

Research on the Control Strategy of Decoupled 3-DOF Joystick for Tele-operation

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Keywords: Joystick, Permanent Magnet Synchronous Motor, Control Strategy, tele-operation.

Abstract. Joystick is a critical equipment for human to interact with an environment in a tele-operation system. In this paper, a decoupled three translational degree of freedom joystick for tele-operation applying Permanent Magnet Synchronous Motor (PMSM) is designed. Then new control strategy based on position constraint space is proposed to realize the position control of the Joystick, and the experiment results show the effectiveness of the structure design of the joystick and the control strategy.

Introduction

High rigidity, strong bearing capacity and high precision are what lead parallel joysticks widely used in tele-operation system [1,2]. In this paper, a decoupled three translational degree of freedom joystick for tele-operation is designed utilizing PMSM. Then the position constraint space control strategy is put forward to realize the force feedback for the joystick.

The design of the decoupled three translational degree of freedom joystick

Kinematics Analysis. The center of the base and the moving platform are respectively denoted as O and P. In this paper, Denavit-Hartenberg [3,4] method is applied to establish the coordinate system of each chain of the joystick.

As showing in figure 1, in chain 1 for instance, reference coordinate system O-X₁₀Y₁₀Z₁₀ is established in the base center. In the reference coordinate system, the X axis is parallel to the plane of the base, and the Y axis is parallel to the plane of the base and has the same as the direction of chain 1, and the Z axis is perpendicular to the plane of the base.

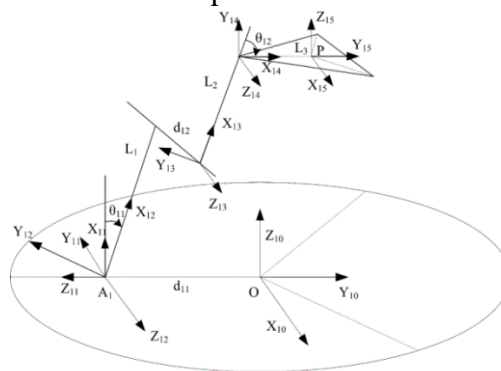


Fig. 1 The reference coordinate system for chain 1 of the joystick

Obviously, the moving platform only has three translational degree of freedom, and the relationship between θ_{11} and θ_{12} can be expressed as $\theta_{12} = -90^\circ - \theta_{11}$. So the pose of P-X₁₅Y₁₅Z₁₅ relative to O-X₁₀Y₁₀Z₁₀ can be formulated by

$$T_1 = {}^0_5T = {}^0_1T {}^1_2T {}^2_3T {}^3_4T {}^4_5T, \quad (1)$$

T_1 is given by

$$T_1 = \begin{bmatrix} 1 & 0 & 0 & d_{12} \\ 0 & 1 & 0 & L_3 - d_{11} - (L_1 + L_2) \sin \theta_{11} \\ 0 & 0 & 1 & (L_1 + L_2) \cos \theta_{11} \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (2)$$

In formula (2), the last column is the position vector of the center point P of the moving platform, if the vector is denoted as $P = [P_x, P_y, P_z]^T$, then the formula (3) is obtained

$$\begin{bmatrix} d_{12} \\ L_3 - d_{11} - (L_1 + L_2) \sin \theta_{11} \\ (L_1 + L_2) \cos \theta_{11} \end{bmatrix} = \begin{bmatrix} P_x \\ P_y \\ P_z \end{bmatrix} \quad (3)$$

Accordingly, we can get

$$\theta_{11} = -\arccos \frac{P_z}{L_1 + L_2}, \quad \theta_{12} = -\arcsin \frac{P_z}{L_1 + L_2}$$

$$d_{11} = -P_y + \sqrt{(L_1 + L_2)^2 - P_z^2} + L_3, \quad d_{12} = P_x$$

For chain 2 and chain 3, the method of establishing the coordinate system and the process to get the inverse solution is identical with the chain 1. When the moving platform position vector $P = [P_x, P_y, P_z]^T$ is given, the inverse solution for all joints can be obtained. So the inverse solution for three chains is given by formula (4)-(6)

$$P_x = \frac{\sqrt{3}}{3} d_{21} - \frac{\sqrt{3}}{3} d_{31}, \quad (4)$$

$$P_y = -\frac{2}{3} d_{11} + \frac{1}{3} d_{21} + \frac{1}{3} d_{31}, \quad (5)$$

$$P_z = \sqrt{(L_1 + L_2)^2 - \left(\frac{d_{11} + d_{21} + d_{31}}{3} - L_3 \right)^2}. \quad (6)$$

As long as displacements d_{11} , d_{21} and d_{31} of three drives are known, we can get the position of the moving platform according to above formulas.

