Haptic Rendering Algorithm based on Force Feedback Handle in the Teleoperation of the Space Manipulator

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Abstract. In this paper, we study the haptic rendering algorithm of the handle for the requirement of designing the force feedback handle which is applied to the teleoperation of the space manipulator, to improve the user experience of the force feedback handle. By the research of arbitrary force and moment at the end of the handle, we propose the operation assisting force based on gravitational potential field method and the precise operation guiding method based on gravitational potential energy model. At the same time, the vibration signal is used in the state information of the slave and state. The experimental results show that the force-aware rendering algorithm applied to the teleoperation of the space manipulator can greatly improve the operation efficiency of the teleoperation task and effectively enhance the telepresence of teleoperation.

Key words: handle of manipulator haptic rendering assisting force

1. Introduction

Force feedback device is a kind of interface that realizes human-computer (Computer or robot) interaction through force. It can collect the movement information of human hands to control the computer or robot. At the same time, it can output regular force feedback to the operator to realize the operator's perception of the physical state of computer or robot. At present, space robotic arm systems that has successfully developed and put into use include SSRMS (Space Station Remote Manipulator)[1] jointly developed by Canada and NASA, ERA (European Robotic Arm)[2] of European Space Agency, and JEMRMS[3] of Japan. For the above-mentioned robotic arm teleoperation system, the master-side handle is the core control component [4], which is operated by professionals and sends control instructions to the slave-side robotic arm. The main control device used in the MSS system of the International Space Station is a pair of 3DOF handles. Professionals can control the movement of the robotic arm outside the cabin by operating the two handles to complete specific tasks. However, the above-mentioned operation handle does not have a force feedback function, cannot provide force feedback to the operator, and cannot realize the operator's perception of the unknown environment at the slave end and the interaction state between the manipulator and the slave end environment through the force channel. Limited by the accuracy and speed of visual information collection, the single visual interaction channel limits the effectiveness, efficiency, and safety of operators in completing professional tasks. Therefore, space robotic arm teleoperation system puts forward a clear and urgent demand for the force sensor interaction channel created by the main-end control handle with force feedback function.

The force rendering of the main-end control handle can effectively enhance the presence of the
main-end operator and improve the efficiency of teleoperation. Introducing it into the teleoperation of space robotic arm, it can feedback the interactive information of the unknown environment with uncertainty to the operator, so that professionals can obtain comprehensive information of vision and force perception; It can also provide effective force alert when an emergency or unexpected situation occurs, to avoid damage to the robot arm or the aircraft. The force rendering algorithm of force feedback handle studied in this paper is not only new development of the application field of force feedback device, but also well meets the engineering requirements of China's space robotic arm construction tasks.

The force feedback handle is used as the interactive device and the main-end of the teleoperation of the robotic arm and it is responsible for the input of the robotic arm movement instructions and the output of the robotic arm force and status information in the control loop. The tasks of the control system of the force feedback handle include: (1) Collect the joint angular displacement of the handle in real-time and calculate the attitude of the end of the handle; (2) Transmit motion instructions to the slave-end robot arm control system; (3) Calculate the feedback force based on the interaction status of the robot arm in the slave-end environment Information; (4) Transmit the feedback force command to the control system of the main-end handle.

The force feedback handle studied in this paper is based on a 3-RRR spherical parallel mechanism. Larger components such as motors, encoders, and brakes are installed on the base, and a rope transmission method with no backlash and low friction is used. Due to the small mass of the end, so the impedance control mode is used.

2. Arbitrary force and moment of force calculation at the end

2.1. Moment of force calculation in any direction

Generally, the speed Jacobian matrix is used to describe the speed relationship between the joint space and the operating space of the mechanism. Therefore, the Jacobian matrix is also called the generalized transmission ratio of the mechanism. Reference [5], the following will calculate the speed Jacobian matrix of 3-RRR spherical parallel mechanism.

