Control Strategy of Master-Slave Manipulator Based on Force Feedback for Decommissioning of Nuclear Facilities

Jin Wang,1,2 Haoyuan Li,2 Fansheng Meng,1 Rui Ma,1 Quanbin Lai,1 Jianwu Li,1 and Xingguang Duan1

1Beijing Advanced Innovation Center for Intelligent Robots and Systems, School of Mechatronic Engineering, Beijing Institute of Technology, 5 Nandajie Zhongguancun, Haidian District, Beijing 100081, China
2China Nuclear Industry Motor Operation Technology Development Co., Ltd., China National Nuclear Corporation, No. 6 Gucheng West Road, Shijingshan District, Beijing 100043, China

Correspondence should be addressed to Xingguang Duan; duanstar@bit.edu.cn

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1. Introduction

Nuclear radiation is fatal to the human body, so remote operation equipment is an indispensable tool for nuclear facilities [1–3]. Generally, due to the influence of nuclear radiation in nuclear facilities, various devices are placed in a closed environment, which has high requirements for radiation protection, dust, temperature, humidity, and pressure. Therefore, the classic master-slave manipulator appeared.

A typical master-slave manipulator (as shown in Figure 1) is a master-slave control system for hot cell in nuclear facilities, which is divided into three parts: cold-end arm (master hand), wall-through pipe, and hot-end arm (slave hand). The most noticeable feature of this manipulator is that it is easy to operate. When the operator is controlling the master arm, the slave hand operating arm follows the master hand to move. At the same time, because of the force feedback function, the operator has a good sense of operation, which has the advantages of large clamping force and free movement. The whole structure adopts a modular method, which can easily and freely replace accessories such as mechanical arms, clamps, tools, adapters, or load hooks. The wall-through pipe uses the coexisting structure of oil seal and drive shaft seal, which effectively blocks the exchange of indoor and outdoor gas, reduces environmental pollution, and improves the protection and shielding level of operators.

The telescopic master-slave manipulator A100 of German Willis Miller was first developed in 1963. After that, it has undergone countless improvements, enhancements, and upgrades. So far, the telescopic manipulator is a revolutionary development and has become the industry standard.
equipment for nuclear facility processing. With the continuous development of technology, based on the requirements of different customers and ability to be used in different environments, the A100 system has become the best-selling master-slave robotic arm operating system.

Since the 1960s, the United States, Germany, and France have developed a series of master-slave manipulators [4–6]. And on this basis, a variety of force feedback electric follow-up master-slave manipulators have been successively developed, and commercial applications have been realized. The German Willis Miller company released the electric master-slave manipulator A100S based on the A100 mechanical master-slave manipulator. The performance of this electric master-slave manipulator is the same as the mechanical master-slave hand. The master hand is replaced with an electric box, and the single-axis control is carried out through the joystick console.

At present, the traditional mechanical master-slave manipulator plays an important role in the entire nuclear facility disposal process and is used very frequently [7–10]. Since the traditional master-slave manipulator equipment is driven by workforce, the master-slave hand is a telescopic structure, so the following problems exist in actual use.

(1) When clamping objects are of a weight of 5 kg and above, the master hand can barely realize the clamping and vertical lifting of the objects, and it is challenging to discover the flexible control of the robot wrist posture, so it is extremely difficult to realize some operation requirements.

(2) The master and slave terminals adopt telescopic structures. When the device is used for medium- and long-distance operation, the motion range of the master hand is extensive, and the operating posture is unergonomic. The excessively large operating range often prevents the operator from standing in the best observation position in front of the viewing window, which has a significant impact on the person’s field of view and observation. Such an operation affects the safety and accuracy of the operation and at the same time reduces the production efficiency.

(3) With the accumulation of time, the cumulative dose absorbed by the viewing window increases, and the color of the lead glass becomes severely yellow, resulting in a serious decrease in the overall visibility of the viewing window. In the absence of video surveillance or insufficient viewing angle of video surveillance, some jobs can only be “blind operation.”

