Design and Performance Assessment of 2-DOF Teleoperation Device with Force Telepresence

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ABSTRACT: Teleoperation device is a man-machine interface of robot master-slave teleoperation system which is important for the operator to perceive the robots’ working condition and control them. Its performance will directly influence the work efficiency, accuracy and mechanical operation of the teleoperation system. Taking the self-designed 2-DOF teleoperation device with force telepresence as the research object, analyze its key technology from the structure pattern, operating performance and other aspects, which can realize the accurate position control and force telepresence of the teleoperation system, providing a certain reference for the design.

Keywords: force telepresence; teleoperation device; robot master-slave teleoperation system

1 INTRODUCTION

The master-slave teleoperation robot system is widely applied in the field of outer space, abysmal sea, nuclear power, medical treatment and other extreme environment. Due to the unknown and complex characteristic of robots’ workspace and the current level of technological development, it is hard to depend on the robots’ autonomous intelligence to make decisions and finish difficult tasks. It is necessary for the operator to monitor the robot by teleoperation device for achieving the remote control of the far-end robots.

The main function of the robot teleoperation device with force telepresence is to exchange information with operators. It can transmit position, speed, force, and other control parameters to the robot outside a certain distance and simultaneously receive the feedback of its real time working condition, which makes operators gain the force telepresence. It can be mainly applied in two aspects: 1) master-slave teleoperation system in extreme environment: abysmal sea, outer space, nuclear reactor, etc.; 2) work in virtual reality system, for example, the simulation surgery, game and all kinds of simulated training.

Up to now, there are many achievements, and all kinds of teleoperation mechanism with multi-degree of freedom are developed [3]. The celebrated four-degree of freedom pins to manhole master-slave teleoperation robot from the laboratory in Johns Hopkins University, and Dextre robot manufactured by the scientific research team from Canadian Space Agency, indicate that during the robots operation process, their working efficiency and mechanical operation performance can be improved by teleoperation device with force telepresence.

After investigation and research, it is discovered that most of them have the problems in expensive cost, complex operation and bad operation smooth feeling. Through the analysis of current 2-DOF mechanism for its dynamics and kinematics, a design scheme of 2-DOF robot teleoperation device has proposed based on the force telepresence technology. Particularly, it can provide a smoother operation hand feeling and improve the accuracy of position, speed control and force feedback, as well as conducting the research for...
drive and gear of mechanism device to improve the mechanism operation performance [5].

2 THE NEW-TYPE 2-DOF TELEOPERATION OPERATION DEVICE CONFIGURATION AND CHARACTERISTIC

2.1 Basic performance requirements for teleoperation device

Generally, the requirements of teleoperation device’s performance depend on the specified master-slave robot application situation. Being the “eyes” of the robot, the camera can be installed in the robot’s finger hand, arm, wrist and other positions. The operators can observe the status of controlled robot in the LCD panel of the teleoperation device and manipulate it by manual control handle. When the remote robot applies the force, the manipulator will send an anti-direction force to the operator. The sense of power will be transmitted directly by the motor, generating the force telepresence to the operators. In total, the designed 2-DOF device with force telepresence should have the following fundamental requirements: simple and compact structure, flexible and fluent operation, two-degree of freedom movement, enough strength, large stiffness, big friction, small inertia, strong market commonality and other characteristic.

2.2 Structure design and working principle

Since the teleoperation device is an important man-machine interface, its structure pattern, dimension, manufacture and machining accuracy will directly influence its operation performance. By the analysis of the existing two-degree of freedom mechanism, a design scheme of 2-DOF robot teleoperation device with force telepresence is proposed, which particularly can provide smoother operation hand feeling and accurate force feedback. The system is following the robot’s modular design idea with simple and convenient mechanical interface and communication interface. It can combine with various kinds of robots to realize the force telepresence function. The overall structure is shown in Figure 1, and the main transmission mechanism is shown in Figure 2.