Set the angular velocity at the end of the mechanism as \( \mathbf{\omega} \), driving joint angular velocity is \( \mathbf{s} \), the speed relationship of the 3-RRR spherical parallel mechanism can be described as:

\[
\mathbf{A} \mathbf{\omega} = \mathbf{B} \mathbf{s}
\]

Among them, \( \mathbf{A} \) is the first type of Jacobian matrix, and \( \mathbf{B} \) is the second type of Jacobian matrix.

\[
\mathbf{A} = \begin{bmatrix}
(w_1 \times v_1)^T \\
(w_2 \times v_2)^T \\
(w_3 \times v_3)^T
\end{bmatrix}
\]

\[
\mathbf{B} = \text{diag}(u_i, w_i, v_i) \quad i = 1, 2, 3;
\]

\( u_i, w_i, v_i \ (i = 1, 2, 3) \) is the direction of the three rotation auxiliary axes of each moving branch chain (the drive shaft, the hinge shaft of the side link and the connecting rod, and the hinge shaft of the connecting rod and the moving platform).

Set \( \mathbf{J} \) as the speed mapping relationship between the input and output of the mechanism (\( \dot{s} = J \omega \)), that is, the speed Jacobian matrix,

\[
\mathbf{J} = \mathbf{B}^{-1} \mathbf{A}
\]

In the control, we need to use the differential of Euler angle to time, so the transformation matrix \( \mathbf{R} \) is introduced,

\[
\mathbf{\omega} = \mathbf{R} \ddot{\mathbf{u}}
\]
Where \( t \) represents the Euler angle vector, \( t = [\phi, \theta, \psi]^T \);

\[
R = \begin{bmatrix}
0 & \cos \phi & -\cos \theta \sin \phi \\
0 & \sin \phi & \cos \theta \cos \phi \\
1 & 0 & \sin \theta
\end{bmatrix}
\]  

(6)

Thus, it can be obtained

\[
\dot{s} = JRt
\]  

(7)

Depending on the task of the operation, it is essential to apply a specific moment of force at the end of the handle. A moment vector can be determined by the axis direction and magnitude of the moment, so the direction and magnitude of the moment need to be given in the force calculation process.

Ignoring the gravity of the mechanism rods and considering the relationship between the moment at the end of the mechanism and the joint driving force. Set the external moment at the end of the handle as \( M_t \), and the moment that drives the joint is \( \tau \).

According to the principle of virtual work, there are

\[
M^T_t \dot{t} = \tau^T \dot{s}
\]  

(8)

Substituting equation (7) into (8) gives

\[
\tau = (JR)^T M_t
\]  

(9)

Therefore, the control system of the motor converts the torque signal into a current command, thereby controlling the motor driver to output a corresponding current.

2.2. Force calculation in any direction

In order to simulate the interactive force information of the slave-end robotic arm and the environment during teleoperation, the force feedback handle should be able to simulate forces in any direction and magnitude. As shown in figure 2, the handle simulates a force vector \( F \), which is directly acting on a human hand. For a force feedback device, \( F \) generates a moment \( M \) with respect to the rotation center \( O \). The size of \( M \) is:

\[
|M| = |h \cdot F \cdot k| = h |F| \cos \langle F, k \rangle
\]  

(10)

In the formula, \( h \) represents the distance from the center of rotation of the handle to the grip center of the human hand; \( k \) represents the unit vector in the z-axis direction of the dynamic coordinate system O-xyz, as shown in Figure 1.

The axis direction of the moment \( M \) is defined as \( e_m \), then

\[
e_m = F \times k
\]  

(11)

So the moment of force vector

\[
M = |M| e_m
\]  

(12)

The calculated torque vector can be controlled according to the calculation method of any torque vector.
3. Auxiliary Force Study of Operation

In the face of complex space operation tasks, it is very difficult to achieve precise teleoperation tasks only by visual feedback, while ensuring safety and avoiding collisions, and the operator will also face great mental pressure. The introduction of tactile assistance to guide the operator will help reduce the difficulty of operation tasks and greatly improve the efficiency, accuracy and safety of operations.

