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Force feedback technique of teleoperation manipulator in spinal surgery

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Abstract. With the rapid development of artificial intelligence and precision medical equipment manufacturing, teleoperation manipulator has become a hot spot in medical equipment manufacturing. In this paper, the force feedback technique in the process of spine surgery teleoperation manipulator has been researched. The force feedback information acquisition method and force feedback information reproduction technology were analyzed mainly. And parameter simulation is carried out. The force feedback technology could achieve the match between the ability of human and surgical tasks. It could provide the rich sense of immediacy information to the doctors and improve the efficiency of the operation, reduce the patient's pain and provide a safe working environment for doctors.

Key words. Surgery, teleoperation manipulator, force feedback, telepresence.

1. Introduction

In the Spinal surgery, the clinician needs to determine the nailing point nail direction and other parameters through the radioscopy. If the parameters are improperly selected, it may damage nerves and blood vessels. And it could lead to paralysis and even death. So the clinicians need to have a fluoroscopy done over and over again. It will cause the radiation exposure. The structure of the existing medical teleoperation manipulator system is very complex such as "Da Vinci" medical robot. It is more suitable for minimally invasive surgery in the abdominal and other parts. According to the characteristics of spine surgery, the teleoperation manipulator is designed which has the advantages for simplified structure, easy operation, low cost as shown in Figure 1.

Force feedback technique is an important part of spine surgery teleoperation manipulator. The main purpose is to provide the operator with the telepresence. It is an important research direction of telecontrol technology. In the course of surgery,

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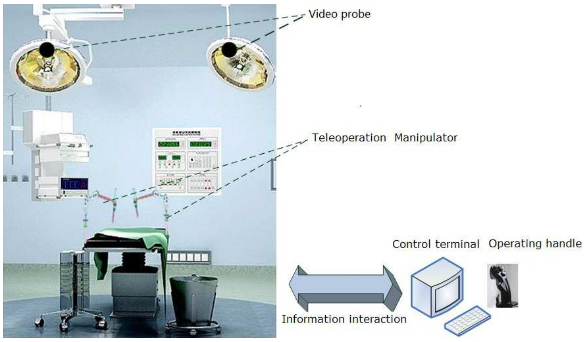

Fig. 1. The composition of the teleoperation manipulator in the spine surgery

the operator can perceive the insertion position, depth and other information of the front-end pedicle screw. And the force telepresence can make the operator experience the real work in the telepresence state. It can improve the accuracy of the operation effectively.

2. Force feedback technology

2.1. Force feedback system components

The schematic diagram of the force feedback technique is shown in Figure 2. It consists of a surgical operator, an operating handle, a communication link, a manipulator, and patient.

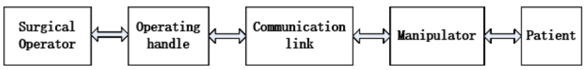

Fig. 2

The surgical operator sends the movement information to the manipulator by controlling the operating handle. When the manipultor touches the position of the patient's focus, the operation information of the robot (such as force, touch and other information) is fed back to the operating handle through the communication link. So the operator could have an effective perception for the actual situation and make accurate judgments timely. Then issue a corresponding operation command and complete the surgical task accurately.

2.2. Force feedback device

Operating handle is divided into tandem type and parallel type in accordance with the structure.

(1) Tandem type

In the tandem mechanism, the follower of the former mechanism is the active part of the latter mechanism. The relationship between the components is clear and the motion control algorithm is simple.

(2) Parallel type

Parallel mechanism of several institutions share the same input components, the output is also input to a multi-degree of freedom of the sub-institutions, can be translational and rotation to achieve decoupling, is conducive to improving the movement accuracy, and the mechanism of large stiffness, strong carrying capacity The

Spinal surgery The manipulator requires a high degree of motion accuracy, so a parallel operating handle is used.

2.3. Technical requirements for force feedback

(1) The range of force perception

The determination of the maximum feedback force of the force feedback device is related to its force sensitivity, so that the operator can clearly distinguish the force information and make the operation force in the range of routine sensitive and fatigue. Manpower of the work of nearly 200 Newton, the maximum working force of the finger does not exceed 10 Newton, so the power feedback for the 10 Newton.

(2) Isotropic

Isotropy refers to the consistency of the kinetic parameters at any position and attitude, which is a function of the position of the manipulator. The numerical change causes a feedback force of the same size and gives a different force in different positions.

(3) Frequency response

The force feedback of the force feedback device is higher than the force response frequency of the manpower in order to have a certain working margin. Human body arm and the robot can pass the frequency of movement is not higher than 5-10Hz, and people can receive the position and force signal frequency is higher than this value, up to 20-30Hz.

To improve transparency is the key to realize the sense of potential, the researchers have put forward a large number of control strategies to improve the transparency of the remote control system to achieve a sense of potential.