(4) The use of manipulators for continuous operation will produce a lot of physical exertion, and the fatigue of personnel will increase the risk of operation, which in turn imposes excessive requirements on the physical fitness and operational proficiency of the operator

To solve the above problems, this paper proposes a new type of electric master-slave operation manipulator with force feedback function, which does not make any changes to the existing slave manipulators and wall-through pipes in the hot cell. The main hand will be replaced with a power box with a built-in servo motor, and a miniaturized desktop force feedback operation main hand and display console will be supplemented. That is, the mechanical master-slave manipulator is optimized into a force feedback electric follow-up master-slave manipulator that can be remotely controlled. The system helps the operator perform safe, reliable, and labor-saving operations based on the sense of force feedback; it is no longer limited by the mechanical master-slave manipulator in distance and human drive.

2. System Overview

The system (as shown in Figure 2) is mainly divided into three parts, namely, the slave hand in the irradiated environment hot cell (yellow area), the servo power box on the wall outside the hot cell, and the display console in the control room. In the control room, the operator can control the slave hand in the hot cell by controlling the joystick on the display console or the force feedback master hand, combined with the monitoring screen and three-dimensional auxiliary information on the display console.

The system adopts master-slave operation mode. Master-slave operation requires 2 robot bodies: one robot is the master hand used as the control terminal and the other robot is the slave hand that performs the work actually. According to the differences in mechanical structure, the master-slave design is divided into 2 types: heterogeneous and isomorphic. The comparison of the advantages and disadvantages of the 2 types is as follows.

(1) The master-hand control method of the robot with heterogeneous mechanical structure is a universal matching type, which has strong versatility and can be used separately from the slave hand as a joystick. The control algorithm is complicated and the forward and inverse solution of kinematics and dynamics need to be converted.
(2) The control mode of the master-slave manipulator with the isomorphic configuration is completely matched, with limited functions and insufficient versatility, because it has the same mechanical structure as the slave hand, the kinematics and dynamics mapping relationship are simple, and it is easier to realize the master-slave 2-way servo control.

Taking into account the large size of the existing master-slave manipulator, the large master-side operation range, and the optimization of the main control room space, this paper adopts the master-slave heterogeneous design method to design a small master hand to realize placement and movement of the entire system in the control room. Regarding the arm drive, the movement mode between the master and slave manipulators is replaced by a servo motor control drive from the original wire drive of steel wire and steel belt. On the one hand, it can realize the electrical connection between the master and the slave and the remote control of the equipment. On the other hand, it is convenient to control the speed, position, and torque of the servo motor, realize the accurate position control of the slave hand and real-time load detection, and provide the necessary information for the force feedback of the master.

3. The Structure Design of Master Hand

3.1. The Structure Design of Force Feedback Master Hand. For the master hand control, the traditional button or joystick control method reduces the amount of labor, but it cannot provide a sense of force presence during operation. This system proposes a design of the manipulator based on force feedback and realizes the presence of the main manipulator through remote force feedback technology. The master hand with force perception uses presence technology to add force perception and feedback to the control loop, which fully provides the operator unique perception, decision-making, and manipulation abilities, and exerts the synergistic effect of operator and machine. The operator receives the force sensor information from the remote workstation and immediately gets a sense of the scene, just like direct control in the field.

The structure of desktop, portable, and mobile small master hand with force feedback is designed to replace the structure of existing steel wire transmission master hand. The master hand based on force feedback has 6 degrees of freedom in structure; 3 degrees of freedom are used to adjust the position of the end of robot arm, and the other 3 degrees of freedom are used to adjust the posture to achieve omnidirectional and full posture control of the slave hand.

In the structure design of the force feedback master hand (as shown in Figure 3), micromotor equipped with an absolute encoder is designed on each joint of the arm. According to the real-time position of each axis in the master hand, calculate the spatial position and posture of the end handle of master hand so as to output the joint change to the servo motor so that the motor rotates at a specific angle to keep the posture of the slave hand and the master hand consistent. The torque sensors are installed from the shaft end of the servo motor at the slave hand and detect the magnitude and direction of the load force from the slave hand in real time. After the algorithm of the control system and a certain proportion of zooming in or out, the motors of each joint of the master hand are controlled to generate a stall or reverse braking to resist the movement trend of the handle. The feedback force of the master hand is obtained at the handle end, which gives the operator the feeling of on-site operation.

3.2. Structure Design of Servo Motion Control Box of Master Hand. The servo control box of master hand is designed to replace the original method of steel wire transmission. The power box is mainly installed with servo motor, reducer,
torque sensor, encoder, and so on. The power box is connected to the cold end of the through-wall pipe and hung on the wall outside the hot cell. The output port of the servo control box is the same as the port of the original steel wire transmission master hand, exactly as shown in Figure 4. The power box drives the slave hand in the hot chamber to perform the target action by the method of “screw the drive shaft through the wall pipe.”