3.1. Artificial Potential Field

APF (Artificial Potential Field) was proposed by Khatib in 1986[6]. It was originally used in mobile robot obstacle avoidance and path planning to calculate virtual force based on the potential energy function related to the robot position. Subsequently, the artificial potential field method was gradually applied to the fields of robot path planning, bilateral teleoperation, and robot safety warning. The basic theory of artificial potential field is that for a target-oriented robot, an artificial potential field can be defined regardless of the presence of static or moving obstacles in the environment. In this potential field, the target position produces attraction, and the obstacle generates repulsive force [7]. Define the pose at the end of the robot as $q$, the target pose as $q_g$, the obstacle pose as $q_w$, the attractive potential associated with the target pose as $U_{att}(q)$, and the repulsive potential associated with the obstacle pose as $U_{rep}(q)$. When a robot approaching an obstacle in an artificial potential field, it will generate repulsive force, and when approaching a target, it will generate an attractive force. Feedback of these repulsive forces and attractive forces to the operator can guide the operator to make correct decisions. Compared with the traditional model based on collision detection and "spring-mass-damping", this article attempts to provide the auxiliary force for remote operation of the robotic arm with the artificial force field. Compared with the former, the artificial potential field method does not require an accurate dynamic model and does not need to understand the mass and inertial properties of the object, thereby making the auxiliary force perception rendering algorithm simple and robust.

The artificial potential field can use different potential field functions to obtain different virtual potential field forces. The commonly used potential field is the gradient potential field method, and the virtual force is the negative gradient of the potential field, that is:

$$F_{att}(q) = -\nabla U_{att}(q)$$ (13)

$$F_{rep}(q) = -\nabla U_{rep}(q)$$ (14)

Among them, $F_{att}(q)$ represents the attractive force of the potential field, and $F_{rep}(q)$ represents the repulsive force of the potential field.

The commonly used potential field model is:

Gravitational field:
The virtual force generated by the above repulsive and gravitational fields is:

\begin{align}
U_{\text{att}}(q) &= \frac{1}{2} \xi \rho_g^2(q) \tag{15} \\
U_{\text{rep}}(q) &= \begin{cases} 
\frac{1}{2} \eta \left( \frac{1}{\rho_w(q)} - \frac{1}{\rho_0} \right), & \rho_w(q) \leq \rho_0 \\
0, & \rho_w(q) > \rho_0
\end{cases} \tag{16}
\end{align}

Among them, \( \rho_g(q) = \|q-q_g\| \) represents the Euclidean distance from the end of the robot to the target pose \( q_g; \rho_0 \) is a constant, and \( \rho_0 > 0 \), which indicates the radius of the range where the obstacle generates repulsive force; \( \rho_w(q) = \min \|q-q_w\| \) represents the minimum distance from the obstacle to the end of the robot; \( \xi, \eta \) represents the proportionality factor; The virtual force generated by the above repulsive and gravitational fields is:

Attractive:

\begin{align}
F_{\text{att}}(q) &= \xi(q - q_g) \tag{17}
\end{align}

Repulsion:

\begin{align}
F_{\text{rep}}(q) &= \begin{cases} 
\frac{\eta}{\rho_w^2(q)} \left( \frac{1}{\rho(q)} - \frac{1}{\rho_0} \right) \nabla \rho(q), & \rho(q) \leq \rho_0 \\
0, & \rho(q) > \rho_0
\end{cases} \tag{18}
\end{align}

Where \( \nabla \rho(q) \) is the unit vector from \( q_w \) to \( q \), \( \nabla \rho(q) = \frac{q-q_w}{\|q-q_w\|} \).

3.2. Gravitational potential energy model

The artificial potential field method is of great significance in avoiding obstacles and ensuring the safety of the robot. Using the artificial potential field to guide the feedback force, so that the operator can control the robot arm to move along the safe path. However, the attractive force of the artificial potential field decreases as it approaches the target point. When it is smaller than the human perception threshold, the effect of the guiding force disappears. For precise operation tasks, such as assembly and alignment, when the end of the robot arm is close enough to the target point, small position and attitude deviations are difficult to distinguish through visual feedback. If the guiding force action disappears at this time, it will be difficult for the operator to accurately complete the task. It is of great significance to improve the accuracy of teleoperation through force guidance. Therefore, when approaching the target point, there must be sufficient guidance force, so that the operator can clearly understand the pose error and movement direction of the current end of the robot arm through force perception.

