

Research and Implementation of an Automatic Reset Force of a Force Feedback Handle

Xin An Qiu^{1,a}, Shi Jia Wang¹ and Dong Tao Ma¹

¹ Lanzhou Institute of Physics, Lanzhou 730000, China

Abstract. Take the force feedback handle applied to the teleoperation of space robotic arm as a requirement. In order to improve users' experience, we studied the automatic reset force of the handle. This paper proposes a spring-damping model and applies it to the torque output of the motor to achieve a good reset of the handle, which is a new development of the application field of the automatic reset force model of the force feedback device. The experiment shows that the automatic reset force model has high accuracy when the handle returns to zero. In addition, through dynamic and reasonable adjustment of the stiffness coefficient and damping coefficient, it can meet the needs of different users for the automatic reset force of the force feedback handle.

1 Introduction

In recent years, China's space industry has developed vigorously. According to the "three-step" development strategy, China will build its own manned space station around 2020. Space robotic arm, which is one of the three key technologies of the space station, will be used in the construction and on-orbit maintenance of our space station^[1].

With the continuous deepening of the construction of China's space station, astronauts can complete the capture docking and indexing of space segments, assisted replacement of out-of-vehicle equipment, self-exit activities, and platform load care by operating robotic arms. Its complicated operation flow and the special environment of the space require the robot arm operating system to have better multi-dimensional interaction capabilities in order to better assist astronauts to complete the robot arm operation processing.

As a human-computer interface of force perception^[2], force interaction device can complete the information collection of operator's operation action, realize the control of the operated object, and feedback the state of the operated object to the operator in the form of force, so as to improve the "sense of presence" and "sense of transparency" of its operation^[3-5]. At present, teleoperation technology based on force sense interaction is widely used in robot systems working in special environments, such as space, danger, radiation, high temperature, toxicity or seabed environment^[4,6]. On the basis of vision and hearing, it increases the way of force information feedback, which greatly improves the efficiency, accuracy and safety of the operating system. It is of great significance to apply it to the master-slave control of the space station manipulator^[7,8].

Based on the above requirements, a force feedback handle based on 3-RRR spherical parallel mechanism is designed. The force feedback handle shall have the function of automatically returning to the zero position. The operator shall overcome the automatic reset force to operate. After the operation, the automatic reset force will return the handle to the zero position. The general handle is installed with spring in the mechanism to form an automatic reset force, but it has many disadvantages such as spring deformation and difficulty in self-regulation, so the user experience is poor. In the parallel mechanism, the motor is used to provide the torque, and the return force of the spring is simulated by the servo motor on three joints.

2 Research on model of automatic reset force of handle

Generally, the control handle needs to have the force of returning to the zero position. When the operator carries out remote control operation, it is necessary to pull the handle to operate against the recovery force. After the operation, the hand leaves the handle, and the handle can automatically return to the zero position. Considering that the working space of the handle is $\pm 40^\circ$ around each axis, in order to have no singular point and member interference in the selected working space, and to have better flexibility index and force transmission performance index, the zero position (initial position) of the mechanism is defined as shown in Figure 1. That is the reclosing position of the axis connecting the moving platform and the connecting rod, and the axis connecting the fixed platform and the connecting rod of the adjacent moving chain.

^a Corresponding author: qiuxinan502@163.com

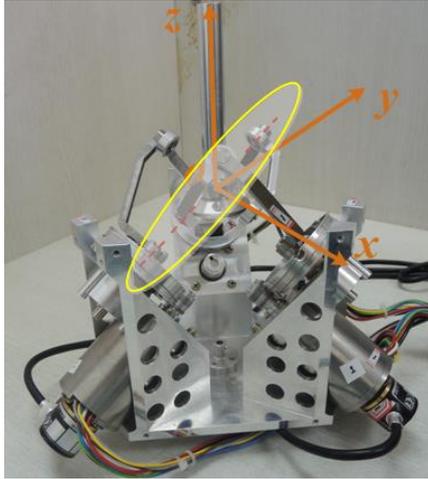


Figure 1. Definition of mechanism zero position

The automatic reset force of the handle is related to the movement of the end. The displacement of the joint angle is detected by the encoder installed at each joint of the handle. The torque required to be output by each driving motor is calculated according to the corresponding automatic reset force calculation method, and the corresponding electric current output by the driving motor is controlled, so as to realize the real-time automatic reset force output of the handle.

The common control handle relies on the return spring to realize the automatic return to zero position. The force feedback handle designed in this paper relies on the motor on three joints to provide power to complete the return to zero position, so it needs to simulate the return force of the spring through the servo motor.