The teleoperation device mainly includes cabinet 1, manipulator 2, dust cover 3, LCD module 5 installed in the surface of the cabinet, control panel 6 and integrated circuit plate 8. small cambered axle 21 in cabinet 1, big cambered axle 23 installed in the axle hole of the support plate in cabinet 1, its main characteristic is the manipulator 25 with spherical joint and the two cambered axle 21, 23 installed in the axle hole of the support in the form of tri-axis space intersection. There are manufactured circular plate-shaped chute in the middle of two-cambered axle’s half torus. The center of sphere overlaps with the center of half torus. The torus at the middle of two cambered axles coincides with the chute. When manipulator 2 is swinging, the lower end of the manipulator will slide inside the toroidal chute. There are DC motors and angular displacement sensor connected with both ends of small cambered axle 21 and the big cambered axle 23 respectively, and they are connected with integrated circuit plate 8 in the device. Because the big cambered axle and the small one rotate without interference, the manipulator’s position and orientation can be determined by the combined results of the two. For this reason, the operation device can realize two-degree of freedom operation.

The characteristic of the teleoperation device is the operating handle structure combined with the spherical joint, and a half torus is manufactured in the middle of the two rotating cambered axles. When installing it in the axle hole in the support of cabinet, and overlapping the center of half a torus with the center of sphere in the handle, the handle and tri-axis of the two cambered axles intersect in space in the center of half torus. There is a switching button in the operating handle. Install the motor respectively in one side of the two cambered axles and angular displacement sensor in the other side. There is an incomplete empty spherical shell with its maximum diameter and transparent up and down in the middle of the upper plate in the cabinet. Manufacture respectively a circular arc sliding chute in half torus of the two cambered axles so that the bottom of the manipulator can pass through the two sliding chute. Fuse a sphere in the middle of the manipulator, the axle journal under the sphere can be put inside the two cambered axles. Movable fit connection between the sphere in the
manipulator and empty spherical shell in the upper plate of the cabinet achieves overlapping between the sphere in the operating handle and spherical shell center in the upper plate of the cabinet. Install a fastening fixed block in the bottom of axle journal in the operating handle, then pass axle end with the fixed block through the two cambered axles and put the fixed block into the bottom-sliding chute of cambered axle. The center of the sphere in the operating handle overlaps with the center of the half torus in two cambered axles.

Figure 3 shows the working principle of 2-DOF teleoperation device with force telepresence. Start the device by the power switch in the control panel, supplying the power to each circuit connected in the system through the guideline. The operator gives the force $F_h$ to the manipulator 2, swinging manipulator 25 with the center of sphere center in the axle through the gear mechanism. Angle displacement sensor 9 can detect the angle displacement signal of operating handle 2 in the two-degree of freedom direction. The shifting signal $X_m$ is outputted by integrated circuit plate 8. Compare the signal with the shifting signal $X_s$ from robot actuator to obtain the difference, put the difference through amplifier, and then input it into the computer control system. Based on the displacement difference signal, the computer control system calculates the corresponding control signal $X_{sd}$ by control algorithm and transmits it to the far-end manipulated robot for controlling its joint motor turning to the relevant angle and far-end robot’s actuator moving with the operating device. Simultaneously, when the far-end robot receives acting force from the action object to the robot-working device, the far-end robot joint torque transducer detects the force signal $F_e$, transmitting it to the integrated circuit plate 8 in the device. It will control the corresponding torque supplied by the motor connected with the small-chambered axle 21 and the big cambered axle 23, actuating the operating handle, then the far-end robot receives the counter-force and brings the operator effective feedback force feeling. This can realize force telepresence and increase the operation accuracy and the whole robot work efficiency.

The teleoperation device of the robot system adopts modular design, with convenient software or hardware interface connected with other modules. The modular design method can shorten the robot development cycle, reducing the repetitive work of research and development. With flexible extension of robots function, it is benefit for the researchers to concentrate on solving the practical problems with robots.

The teleoperation device adopts motor drive, which can provide the force feedback stably and accurately. Since the two-degree of freedom mechanism mutual movement without coupling, there is no need to decouple which simplifies the control algorithm. The device uses the design idea of modular, connecting the sensor and motor with circuit board by slot, which is convenient to replace and protect. Simultaneously, the modular structure has small volume and strong universality and other characteristic. The modular can be applied into different kinds of robots teleoperation system as standardization component. This kind of structural design is apt to extend its practical application range.

The teleoperation device can transmit the detected displacement information to the robot system’s main control computer by communication interface in real time. When it is individually used as portable device, it can acquire the slave robot’s video information through LCD module in the outer shell. What’s more, the storage modular can record the information of detected position, torque during on-line operation, which is convenient for analysis and management of off-line detected data.