Due to the small interface surface of the existing through-wall pipe, the space layout of the seven joint control axes is too compact. Therefore, in the layout design of the power box, the structure of the multilevel and multilevel gear set is designed to expand the disk interface. The design parameters of expansion distance between each axis depend on the size and specifications of the supporting servo motor required for each joint load.

In design of each rotating or telescopic shaft, the structure of the “torque sensor-reducer-servo motor” is adopted. The motor and reducer are used to precisely control the motion position of the joint, and the torque sensor is used to detect the actual torque on the joint. Through the equivalent conversion of reduction ratio, arm weight, and friction, the magnitude and direction of the current external force (load) can be deduced, providing the calculation basis for the master hand based on force feedback.

4. Operation Algorithm


In the master-slave robot system, the remote operation is implemented between the master hand and the slave hand through bilateral control [8, 11–13]. The system adopts a force-position hybrid control type. The principle block diagram is shown in Figure 5.

During the control process, the master operator sends the desired position information $X_m$ to the slave manipulator, and the slave manipulator performs corresponding actions according to the received control information. The position information $X_s$ of the slave robot arm during the movement is collected by the displacement sensor in real time. By comparing the difference of the position information $X_m$ and $X_s$ of the master and slave hands, the position deviation is sent to the slave controller to realize the closed-loop control of the position accuracy. In addition, the force sensor information $F_s$ at the end of the slave robotic arm collects force perception information during the interaction between the robotic arm and the environment and sends it to the master operator. At the same time, the position difference $(X_m - X_s)$ between the master and slave hands is fed back to the master operator, and the actual force information is fused with the position difference information and fed back to the operator’s hand as force information $F_m$.

The control matrix of the bilateral control strategy of force-position hybrid control is shown below.

$$Z_r(s) = \frac{G_m(s)G_s(s)}{(1 + G_s(s))Z_e(s)} + \frac{G_m(s)}{s(1 + G_s(s))}$$  \hspace{1cm} (1)

where $Z_e(s)$ is environmental impedance of slave hand and $Z_r(s)$ is impedance of master hand. The actual interaction force between the robotic arm and the environment is fed to the master operator. However, due to the feedback information of the position error in the system, the ideal force telepresence cannot be obtained by adjusting the transfer function, resulting in a certain stickiness in the system during the force feedback process. At the same time, the position difference $(X_m - X_s)$ between the master manipulator and the slave manipulator will be fed back to the force feedback of the master manipulator to improve the followability. The force-position hybrid control strategy effectively balances transparency and tracking. Although some transparency is lost in the control method, its tracking performance is improved.

4.2. Incremental Position Closed-Loop Control Method.

In order to facilitate the master-slave operation, the system adopts incremental position control method to realize the workspace mapping between the master and the slave manipulator. In this method, the relative origin between the master and slave hands is not fixed; that is, the master and slave hands can establish a relative origin in any posture and
then quickly establish a relative mapping relationship and implement corresponding control operations. In this control method, the input of the system is the change in the coordinate of the master operating hand in the unit time interval.

\[ X_m = M_f - M_i, \quad (2) \]

where \( M_i \) is the initial pose of the master operator relative to the absolute origin, \( M_f \) is the actual pose of the master operator after unit time interval, and \( X_m \) is the pose change of the master operating hand.

After obtaining the pose change \( X_m \) of the master hand, multiply it with the matrix coefficient \( K \) and then add it to the current pose \( X_i \) of the slave hand to obtain the target pose \( X_f \) of the slave hand.

\[ X_f = X_i + KX_m, \quad (3) \]

In order to improve the motion accuracy in the master-slave control process, the following error of the system is optimized. Position feedback is added to the control strategy to make the control system form a closed-loop control and obtain an incremental workspace mapping based on position feedback, as shown in Figure 6.

By solving the inverse kinematics of the manipulator, the corresponding joint angles in the target pose are obtained, and then control the slave to perform corresponding actions. At the same time, the pose change of the slave hand can be obtained through the positive kinematics calculation of each joint angle. The difference between the end of the master and slave hand is the following error, which is added to the pose increment obtained at the next sampling time \( t + 1 \) to compensate for the motion accuracy of the slave hand, thereby improving the motion accuracy in the master-slave control process.