2.1 Motor simulation of spring

In order to obtain more physical recovery force, the coordinate system is established at the end handle of the mechanism, and the zero-position attitude is defined as the fixed coordinate system O-x0y0z0, the real-time attitude of the handle is the dynamic coordinate system O-xyz, as shown in Figure 2. In the figure, i, j, k represents the unit vector of the dynamic coordinate system O-xyz, i_0, j_0, k_0 represents the unit vector of the fixed coordinate system O-x0y0z0.

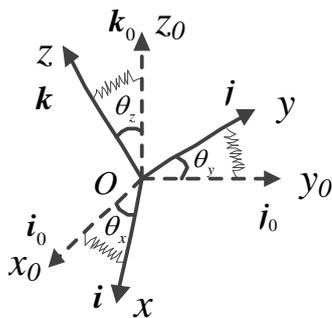


Figure 2. Definition of the included angle between the actual end position of the handle and the zero position

Let $\theta_x, \theta_y, \theta_z$ be the angle between the unit vectors i_0 and i, j_0 and j, k_0 and k , then

$$\begin{cases} \cos \theta_x = i^T \cdot i_0 \\ \cos \theta_y = j^T \cdot j_0 \\ \cos \theta_z = k^T \cdot k_0 \end{cases} \quad (1)$$

Assuming that a spring (or torsion spring) is installed between each coordinate axis of the coordinate system O-x0y0z0 to the dynamic coordinate system O-xyz the angle between the return moment and the coordinate axis is proportional. Set the return moment between the x axis and x0 axis as T_{yz} , the return moment between the y axis and y0 axis is T_{xz} , and the return moment between the z axis and the z0 axis be T_{xy} , The stiffness coefficient of each spring is k_{yz}, k_{xz}, k_{xy} , then

$$\begin{cases} T_{yz} = k_{yz} \theta_x \\ T_{xz} = k_{xz} \theta_y \\ T_{xy} = k_{xy} \theta_z \end{cases} \quad (2)$$

The axis direction of T_{yz}, T_{xz}, T_{xy} is set to e_{yz}, e_{xz}, e_{xy} , then

$$\begin{cases} e_{yz} = i_0 \times i \\ e_{xz} = j_0 \times j \\ e_{xy} = k_0 \times k \end{cases} \quad (3)$$

Define the torque vector as T_{yz}, T_{xz}, T_{xy} , then

$$\begin{cases} T_{yz} = T_{yz} e_{yz} \\ T_{xz} = T_{xz} e_{xz} \\ T_{xy} = T_{xy} e_{xy} \end{cases} \quad (4)$$

The resultant torque vector of the automatic reset force at the end of the handle is

$$T_r = T_{yz} + T_{xz} + T_{xy} \quad (5)$$

Let the angular velocity of the end of the mechanism be ω , and the angular velocity of the driving joint be \dot{s} . From reference [5], the speed relationship of the 3-RRR spherical parallel mechanism can be described as:

$$A\omega = B\dot{s} \quad (6)$$

Among them, A is the first type of Jacobian matrix, and B is the second type of Jacobian matrix

$$A = \begin{bmatrix} (w_1 \times v_1)^T \\ (w_2 \times v_2)^T \\ (w_3 \times v_3)^T \end{bmatrix} \quad (7)$$

$$B = \text{diag}(u_i \times w_i \cdot v_i) \quad i = 1, 2, 3; \quad (8)$$

u_i, w_i, v_i ($i=1,2,3$) are the direction of the three rotating auxiliary axes (drive shafts, hinges of connecting rods and connecting rods, hinges of connecting rods and moving platforms) of each moving branch chain.

Let \mathbf{J} be the speed mapping relationship between the input and output of the mechanism ($\dot{\mathbf{s}} = \mathbf{J}\boldsymbol{\omega}$), namely the speed Jacobian matrix, then

$$\mathbf{J} = \mathbf{B}^{-1}\mathbf{A} \quad (9)$$

In the control, it is necessary to make use of the Euler angle to differentiate the time, so the transformation matrix \mathbf{R} is introduced.

$$\boldsymbol{\omega} = \mathbf{R}\dot{\mathbf{t}} \quad (10)$$

Where \mathbf{t} is the Euler angle vector, $\mathbf{t} = [\phi, \theta, \psi]^T$.

$$\mathbf{R} = \begin{bmatrix} 0 & \cos \phi & -\cos \theta \sin \phi \\ 0 & \sin \phi & \cos \theta \cos \phi \\ 1 & 0 & \sin \theta \end{bmatrix} \quad (11)$$

Thus, it can be obtained

$$\dot{\mathbf{s}} = \mathbf{J}\mathbf{R}\dot{\mathbf{t}} \quad (12)$$

Let the driving torque of the drive motor be $\boldsymbol{\tau}$, According to the principle of virtual work, there are

$$\mathbf{T}_r^T \dot{\mathbf{t}} = \boldsymbol{\tau}^T \dot{\mathbf{s}} \quad (13)$$

Substituting equation (12) into (13) gives

$$\boldsymbol{\tau} = (\mathbf{J}\mathbf{R})^{-T} \mathbf{T}_r \quad (14)$$

In the formula, $\mathbf{J}\mathbf{R}$ is an extended Jacobian matrix.

