turn or immediately retreat. So we must ensure that the feedback force acted on the surgeon’s hand is the same with the current stress on the guide wire. At present, most vascular interventional surgery robots force feedback system generally provide the doctor with the contact force--only a fuzzy feedback force guidance--between the guide wire and the vessel wall, this defect can not only reduce the force guidance in the operating procedure, but also reduce the sense of reality and the operation efficiency during the doctor operation process. Enhancing the accuracy control of force feedback and allowing doctors to feel the real force accurately from the slave, which has become an important research direction in the aspect of improving the vascular interventional surgery robot force feedback control.

Now, many vascular intervention surgical robot systems have been used in clinical trials [9]-[16]. But in these systems, there are still many serious problems in the doctor operating process, especially the accuracy problems of force feedback [17]-[18]. On the one hand, during the guide wire insertion process, some mechanical loss of output device of force feedback cause that the output power is not a precise value. It has a serious deviation between the force information detected from the slave and the force feedback information detected from the master [19]. Meanwhile, we can see from the phantom instructions that its force feedback precision of output is very high, but in the actual operation process, by measuring the feedback force from the master, the actual value is much more than the value of force feedback value from the slave. This result also proved that the simple force feedback...
can’t guarantee that the surgeon feel the real force feedback in
the master [20]-[23]. On the other hand, the simple force
feedback device mostly offer the force feedback information
between the guide wire and vascular wall [24]-[26]. In fact, in
order to ensure the safety and efficiency of surgery operation,
the doctor need to feel a very precise force in the master
during the operation process. In other words, we need to
reduce the error caused by mechanical loss and other reasons
as small as possible. It does not well in the most force
feedback system, so it becomes the key problem that
influences the real-time and accuracy during the operation.
Therefore, in order to allow the surgeon feel more real and
more accurate force feedback information, improving the real-
time and precision of the master-slave control, it is the key
that design a set of more accurate force feedback devices to
strengthen the sense of reality and the operation efficiency in
the operation process.

In view of the force feedback accuracy problem, this
paper put forward the real-time force feedback closed-loop
control strategy. In order to detect the force between the
surgeon’s hand and the handle used on the Phantom, a new
handle structure has been designed. By measuring the
proximal guide wire force and the force acted on the surgeon’s
hand, the force feedback closed-loop control can effectively
eliminate the loss of mechanical impedance of force feedback
information. Then, during the operation, the surgeon will
make it more real and more accurate to feel the force feedback
information. And the new strategy not only can improve the
real-time and precision of the master-slave control, but also
can enhance the operation efficiency and the sense of reality.
This paper will be introduced as the following chapters: the
second part introduces the system structure of a master-slave
robot, detection of the force feedback and the closed-loop
force feedback control algorithm, the third part introduces the
experimental scheme and results analysis, the final conclusion
will be given in the fourth part.

II. THE ROBOTIC SYSTEM

A. System Description

The system consists of two parts: the master platform for
the operation and the slave platform for the guide wire
insertion. The master platform for the operation includes the
Phantom Omni and image display. The slave platform for the
guide wire insertion includes the guide wire delivery system.
The block diagram of the whole system structure is shown in
Fig.1.

![Fig.1. The block diagram of the whole system structure](image)

A Phantom Omni is employed as the master manipulator.

Because the Phantom has 6 degrees of freedom and only two
DOFs are needed when operating the guide-wire, we fixed the
movement of the Phantom by program. As shown in the Fig.2,
the Y axis motion direction and along the Y axis rotation
direction are chose as the two DOFs. When the surgeon
pushed the handle along the Y axis, then the slave completed
the push for the guide wire. When the surgeon rotated the
handle along the Y axis rotation direction, then the slave
completed the rotation for the guide wire.

![Fig.2. The Phantom and its control coordinate system](image)

The Phantom’s instructions show that its feedback force
precision of output is very high, and the feedback force acted
on the direction of the Y axis. In order to measure the force
between the surgeon’s hand and the handle when operating the
guide wire, we designed a new handle, and there is a force
sensor embedded in the handle. The force sensor has a high
sensitivity. The small force can be measured by the force
sensor when the Phantom is working. By using the novel
handle, the feedback force in the Y axis can be measured
accurately. The Fig.3 shows the handle used on the Phantom.

![Fig.3. The handle used on the Phantom](image)

Fig.4 details the structure of the novel designed handle, it
is mainly consisted of a force sensor, an interconnecting piece,
two splints and a cover. The structure can accurately measure
the feedback force of the Phantom when operating the guide
wire. The interconnecting piece is connected with the Phantom,
when the surgeon hold the handle remain stationary, the
feedback force of the Phantom acted on interconnecting piece
reach the Splint 2 through Part 2. Because the Splint 1 and Part 1 are connected with the Handle, the force sensor is squeezed by the Splint 2 and the corresponding force is measured, and the size of the measured force is the force acting on the surgeon’s hand and the handle. From the novel handle, we can accurately measure the feedback force in the master.

Now, in the slave, the system can get a real force feedback value, according to the guide wire clamping device. Meanwhile, the actual force feedback value between the surgeon’s hand and the Phantom can be got, according to the novel handle.

### B. System control of the Robot

The whole system control of the robot includes the master-slave tracking control and force feedback control. We only studied the accuracy of force feedback, and the research on the block diagram of the force feedback control is carried out.