In order to verify the effectiveness of the control method, the tracking performance of the master-slave movement process has experimented in the master-slave system. Taking a single joint as an example, the following curve of the master-slave hand during the movement is shown in Figure 10, which indicates that a better following performance can be obtained between the master and slave hand in the closed-loop incremental workspace mapping control strategy.

4.3. Zero-Gravity Compensation Design. Gravity compensation equipment usually uses the reverse torque of the motor as the output source of the feedback force [14–16]. In the gravity balance of the operating arm itself, springs are often used for compensation. The advantage is that the spring is light and does not add too much weight and inertia to the force feedback device.

In this system, linear springs, fixed pulleys, and wire ropes are combined to compose a zero-free length spring gravity compensation structure to realize the gravity compensation of the mechanical arm. Take joint 2 in the robotic arm as an example, analyze the gravity compensation theory based on a zero, free-length spring, and create an analysis coordinate system, as shown in Figure 7.

\( O, O_{01}, O_{21}, \) and \( O_{31} \), respectively, are the rotation axis of joint 2, the fixed point on the ground, the rotation axis of joint 3, the end coordinate center, and the axis of fixed pulley. Point \( Q \) is the position of the fixed wire rope on the outside of the driven wheel of joint 2 and point \( P \) is the tangent point of the fixed pulley passing point \( Q \). One end of the linear spring is fixed at point \( M \), and the other end is connected with a wire rope, bypassing the fixed pulley and connected to point \( Q \). \( a \) is the distance from \( O \) to \( O_{01} \), \( r \) is the radius of the driven wheel, and \( r' \) is the radius of the fixed pulley.
In order to ensure that the zero, free-length pulley part is simplified as shown in Figure 8. As shown on the left in Figure 8, when the connecting rod \(O_0O_1\) and \(O_0O_3\) coincide at this time, the gravitational moment \(T = B \cos \theta\), and the length of the spring is \(r' \cos \beta\), and the length of DP is equal to the length of ER. So, the QD length is \(a - r \sin \theta - 1 + r' \cos \beta\), and the DP length is \(r \cos \theta - r' \sin \beta\). The length of the wire rope \(QR_1\) is as shown in the following formula.

\[
QR_1 = \sqrt{(a - r \sin \theta - l + r' \cos \beta)^2 + (r \cos \theta - r' \sin \beta)^2 + r' \beta}.
\]  

Therefore, the extension length of the spring is \(\Delta QR = QR - QR_0\), the tension of the spring is \(F_s = K \Delta QR\), and the moment of the spring is \(T_s = K \Delta QR h\), where \(h = r \cdot \cos(\theta - \theta_1)\). Using the obtained QD, DP, and QP lengths, the angle can be calculated.

\[
\sin \theta_1 = \frac{r \cos \theta - r' \sin \beta}{\sqrt{(a - r \sin \theta - l + r' \cos \beta)^2 - (r \cos \theta - r' \sin \beta)^2}}.
\]

\[
\cos \theta_1 = \frac{a - r \sin \theta - l + r' \cos \beta}{\sqrt{(a - r \sin \theta - l + r' \cos \beta)^2 - (r \cos \theta - r' \sin \beta)^2}}.
\]

It is known that the spring tension moment can fully compensate the gravity moment of the connecting rod, so the following equation holds.

\[
B \cos \theta = K \Delta QR h = Kr \Delta QR \cos(\theta - \theta_1).
\]  

Therefore, the required spring rate coefficient \(K\) is expressed.

\[
K = \frac{B}{r \Phi [a' - u' \tan \theta]}.
\]

where \(\Phi = (QF + r' \beta 0 - QR_0)/QP\), \(a' = a - l + r' \cos \beta\), \(u' = r' \sin \beta\).

Through the above mathematical derivation, it is proved that the novel zero-length spring compensation can completely realize the full gravity compensation of the force feedback device in theory. In the actual design process, if \(a\) is equal to the radius of the deceleration mechanism, and the supporting length \(l\) and the radius \(r'\) of the fixed pulley are
very small, the stiffness coefficient $K$ of the spring can be approximately constant, and the gravity compensation method can be realized. Through the same compensation principle, the gravity compensation of each joint can be further realized.