Taking the end of the robotic arm and the target point into two particle gravity models, the attraction of the target point to the end of the robotic arm will increase with the decrease of distance. This law is suitable for precise operation control guidance after the end of the robotic arm approaches the target point. Change the gravitational field in the aforementioned artificial potential field to a gravitational potential energy model:

\begin{align}
U_{\text{att}}(q) &= \frac{G}{\rho_g(q)} \tag{19}
\end{align}

The attractive force generated by this potential energy field is:
\[ F_{\text{att}}(q) = -\frac{G}{\rho_g^2(q)} \] (20)

When the end of the robot arm approaches the target point infinitely, the attractive force will tend to infinity. Excessive feedback force will affect the stability of the equipment and the safety of operation. Therefore, the force guidance of the precise alignment operation process is divided into three stages. In stage one, define the domain of attraction \( A(q) \), the end of the robot arm enters the attraction domain, and the attraction of the target point to the robot arm is calculated according to formula (20); In stage two, when the attractive force of the target point increases beyond a certain threshold, the attractive force is changed to a constant force. At this time, only the direction of the force is changed and the magnitude of the force is not changed. In stage three, when the pose error between the end of the robotic arm and the target point is very small, the attraction force will be zero when it is within the allowable error range of the assembly or docking task. Therefore, the formula for attraction is modified as:

\[
F_{\text{att}}(q) = \begin{cases} 
-\frac{G}{\rho_g^2(q)}, & \rho_g(q) \geq \rho_a \\
F_{\text{max}}, & \varepsilon < \rho_g(q) < \rho_a \\
0, & \rho_g(q) < \varepsilon 
\end{cases}
\] (21)

Among them, \( \rho_a \) is the radius of attraction domain, \( \varepsilon \) is allowable pose error, \( F_{\text{max}} \) is the maximum output force to ensure system stability. The change law of attractive force with distance after correction is shown in Figure 2.

![Figure 2. Law of Attraction](image)

### 3.3. Research on State Warning Signals

The use of haptic vibration information to provide warning signals has been widely studied and applied in many fields. Compared to visual cues and acoustic cues, the haptic signal will not be ignored due to inattention or environmental impact. Among many researches on tactile vibration warning, lane departure warning system (LDWS) is an important application field and a research hotspot in recent years. Generally, the haptic signals of LDWS can be divided into two types: one is the additional torque, and the other is the vibration signal[8]. Both types of haptic signals are applied to the steering wheel of the car, because the driver will always touch the steering wheel, so that he can feel the haptic prompt signal at any time. Compared with the torque signal, the vibration signal can more attract the operator's attention, and the warning effect is stronger. Ziegler [9] and others first studied the application of haptic vibration signals in LDWS, and then more scholars carried out a deep research in this field, such as Rothe [10], Tijerina [11], and so on. The frequency of the vibration prompt signal of LDWS is generally 5 ~ 20Hz, and the amplitude is generally 0.4 ~ 1.5Nm. In addition, Fu et al developed a tactile shoe that uses vibration signals to prompt stock market trading information to help investors understand the stock market in a timely manner[12]. Vibration signals
are also widely used in touch screens, mobile phones, and game equipment.

This paper introduces the vibration signal into the force feedback handle. By generating a small high-frequency vibration at the end of the handle, it provides a certain stimulus to the operator and achieves status information such as success, failure, danger, and mode switching of the robotic arm's operating tasks prompt. The factors that determine the properties of the vibration signal are the vibration law, vibration amplitude, and vibration frequency. This article attempts a square wave, triangle, and sine vibration laws. Based on the subjective experience of the participants, the sine vibration signal is considered (Figure 3) to be more conducive to the perception of the operator. By changing the amplitude and frequency of the sinusoidal signal, the operator's subjective perception and evaluation of the vibration prompt signal will also change. Finally, it was determined through experiments that a sinusoidal vibration signal with an amplitude of 40 Nmm and a frequency of 50 Hz was used as a warning signal of the slave-end state. The operator felt that the prompting effect was obvious and the hands felt comfortable.