2.2. Study of damping force

The spring model can be used to simulate the return force of the spring. In the actual debugging, the spring stiffness coefficient must be set carefully. If the spring stiffness coefficient is too small, the handle will lose power when it returns to the zero position, causing a large zero -return error. If the spring stiffness coefficient is too large, the automatic reset force is too large, and the handle is easy to cause oscillation due to the excessively fast restoring speed. In order to ensure that the handle has a high return-to-zero accuracy, and to minimize the back and forth oscillation phenomenon, a damping force needs to be introduced into the mechanism.

The damping force is a resistive moment that is proportional to the angular velocity, and its direction is opposite to the movement direction. Damping helps reduce the transient impact received by the mechanical system, hinders the structure from transmitting vibrations, and is beneficial to the stability of the device. In practical mechanical systems, damping is always present because of friction. In the automatic reset force control of the force feedback handle, increasing the damping term helps to increase the reliability of the zero return and reduce vibration.

The most commonly used damping model is linear viscous damping. The magnitude of the damping force is proportional to the speed and opposite to the direction.

For the force feedback devices, when the spring stiffness coefficient is too large, it often causes oscillation. Adding a damping term can significantly improve this situation, so a damping term should be added to the force control model.

Let the damping force be T_{dmp} , then

$$T_{dmp} = B\boldsymbol{\omega} \quad (15)$$

Here B is the damping coefficient and $\boldsymbol{\omega}$ is the joint angular velocity. For discrete systems,

$$\boldsymbol{\omega} = (\theta_t - \theta_{t-1})/t_{sample} \quad (16)$$

In the formula, θ_t refers to the angular displacement at time t ; θ_{t-1} refers to the angular displacement at time $t-1$, t_{sample} is the sampling time interval.

For force feedback control systems, higher sampling frequency is usually required. t_{sample} is generally set to 10ms or less. In discrete sampling, the calculation of speed is not continuous and it is prone to sudden changes in speed. This requires the selection of a suitable damping coefficient B . If B is too large, it may cause instability due to discontinuities; if B is too small, the effect of the damping term is not obvious, which is also not conducive to the stability of the control.

The calculation of the damping term is directly calculated at each drive joint. The angular displacement in each sampling period is collected by the encoder, and after the angular velocity is calculated, we can obtain the damping moment: T_{dmp} , and then superimpose it with the automatic reset force calculated by the previous inverse solution and output it to the motor.

3 Achieve

The handle automatic reset force is calculated using the spring-damping model, as shown in Figure 3.

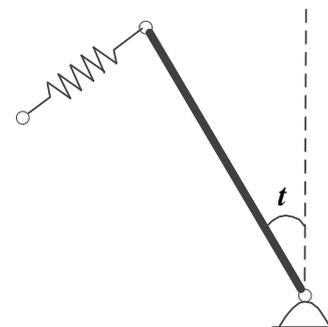


Figure 3. Spring-damped model

The formula for calculating the automatic reset force can be expressed as:

$$\mathbf{F} = \mathbf{K}\mathbf{t} + \mathbf{B}\dot{\mathbf{t}}$$

Among them, $\mathbf{t} = [\phi, \theta, \psi]^T$ is the Euler angle at the end, \mathbf{K} is the stiffness matrix, \mathbf{B} is the damping matrix.

Suppose the Euler angle obtained by iterative calculation is ϕ, θ, ψ , then the calculation process of

the spring force is shown in figure 4, the calculation process of the damping force is shown in Figure 5.