Compared with the existing technology, the teleoperation device has the following advantages. Firstly, because teleoperation device adopts the modular structure design, it is applicable to different kinds of robot system with teleoperation that requires force telepresence in helping far-end robot in operation finish the relevant dangerous work. Secondly, the teleoperation device can stably and accurately give in far-end dangerous and extreme environment robot and action object acting force information feedback to the manipulator. This can provide force sense perception to the operator. Thirdly, compare the operator’s control force multiplied by a certain ratio with the force applied by the far-end robot-working device, using the difference value to drive motor connected with the device, generating the proper torque. Fourthly, detect...
the position information of the transmission mechanism in the teleoperation device and transmit it to the far-end slave robot’s joint motor to form the closed loop position. The far-end slave robot will follow the master teleoperation device’s movement. Fifthly, the manipulator blends in the dynamic connection similar as spherical joint in structure, which increases the operating smooth feeling. It not only increases the position control accuracy, but also highly improves the operator’s force telepresence.

Manipulator of the teleoperation device can completely realize the designed force telepresence function, increasing robots’ work efficiency.

3 MECHANISM KINETIC OF MANIPULATOR AND DYNAMIC ANALYSIS

3.1 Kinematic analysis

For manipulator mechanism, establishing a coordinate system with rotation point defined as coordinate origin and two vertical cambered axle as X, Y axis. As shown in the Figure 4, P spot locates at the end of manipulator. $\theta_1$, $\theta_2$ are respectively the angle of vertical axis and cambered axis related to X,Y axis. $\theta_3$ is the angle between manipulator and Z axis. The manipulator end position at the work-space is determined by $\theta_1$, $\theta_2$ and the length of manipulator.

The following results are based on the geometric relationships:

\[
x = l \cdot \tan \theta_1 / \sqrt{1 + \tan^2 \theta_1 + \tan^2 \theta_2} = l \cdot \tan \theta_1 / K
\]
\[
y = l \cdot \tan \theta_2 / \sqrt{1 + \tan^2 \theta_1 + \tan^2 \theta_2} = l \cdot \tan \theta_2 / K
\]
\[
z = l / \sqrt{1 + \tan^2 \theta_1 + \tan^2 \theta_2} = l / K
\]

Reverse kinematics of manipulator:

\[
\theta_1 = \arctan\left(x / \sqrt{1 + (l^2 - x^2 - y^2)}\right)
\]
\[
\theta_2 = \arctan\left(y / \sqrt{1 + (l^2 - x^2 - y^2)}\right)
\]

Positive solutions of speed:

\[
V = [\dot{x} \ \dot{y} \ \dot{z}] = J\begin{bmatrix} \dot{\theta}_1 \\ \dot{\theta}_2 \end{bmatrix}
\]

According to kinematics analysis, the trajectory of manipulator end is the part of spherical surface of sphere centered at the rotation point with radius of manipulator length $l=200$mm. There is no singularity in the workspace, which means the relational mapping is unique and determined. The sphere surface range is restricted by the two angles: $-45^\circ \leq \theta_1 \leq 45^\circ$, $-45^\circ \leq \theta_2 \leq 45^\circ$ (as shown in the Figure 5).

![Figure 5. The sphere surface range is restricted by the two angles.](image)

3.2 Statics analysis

To conduct performance analysis for 2-DOF robot teleoperation device with force telepresence requires establishing statics model of mechanism, studying the relationship between input and output forces. As shown in Figure 5, assume that the DC motor torque acting on cambered axle are $M_1$, $M_2$ respectively, therefore three components $F_x$, $F_y$, $F_z$ of F force from operator with force balance at the manipulator end are shown as follow:

\[
F_x = F_1 \sin \theta_1 + F_2 \sin \theta_2 = K (M_1 \sin \theta_1 \cos \theta_2 + M_2 \sin \theta_2 \cos \theta_1) / l
\]
\[
F_y = F_1 \cos \theta_1 = M_1 \cos^2 \theta_1 / l
\]
\[
F_z = F_2 \cos \theta_2 = M_2 \cos^2 \theta_2 / l
\]

Turn the above formulas into forms of matrix

\[
\begin{bmatrix} F_x \\ F_y \\ F_z \end{bmatrix} = \begin{bmatrix} 0 & \cos \theta_2 \\ \cos \theta_1 & 0 \\ \sin \theta_1 \cos \theta_2 & \sin \theta_1 \cos \theta_1 \end{bmatrix} \begin{bmatrix} M_1 \\ M_2 \end{bmatrix} = [G] \begin{bmatrix} M_1 \\ M_2 \end{bmatrix}
\]