3. Force feedback bidirectional control system

3.1. Force feedback two-way control structure

For the master-slave bi-directional servo control structure and control method, scholars put forward a variety of bidirectional servo control structures and control strategies based on the different fusion methods of the position and force information of the master-slave. Commonly used control structure with position symmetry, force direct feedback type, force feedback servo type, force - position integrated type, comprehensive analysis and analysis, operational performance (transparency) is better force direct feedback control structure and force feedback servo type Control structure, etc., the advantages of the robot using a force sensor, isolated its dynamic effects, directly to the robot and the environment of the force, with a good force transmission structure advantages, and in the use of force feedback feedback servo control structure, When the feedback gain is large enough, the operator can get the ideal force to feel the spot. This paper presents a direct drive type differential feedback control structure, as shown in Figure 3. The operating force of the operating handle directly drives the manipulator, and introduces the double-end difference signal to correct the position of the manipulator; the reverse driving of the operating handle eliminates the feedback force shock and vibration of the operating handle with the double end difference signal.

An operating system with a direct drive type differential feedback control structure is used, and if the operating force acting on the manipulator is less than the load force, the operator obtains the feeling of being blocked or pushed back. When the operating force is equal to the load force, the operator obtains a force feeling comparable to the operating force, the manipulator does not move or maintains the uniform motion; when the operating force is greater than the load force, the manipulator moves in accordance with the action effect of the manipulator, Force after the manipulation of force. This control method is more fully reflects the manipulation of the will, reflecting the operation of the mechanical force of the meaning of telepathy.

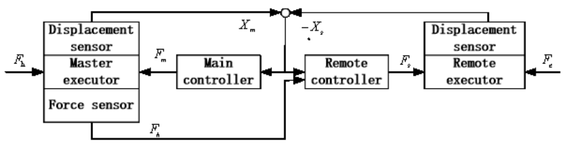

Fig. 3. Direct drive type differential feedback control structure

In the figure, F_h is the interactive force between the operator and the operating handle. F_m is the driving force of the operating handle. F_e is the interactive force between the manipulator and the environment. F_s is the driving force of the manipulator force. X_m is the displacement of the operating handle. X_s is he displacement of the manipulator.

The manipulator controls the use of the operating handle force directly to drive the way that enhances the master-slave operating from the master-slave. The manipulator controls the simultaneous introduction of the master-slave bit difference signal to ensure that both positions follow. Direct drive type differential feedback control eliminates the need for mechanical force sensor, because there is no environmental force into the control of the robot, so the robot retains its own dynamic characteristics, when the operator operates the handle, the action force directly to the The dynamics of the manipulator, such as the manipulator, will allow the operator to operate the manipulator like a manipulator, and to obtain a real sense of presence like a manipulator.

3.2. Direct drive type differential feedback control strategy analysis

With a delay master - from the operating system differential feedback control system block diagram shown in Figure 4.

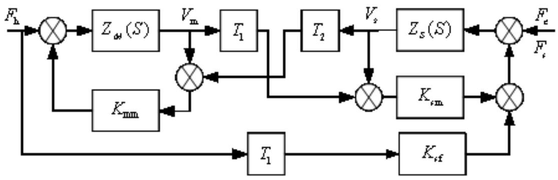

Fig. 4. Direct drive type differential feedback control schematic

M_m, B_m, M_s, B_s , Respectively, are the handle of the handle, the quality of the robot and the damping coefficient.

Table 1. Mechanical quantity - electric quantity mapping table

Main hand speed V_m I_m	The main hand side drive f_m V_m
From hand speed V_s I_s	From the hand side drive f_s V_s
Operating force f_h V_h	Environmental forces f_e V_e

The operating controller dynamic model is

$$M_m\dot{V}_{\mathrm{m}}(t) + B_m V_m(t) = F_h(t) - F_m(t) \quad (1)$$

The manipulator dynamics model is

$$M_s\dot{V}_s(t) + B_s V_s(t) = F_s(t) - F_e(t) \quad (2)$$

The model of the operating controller controlled by the ratio of bit difference is

$$F_m(t) = K_{\mathrm{mm}}\int[V_{\mathrm{m}}(t) - V_s(t - T_2)]dt \quad (3)$$

The manipulator controller model controlled by the handle and bit difference ratio is

$$F_s(t) = K_{\mathrm{sf}}F_h(t - T_1) + K_{sm}\int[V_{\mathrm{m}}(t - T_1) - V_s]dt \quad (4)$$

Environmental dynamics model is

$$F_e(t) = F_s(t) - (M_{\mathrm{e}}\dot{V}_s + B_{\mathrm{e}}V_s) \quad (5)$$

The uniform formula is derived from formula (1) - (5).

$$F_h(t) = (M_m s + B_m)V_m + F_m = (M_m s + B_m + \frac{K_m}{s})V_m - \frac{K_m e^{-sT_2}}{s}V_S \quad (6)$$

$$F_e = [K_{sf}(M_m s + B_m + \tfrac{K_{mm}}{s})\tfrac{e^{-sT_1}}{s} + K_{sm}\tfrac{e^{-sT_1}}{s}]V_m \\ - [\tfrac{K_{sf}K_{mm}e^{-s(T_2+T_1)}}{s^2} + \tfrac{K_{sm}}{s} + (M_s s + B_s)]V_S \tag{7}$$

In the robot control system, the operator is equivalent to the voltage source; the patient environment is equivalent to load; the master-slave system is equivalent to the two-terminal network, the equivalent circuit shown in Figure 5, reflecting the operator (V_m, I_m) and the environment (V_s, I_s) interacting with it. The equivalence relationship is shown in Table 1.