5. Result and Discussion

5.1. Position Accuracy and Force Feedback Accuracy Experiment. In the experimental system (as shown in Figure 9), the operator can control the movement of the end effector of the slave hand through the master hand operation. In order to better observe the result of the master-slave operation, the operation model is simplified in the experimental design, and the single direction operation of the master hand is used to control the end effector. In the experiment, the operator holds the master hand to move up and down. The movement of the center point of the master hand in the vertical direction can be recorded in real time and the environmental force of slave hand is given through the tension measurement instrument. The software system transfers the collected force-position information to the slave robot in real time through the intermediate communication link and uses the optical tracking system to obtain the relative movement distance of the end effector of slave hand in real time. The force sensor feedbacks the reaction force generated of the end effector of slave hand during the movement.

During the experimental operation, record the position change of the center point of the master hand and the corresponding position change of the end effector of slave hand and compare them to determine the following error of the robot master-slave operation based on the navigation system. In addition, at 5 different positions, by applying force to the end of the slave hand, record the force at the end of the master hand at this time and calculate the error of the force.

The experimental results are shown in Figure 10. The movement position of the master hand center point and the slave end actuator along a certain coordinate axis changes with time. From the position error corresponding to the master-slave operation in the figure, it can be seen that the master-slave operation has good following performance, and it is unidirectional, and the error caused by one direction is small. At the same time, experiments show that the system can prepare to feedback the force from the hand to the main hand so that the operator can feel the force of the operation.

5.2. Carrying Capacity Experiment. The purpose of this experiment is to verify the load performance of the slave manipulator. The slave manipulator clamps the counter-weight, and within the working range of the manipulator, it moves from different directions to the limit position at the maximum speed (0.4 m/s), which are 45° left, 45° right, and left 45°. This experiment was carried out 30 times, and the experimental results show that the slave manipulator can reach smoothly without damage.

The experimental photos are shown in Figure 11. The photos A and B of Figure 11 are experimental photos of unloaded slave manipulator from initial position to limit position. The photos C, D, E, and F of Figure 11 are experimental photos of slave manipulator carrying objects of different weights from initial position to limit position.

5.3. Master-Slave Follow Delay Experiment. The purpose of this experiment is to test the delay of the master-slave manipulator. The specific test steps are as follows:

1. Fix the camera to ensure that the camera’s field of view can capture both the master and slave hands
2. Start the video recording function; the operator operates the master hand to drive the slave hand movement and completes the operation to end the video recording
Conduct 20 sets of experiments and obtain 20 videos, and calculate the average delay of master-slave operation of each video. Through frame-by-frame analysis, the time difference is obtained as shown in Figure 12. The physical meaning of the abscissa in Figure 12 is the number of tests. And the physical meaning of the ordinate in Figure 12 is time difference.

By analyzing the video of the experiment, the time when the master hand starts to move and the time when the slave hand starts to move can be accurately obtained. The delay of the master-slave control can be measured by calculating the time difference between the start of the master-slave hand movement. Figure 12 shows the average time difference of the slave hand following the master hand for each test experiment. The average time difference of 20 experiments is 0.0604s, which can indicate that the system has a small delay and can basically realize telepresence operation.

6. Discussion and Conclusion

This paper proposes a master-slave manipulation robot system based on force feedback for decommissioning of nuclear facilities, which is divided into three parts: master hand, wall-through pipe, and slave hand. In order to facilitate the operation, the structure of master hand is
designed according to the human-computer interaction design. The master-slave manipulation system adopts a force-position hybrid control strategy; the position and force are sent to master and slave hand to realize telepresence operation. Incremental position control method realizes the workspace mapping between the master and the slave manipulator to improve the accuracy of the following performance. The novel zero-length spring compensation is designed to realize the full gravity compensation of the force feedback device. Finally, the positioning accuracy experiments are conducted to verify the work effectiveness.

From the analysis of operation results and operator feedback, the new system has improved the satisfaction of operators compared with traditional wire-driven master-slave manipulators because of easier working conditions and less physical and mental labor. In addition, the new system enhances safety, improves health and working conditions, and optimizes all constraints and difficulties encountered during operation (operator posture, visual restrictions, weightlifting, and mirror movement). Next, the force perception and operating performance of the system will be further optimized to make it more convenient for operators to work.

**Data Availability**

The data used to support the findings of this study are available from the corresponding author upon request.

**Conflicts of Interest**

The authors declare that they have no conflicts of interest regarding the publication of this paper.

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