The above formulas indicates the relationship between the input and output torque. $[G]$ is force Jacobian matrix of mechanism, which shows the transitions relationships from joint space torque into manipulations force.$^{[12]}$

3.3 Kinetics analysis

2-DOF robot teleoperation device with force telepresence could be classified into multi-rigid-body system, modeling the mechanism kinetics by Lagrange equation, the Lagrange equation expression as shown below:
\[
\frac{d}{dt}\left( \frac{\partial L}{\partial \dot{q}_j} \right) - \frac{\partial L}{\partial q_j} = F_j \quad (j = 1, 2, \ldots, n)
\]

The potential energy of manipulator drive mechanism is:

\[
V = -m_1gR_1 \cos \theta_1 - m_2gR_2 \cos \theta_2
+ m_1g \left( 1 + R \right)/\sqrt{1 + \tan^2 \theta_1 + \tan^2 \theta_2}
\]

Kinetic energy:

\[
T = \frac{1}{2} I_1 \dot{\theta}_1^2 + \frac{1}{2} I_2 \dot{\theta}_2^2 + \frac{1}{2} I_3 \dot{\theta}_3^2
\]

According to geometric relationships of mechanism:

\[
\dot{\theta}_2 = \dot{\theta}_1^2 + \dot{\theta}_3^2, \quad I_1 = I_2
\]

The moment inertia of manipulator:

\[
I_3 = \frac{1}{12} m_1 \left( 1 + R \right)^2 + m_1 \left( 1 - \frac{1}{2} R \right)^2 = \frac{1}{3} m_3 \left( I^2 - I_3 \right)
\]

According to Lagrange equation:

\[
(1 + I_1) \ddot{\theta}_1 - m_1gR_1 \sin \theta_1 - \beta_1 m_2g \left( 1 + R \right) \sin \theta_1 = M_1 - M_x (F)
\]

\[
(1 + I_3) \ddot{\theta}_3 - m_2gR_3 \sin \theta_3 - \beta_2 m_2g \left( 1 + R \right) \sin \theta_3 = M_2 - M_y (F)
\]

Respectively, \( I_1, I_2, I_3 \)--big cambered axle, small cambered axle, moment of inertia;

\( m_1, m_2, m_3 \)-- mass of big cambered axle, small cambered axle, manipulator, respectively;

\( r_1, r_2 \)-- straight axle diameter of big cambered axle, small cambered axle, respectively;

\( R_1, R_2 \)-- arc radius of big cambered axle, small cambered axle, respectively;

\( M_x (F), M_y (F) \)-- reaction torque of manipulator end relevant to straight axle and cambered axle, respectively.

\[
\beta_1 = \frac{\sqrt{1 + \tan^2 \theta_1 + \tan^2 \theta_3}}{2 \cos \theta_1 (1 + \tan \theta_1 + \tan \theta_3)}
\]

\[
\beta_2 = \frac{\sqrt{1 + \tan^2 \theta_3 + \tan^2 \theta_2}}{2 \cos \theta_2 (1 + \tan \theta_2 + \tan \theta_3)}
\]

Driving torque of two axles is respectively:

\[
M_1 = (1 + I_1) \ddot{\theta}_1 - m_1gR_1 \sin \theta_1 - \beta_1 m_2g \left( 1 + R \right) \sin \theta_1 + M_x (F)
\]

\[
M_2 = (1 + I_3) \ddot{\theta}_3 - m_2gR_3 \sin \theta_3 - \beta_2 m_2g \left( 1 + R \right) \sin \theta_3 + M_y (F)
\]

For the above-mentioned formulas, known from the mass of all components of manipulator and structural parameters, the rotation angle of axle can be detected by corresponding sensors, therefore, the above two formulas can be used to realize the control of manipulator with 2-DOF force feedback.

4 MANIPULATOR PERFORMANCE ASSESSMENT

4.1 Drive performance

The manipulator’s drive performance is shown in positive drive and reverse drive\(^{[13]}\). When the manipulator mechanism is driving positively, two motors connected with big and small cambered axle respectively drive the cambered turning around axle central line, and then drive the end of manipulator to input force to operator who contacts with the manipulator end. As the manipulator is driving reversely, with two motors power off, drive mechanism is in a free state. When the operator input force to manipulator end to move, two cambered axles move with the manipulator.