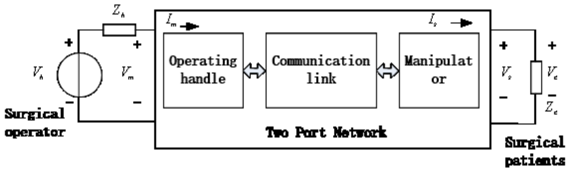

Fig. 5. Two-terminal network equivalent circuit

The two-terminal network model is derived from formula (6) and (7) .

$$\begin{bmatrix} F_h \\ F_e \end{bmatrix} = \begin{bmatrix} M_m s + B_m + \frac{K_m}{s} & K_{mm}\frac{e^{-sT_2}}{s} \\ K_{sf}(M_m s + B_m + \frac{K_{mm}}{s})\frac{e^{-sT_1}}{s} & \frac{K_{sf}K_{mm}e^{-s(T_2+T_1)}}{s^2} + \frac{K_{sm}}{s} + (M_s s + B_s) \end{bmatrix}. \\ \begin{bmatrix} V_m \\ -V_s \end{bmatrix} = \begin{bmatrix} Z_{11} & Z_{12} \\ Z_{21} & Z_{22} \end{bmatrix} \begin{bmatrix} V_m \\ -V_s \end{bmatrix} \tag{8}$$

4. Performance analysis of the control system

The performance of the direct drive differential feedback control system is analyzed by using the mixed matrix of the two - port network model, and the conditions of the system stability are deduced. The two-terminal network model mixes the matrix elements as follows

$$\begin{aligned} h_{11} &= \left.\frac{F_h}{V_h}\right|_{F_e=0} = \frac{Z_{\mathrm{m}}(s)K_m(s)}{s[K_m(s)Z_{\mathrm{m}}(s)K_s(s)Z_s(s)-1]} \\ h_{12} &= \left.\frac{F_h}{F_e}\right|_{V_h=0} = \frac{K_m(s)Z_{\mathrm{m}}(s)K_s(s)Z_s(s)}{K_m(s)Z_{\mathrm{m}}(s)K_s(s)Z_s(s)-1} \\ h_{21} &= \left.\frac{V_e}{V_h}\right|_{F_e=0} = \frac{K_m(s)Z_{\mathrm{m}}(s)K_s(s)Z_s(s)}{K_m(s)Z_{\mathrm{m}}(s)K_s(s)Z_s(s)-1} \\ h_{22} &= \left.\frac{V_e}{F_e}\right|_{V_h=0} = \frac{K_s(s)Z_s(s)}{s[K_m(s)Z_{\mathrm{m}}(s)K_s(s)Z_s(s)-1]} \end{aligned} \tag{9}$$

h_{11} is the impedance of the operating handle when the robot is free to move. The larger the value, the greater the effect of the operating handle speed on the feedback force, the greater the transparency, in order to reduce the force perception error, the smaller the value the better.

h_{12} is the scale factor between the main and from the force. For optimum transparency, it is required to equal the force feedback gain required by the operator and to be constant over the entire frequency domain.

h_{21} named the scale factor between master and slave speed, it means that the effect from the handle speed to the manipulator's speed. When the hand is not in contact with the environment, to obtain the best transparency, h_{21} should be the same as h_{12}that it remains unchanged in the entire frequency domain range.

h_{22} means the flexibility of the operating handle when the manipulator is in rigid contact with the environment, that is, the influence of the contact force on the speed and position of the manipulator. In order to make the hand position from the external force, hope its value as small as possible.

According to the conditions of obtaining the ideal system of the power sense, $h_{11} \to 0$, the gain of the controller is increased as much as possible to meet the operation speed of the operating handle as much as possible. Similarly, h_{22} is same as h_{11},the impedance of the manipulator and the gain of the controller are also increased. Stability and transparency there is a certain contradiction between the control system design, should be based on the actual situation and the specific application of stability and operational performance of the choice.

5. Conclusion

For the master-slave operating system of the direct-drive differential feedback control strategy designed in this paper, in order to obtain the ideal master-slave position-following characteristic and force telepresence, in the system design, according to the direct-drive differential feedback control The main features of the method are to reduce the impedance of the main manipulator by means of the bit difference signal, and to improve its operation performance. To increase the impedance of the main manipulator from the manipulator, it has good flexibility to the environment The According to the above analysis, using the appropriate control parameters, direct-drive differential feedback control strategy can not only meet the stability requirements of the system, but also improve the operational performance, is a better two-way servo control method.

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