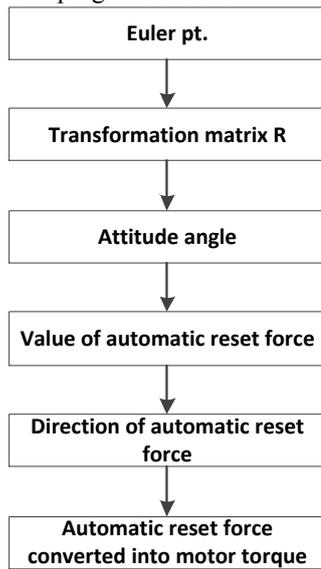


Figure 4. Calculation process of automatic reset force

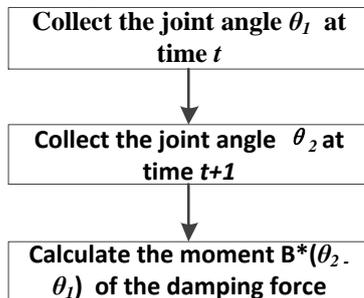


Figure 5. Calculation process of damping force

4 Experimental verification

The automatic reset force of the handle is the center force of the handle returning to zero, which is reflected as a force that always points to the center zero during the operation. When the operation is completed and the operator's hand leaves the handle, the handle mechanism automatically returns to the zero position under the action of the automatic reset force. The magnitude of the automatic reset force and the accuracy of returning to zero are indicators for evaluating whether the law of returning force is appropriate. A larger returning force will increase the resistance during operation, which will easily cause the operator's fatigue. A smaller returning force will make the return to zero slowly and zero-return accuracy is poor. Reasonably adjusting the parameter stiffness coefficient K and damping coefficient B can change the magnitude of return force and zero return error. The automatic reset force experiment is shown in Figure 6.

(1) the effect of damping coefficient on the stability of the automatic reset of the handle

Set the constant spring stiffness coefficient as $K=[8\text{Nmm}/^\circ \ 3\text{Nmm}/^\circ \ 3\text{Nmm}/^\circ]^T$, change the damping coefficient from 0.5 Nmm/rpm to 1.6Nmm/rpm, Set the constant spring stiffness coefficient as $K = 1$, change the

damping coefficient from 0.5 Nmm / rpm to 1.6Nmm / rpm, perform an automatic reset experiment on the handle, record the angle difference between the Z-axis direction of the handle and the zero position and the recovery torque of motor output to handle, and the experimental results are shown in figure 7.

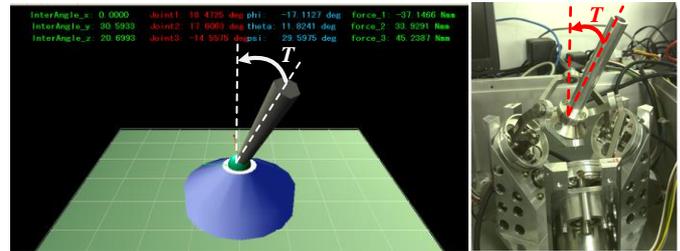


Figure 6. The automatic reset force experiment

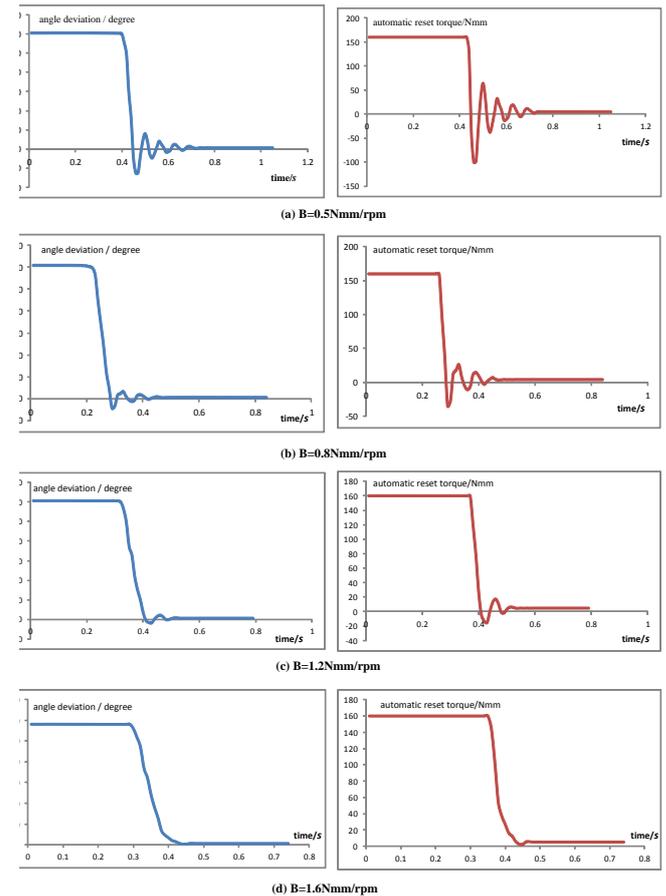


Figure 7. Effect of damping coefficient on the return-to-zero process

From the above comparison, it can be seen that when the damping coefficient $B = 0.5\text{Nmm}/\text{rpm}$, the handle will oscillate obviously around the zero position of automatic reset. When the damping coefficient is increased, the back and forth oscillation phenomenon gradually weakens, and the handle will soon stop at the zero position. When the damping coefficient is increased to $B=1.6\text{Nmm}/\text{rpm}$, the oscillation phenomenon disappears, and the handle can automatically return to the zero position and stop. The above phenomenon shows that the damping term is of great significance to the improvement of the zero-return stability of the handle and reasonably setting the damping coefficient can control the handle to return to zero automatically and stably.