![Fig.6. The closed-loop block diagram of the force feedback](image)

Though many master-slave robot systems have the force feedback, it is the open loop control and they all have a large error on the aspect. So we take the closed-loop control to improve the accuracy. Fig.6 shows the realization of reconfiguration force feedback: The surgeon feel the actual feedback force in the master measured by the force sensor embedded in the handle, the real force feedback signal from the slave measured by the force sensor fixed in the guide wire clamping device, by the acquisition of the two force signal, signal processing, the PID control, and ultimately the surgeon will feel the accurate force feedback in the master. Specific methods are as follows: the real force feedback signal from the slave will be collected as input, the actual force feedback signal in the master will be collected as output, through signal processing and PID control, and both of the two signals reach the same accuracy.

According to the Fig.6, the vascular interventional master-slave robot system is simplified by the surgeon, the master, PC, the slave and the guide wire. The dynamic model of some parts of the system are as follows:

**The master:**

\[ f_m - f_{dm} = m_m x_m' + b_m x_m'' + k_m x_m \]  

(1)

**The slave:**

\[ f_{ds} - f_s = m_s x_s' + b_s x_s'' + k_s x_s \]  

(2)

\[ m_m, b_m, k_m \] represent mass, damping and elasticity coefficient of Phantom. \( m_s, b_s, k_s \) respectively, represent mass, damping and elasticity coefficient of the slave. \( x_m, x_m', x_m'' \) and \( x_s, x_s', x_s'' \) respectively, represent the Phantom and the slave’s displacement, velocity and acceleration. \( f_m \) represents the force between the Phantom and the surgeon. \( f_s \) represents the force between the slave and the torque. \( f_{dm} \) represents the force between the slave and the guide wire. In order to improve the accuracy of the force feedback, a PID controller is adapted to achieve the closed-loop force
feedback control. The closed-loop control system can accurately reduce the error, and it has good stability, accuracy and real-time. The controller block diagram as shown in the Fig.7, and the control law for PID controller is shown in (3)-(4). According to the closed-loop control algorithm, we can effectively achieve the error elimination of the force feedback.

\[
u(t) = K_p \left[ e(t) + \frac{1}{T_i} \int_0^t e(t) dt + T_d \frac{de(t)}{dt} \right] \tag{3}
\]

\[
u(t) = K_p e(t) + K_i \int_0^t e(t) dt + K_d \frac{de(t)}{dt} \tag{4}
\]

\[e(t) = f_s(t) - f_m(t)\]

According to the analysis of the closed-loop dynamic model of the system, \(f_s(t)\) is the input, \(f_m(t)\) is the output. In order to decrease the error as soon as possible, the system choose the proper PID parameters to get the optimal control.

III. EXPERIMENTS AND RESULTS ANALYSIS

In order to prove the superiority of the new handle structure and the algorithm, we take the comparative method to make the experiments.

In the first experiment, when operating the guide wire, we use the specific signal to simulate the real force feedback signal resembling to the force acted on the guide wire. The special signal is generated by a previous program. The force sensor loaded in the clamping device can measure the force, and the PC can get the real value on the screen. The value acted as the real input value of the force feedback signal. At the same time, the Phantom keep fixed position in the master, through the embedded force sensor to detect the force between the surgeon’s hand and the handle used on the Phantom. The value displayed on the screen acted as the actual output value of the force feedback signal. The blue curve in Fig.8 represents the true value of the force feedback signal from the slave as the input, and the black curve represents the actual value of the force feedback signal detected by the pressure force sensor in the master. The X axis represent the time, and the Y axis represent the force.

In the second experiment, according to the upper block diagram of force feedback system (Fig.6), we join the closed-loop force feedback algorithm in the system. Firstly, we get the curve fitting for the two signal data, the real force feedback signal from the slave as the input, the detected force feedback signal in the master as the output value, obtaining the fitting function. Then the system are controlled by the PID algorithm, reaching the force feedback precisely control. The red curve in Fig.9 represents the improved force feedback signal detected by the force sensor after adding the PID algorithm. From the two pictures, the error values between the real force feedback signal and the improved force sensor signal can be compared obviously.

As can be seen from Fig.8, many force feedback systems can’t guarantee that the feedback force acted on the surgeon’s hand is the same as the current stress on the guide-wire. In fact, there is a large accuracy problem for general force feedback systems. And the Fig.9 shows that the closed-loop control of the force feedback improves the accuracy of the actual value of the force feedback in the master. According to the Fig.8, the maximum error can be reached 1.42N. After joining the closed-loop force feedback algorithm, the maximum error between the improved actual value of the force feedback and the real value of the force feedback decrease to 0.48N. Thus the actual value of the force feedback in the master is much closer to the real value after adding the force feedback algorithm. In other words, the surgeon can feel more real and more precise force feedback information during the operation process. This result also reflects that the force feedback algorithm can greatly improve the real-time and high accuracy.

IV. CONCLUSION

This paper proposes a closed-loop force feedback algorithm based on measuring the proximal guide wire force. In order to detect the force between the surgeon’s hand and the handle used on the Phantom, a new handle structure has been
designed. There is a force sensor embedded in the handle. When the algorithm is added in a master-slave robot system, by simulating the insertion of the guide wire, the real values of the force feedback from the slave and the actual values of the force feedback in the master are compared, the result indicates that the closed-loop control can reduce the error values between the real force feedback value and the actual force feedback, and the surgeon can feel more real and more accurate force feedback information. It also improved the real-time and precision of the master-slave manipulation, so as to strengthen the sense of reality and the operation efficiency during the operation process.

ACKNOWLEDGEMENTS

This research is partly supported by the National Natural Science Foundation of China (61375094), National High Tech Research and Development Program of China (No.2015AA043202).

REFERENCES