![Figure 3. Sine vibration alert signal](image)

### 4. Experimental verification

The designed simulation task is that the operator completes the capture and auxiliary docking of the spacecraft by remotely operating the space robotic arm with the force feedback handle and a three-degree-of-freedom translation handle developed in this paper, as shown in Figure 4. During the operation, the force feedback needed to be realized includes the auxiliary guidance force of the precision operation of the mechanical arm, the impact force caused by grasping and collision, and the tactile signal to warn the operation status of the task. In order to facilitate control, the entire task process is divided into three stages, and the feedback force is calculated according to the tasks in each stage. The first stage is to capture the spacecraft with a robotic arm, the second stage is to adjust the position and attitude of the spacecraft to approach the docking hatch, and the third stage is to dock the spacecraft.

In the first stage, the operator controls the manipulator to move towards the spacecraft. In this process, the position and attitude of the manipulator must be adjusted continuously. The remote operation adopts the speed mapping mode. The movement speed and direction of the manipulator are controlled by the offset and direction of the control handle offset zero position. When the manipulator is close to the spacecraft, the gravitational potential field is used to guide the operator to accurately adjust the manipulator, so as to quickly capture the spacecraft, as shown in Figure 5. When the spacecraft is captured, the force feedback handle outputs a vibration prompt signal to prompt the operator to capture successfully and enter the next stage of operation.

In the second stage, the robotic arm moves with the spacecraft toward the node module. In this process, the position and attitude of the spacecraft are adjusted continuously, as shown in Figure 6. It is difficult to achieve accurate attitude adjustment through visual feedback, so the artificial potential field model is used to output auxiliary force in the process of attitude adjustment, which greatly reduces the operator's operation difficulty. When the attitude of the spacecraft is adjusted and the direction of the docking hatch axis is the same as that of the docking hatch axis of the node cabin, the handle will output a vibration prompt signal to prompt the operator to enter stage 3 and start the docking of the spacecraft. In the docking stage, the gravitational potential field model is still used to generate the attraction centered on the target position, assisting the operator to complete the precise docking task, as shown in Figure 7. At the same time, the collision force in the docking process is also output to the human hand through the force feedback handle, so that the operator can directly feel the
force state of the spacecraft.

**Figure 4.** Experimental environment for simulated docking tasks

**Figure 5.** In the first stage, spacecraft capture

**Figure 6.** In the second stage, adjustment of spacecraft attitude

**Figure 7.** The third stage, spacecraft docking

**Figure 8.** Time for operator to complete simulation task

Seven operators were invited to complete the simulation tasks in the above three stages. Each operator's experiment was divided into two groups, one was the operation with force perception rendering, and the other was the operation that blocked force perception rendering. The time they took to complete the task was shown in Figure 8. From the experimental results, it can be seen that the time taken for the seven operators to complete the operation tasks after adding auxiliary forces and status prompts is greatly reduced. When rendering incapable, relying only on visual feedback to operate the robotic arm to complete the simulation task, the average time taken by the seven operators is 2.6 times
that when operating with force feedback. Through interviews after the experiment, operators generally report that when rendering with force sense, the operation task becomes simpler and the teleoperation process is more realistic. This shows that the robot arm teleoperation force rendering algorithm studied in this paper can greatly improve the operation efficiency of teleoperation tasks and effectively enhance the presence of teleoperation.

5. Conclusion
This paper studies the auxiliary forces in the teleoperation to improve operational efficiency and operational friendliness. The traditional artificial potential field method is introduced into the teleoperation of the space manipulator. For precision operational tasks, a method was proposed that using the gravitational potential field model calculate the attractiveness of the target point. The method can achieve an increase in the guiding force when the mechanical arm is reduced from the target position. It helps the operator to complete tasks such as precision assembly or alignment. At the same time, the amplitude and frequency of the vibration signal suitable for the human hand are proposed when the vibration feedback is used in teleoperation. It can be seen from the experimental results that the haptic rendering algorithm proposed in this paper can greatly improve the operation efficiency of the teleoperation task and effectively enhance the telepresence of teleoperation when the force feedback handle is used for the teleoperation of the space manipulator.

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