(2) Effect of spring stiffness coefficient on zero return accuracy

Spring stiffness coefficient $\mathbf{K}=[k_{xy}, k_{yz}, k_{xz}]^T$, The latter two components are the restoring moments when the handle is rotated around its Z-axis. Because the force arm perpendicular to the Z-axis is short, the moment in this direction should be set smaller, or it will make operation difficult. Here only study the zero return situation where the handle deviates from the vertical direction, so only change the value of k_{xy} from $6\text{Nmm}/^\circ$ to $14\text{Nmm}/^\circ$, investigate the angular error of the handle returning to zero (represented by the mean error of the ZXY Euler angle), and the experimental results are shown in the figure.

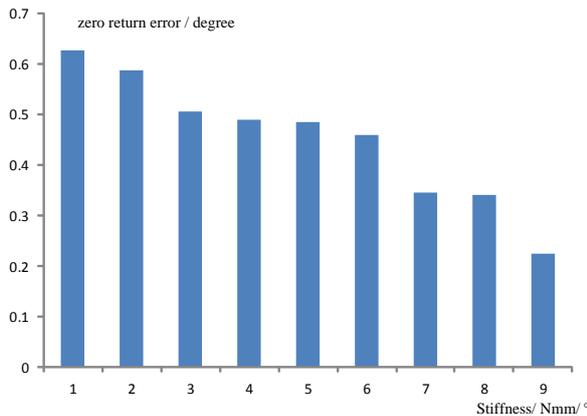


Figure 8. Effect of changing spring stiffness coefficient on return-to-zero accuracy

The above experiments show that increasing the spring stiffness coefficient is conducive to improving the zero-return accuracy of the handle. However, a large spring stiffness will cause overshoot to zero and back and forth oscillation, which is not conducive to the stability of zero return. Therefore, a suitable spring stiffness should be selected in combination with the damping.

5 Conclusion

Aiming at the requirement that the force feedback handle needs to return to zero automatically, this paper studies a spring-damping model and applies its model to the torque output of the motor to achieve a reliable reset of the

handle. The experiment shows that the reasonable setting of the damping coefficient can control the handle to return to the zero position stably and reliably, and the reasonable stiffness coefficient can balance the accuracy and stability of returning to zero. By dynamically and reasonably adjusting the stiffness coefficient and the damping coefficient, it can meet the needs of different users for the automatic reset force of the force feedback handle.

References

1. LI Daming, RAO Wei, HU Chengwei. Key Technology Review of the Research on the Space Station Manipulator [J]. *Manned Spaceflight*, **20**, 3 (2014) : 238-242.
2. Chipalkatty R, Daep H, Egerstedt M, et al. Human-in-the-loop: MPC for shared control of a quadruped rescue robot[C]. *IEEE/RSJ International Conference on Intelligent Robots and Systems*. IEEE, (2011) : 4556-4561.
3. Preusche C, Hirzinger G. Haptics in telerobotics[J]. *The Visual Computer*, **23**, 4 (2007): 273-284.
4. Goertz R C. Mechanical master-slave manipulator[J]. *Nucleonics (US) Ceased publication*, (1954).
5. Munjal Desai M, Tsui K M, Yanco H A, et al. Essential features of telepresence robots[C]. *IEEE Conference on Technologies for Practical Robot Applications*, (2011) :15-20
6. SONG Aiguo. Force Telepresence Telerobot : Review of the history and development[J]. *Journal of Nanjing University of Information Science and Technology: Natural Science Edition*, **5**, 1 (2013) : 1-19
7. Xiao dongg ZHANG Xiaodong. Research on Control Strategy of Space Flexible Manipulator[D]. Bei Jing: Beijing University of Posts and Telecommunications, (2008).
8. Deng Le, Zhao Ding-xuan, Tang Xin-xing. Research on key technologies of controller for teleoperation force reflecting telepresence [J]. *Journal of Engineering Design*, **12**, 3 (2005) :159-162.