The output force \( F \) that acts on manipulator end is calculated by static analysis

\[
F = \sqrt{M_1^2 + M_2^2} / l
\]

As seen from formula (5), in order to maximize \( F \), acts on the manipulator end only maximize the equal of right side. It becomes easy to change the motor output torque by means of regulating system voltage, which would maximize \( M_1, M_2 \) within the allowable scope.

When the manipulator mechanism is driven reversely by operator’s force, with the two motors power off, the motor drive torque becomes zero. The simplified kinematic equation as follow:

\[
F = M \ddot{X}
\]

\( M \)-- inertial matrix

Further transformation as follow:

\[
\ddot{X}^T \ddot{X} = F^T (M_x^{-1})^T M_x^{-1} F
\]

According to the literature analysis, the valuation criterion for manipulator reverse driving performance is: Assume the acceleration at manipulator end is 1 unit, analyzing the mechanism output force value. If you get less operating force, it means you get better sensitivity during the reverse driving. To make \( \ddot{X}^T \ddot{X} = 1 \), The formula(6) can be changed into

\[
F^T (M_x^{-1})^T M_x^{-1} F = 1
\]

The math model described by formula(7) can be considered as a ellipse, and the length of semi major axis and semi minor axis is \( F_x \) and \( F_y \) respectively, using MATLAB software to simulate the force elliptic equation which is established by formula (7). The result is shown in the Figure 6 and 7.
Figure 6. Force ellipse in the work space.

Figure 7. The relationship between ellipse area and material density.

Figure 6 shows that the force ellipses obtained by different spot relevant to manipulator at whole work-space are identical. No matter where the manipulator is in workspace, you will get the same force fluency and high sensitivity. The shorter semi major axis $a$ is, the better sensitivity of manipulator you have. Figure 7 shows the different ellipses area are related to varied material density, and it shows that manipulator which is made of less density will obtain higher sensitivity.

Global dexterity index

Global dexterity index $\eta$ is firstly put forward by Gosselin to describe kinematic performance of robot. Global dexterity index $\eta$ is calculated by average value of reciprocal of Jacobian’s matrix condition number in whole workspace $W$, which can be defined as:

$$\eta = \frac{1}{\pi} \int \int \frac{1}{\sqrt{\Delta}} dW$$

The range of workspace of manipulator has already obtained by mechanism kinematic analysis, turning the curved surface integral into double integral in projection area $D_{xy}$ of $XOY$ plane. Angle range: $\theta_1 < 45^\circ, \theta_2 < 45^\circ$ obtain the global dexterity index $\eta$:

$$\eta = \int \int \frac{1}{\sqrt{r^2 - x^2 - y^2}} dxdy / \int \int \frac{1}{\sqrt{r^2 - x^2 - y^2}} dxdy$$

After analyzing workspace of 2-DOF teleoperation device with force telepresence manipulator, we know that if $\theta_1 = \theta_2 = 45^\circ$, denominator of integrand at right side of equal sign will be zero, so define the integration interval as $-\sqrt{2} < x < \sqrt{2}, -\sqrt{2} < y < \sqrt{2}$. Calculating the above-mentioned global dexterity index $\eta$ by MATLAB software, simulate the result and set horizontal axis as the angle of position and orientation of manipulator $\theta_2$, calculating simulation curve of $\eta$ as $\theta_1$ varying within $10-40^\circ$. The result can be shown in Figure 8. As we can see from the curve: $\eta$ increases gradually as the angle $\theta_1, \theta_2$ increase, but it maintain around standard value 1 without big aberrations, therefore, through the simulated analysis of global dexterity, we know the performance of operation is quite stable.

Figure 8. Change rule of global dexterity varies with angle.

5 CONCLUSION

The teleoperation device with telepresence is the vital human-machine interface of teleoperation system. The article analyzes the self-designed teleoperation device from several aspects: performance requirements, structural design, performance assessment, designing and selecting the main components, analyzing the structural features and performance assessment of the teleoperation device. With more and more application field of teleoperation technique, it is optimistic to believe that the research and development of telepresence for teleoperation device with high precision, high rigidity, compact structure, and multi-function will have important theory significance and wide application prospects.

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