Workspace Analysis. The simulation model is built in *Matlab/Simulink* using the Monte Carlo method [5,6] and takes N random values within the range of motion of each slider at the bottom of the chain, then the lower and upper limit of three sliders can be expressed as:

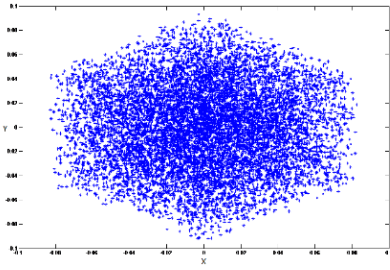
$$d_{li} = d_{li}^{\min} + (d_{li}^{\max} - d_{li}^{\min}) \times \text{Rand}(N, 1). \quad (7)$$

In this paper, the size of the designed joystick is shown in Table 1,

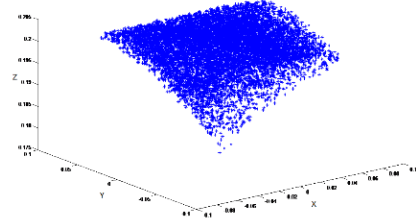
Tab. 1 The size of the designed joystick

	Slider of the screw-nut	Lower link	Upper link	Moving platform
Size (cm)	irregular	L1 = 68	L2 = 69	L3 = 45

Gathering the following points of the moving platform, and the generated point set is the workspace of the joystick. The result is shown in Figure 2.

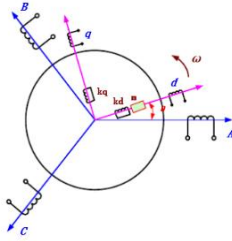


(a) The projection on the plane XOY

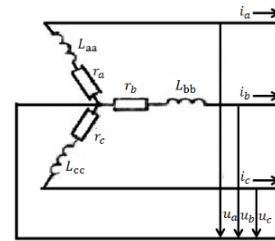


(b) Three-dimensional plot of the workspace

Fig. 2 the workspace of the three translational degree of freedom joystick



(a) The simplified schematic



(b) The equivalent circuit

Fig. 3 The simplified schematic and equivalent circuit of Permanent Magnet Synchronous Motor

Design of Electronic Controlled Driving System. In this paper, PMSM is utilized as the actuator to drive the joystick, which has the advantages of high power factor, low inertia, high control precision, slow running stability and high cost-effectiveness [7,8]. The simplified schematic and equivalent circuit of Permanent Magnet Synchronous Motor are showing in the figure 3.

$$\begin{cases} \frac{di_d}{dt} = \frac{1}{L_d} u_d - \frac{r}{L_d} i_d + \frac{L_q}{L_d} \omega_e i_q \\ \frac{di_q}{dt} = \frac{1}{L_q} u_q - \frac{r}{L_q} i_q - \frac{L_d}{L_q} \omega_e i_d - \frac{\omega_e \psi_f}{L_q} \end{cases} \quad (8)$$

Where u_a, u_b, u_c are the voltage of stator winding phase, unit are V; r_a, r_b, r_c are the winding resistance of each phase, unit are Ω ; i_a, i_b, i_c are the winding current of each stator phase, unit are A; ω_e is angular velocity of the rotor; $L_d = L_q = L - M$.

$$J \frac{d\omega}{dt} + B\omega = P(T_e - T_l), \quad (9)$$

where J is the moment of inertia; ω is the angular velocity, B is viscous friction factor, P is differential operator; T_l is load torque.

Control strategy of the joystick for tele-operation

In the existing bilateral servo control system, the information of direction and action point cannot be determined, thus affecting accurate perception for operators interacting with the environment [9,10]. In this paper, as shown in Figure 4, the position constraint space control strategy is put forward to realize the force feedback for the joystick.

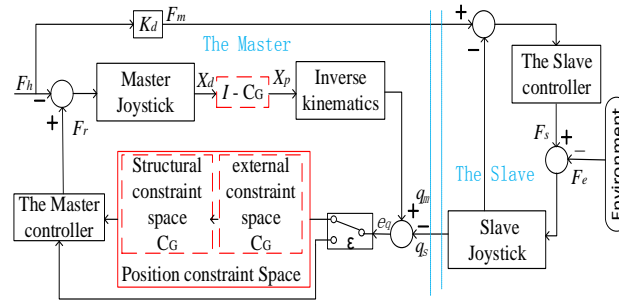


Fig. 4 The position constraint space control strategy

Assuming that the feedback force caused by the structural constraint is F_{RG} , clearly, it satisfies $F_{RG} \in C_G$,

$$C_G = -K_G(I - J_s J_s^+). \quad (10)$$

Likewise, assuming that the feedback force caused by the external constraint is F_{RE} , clearly, it satisfies $F_{RE} \in C_E$,

$$C_E = -K_E(I - J_s^\ominus J_s^{\ominus+})J_s J_s^+, \quad (11)$$

where J_s is the Jacobian matrix of the slave joystick, J_s^\ominus is generated new matrix crossing out the corresponding column vector and replaced by zero column when the joints in the chain of slave joystick is impeded by obstacle and cannot move. Then the feedback force of the bilateral system can be calculate by

$$F_R = F_{RG} + F_{RE} = (C_G + C_E)e_q = -(K_G(I - J_s J_s^+) + K_E(I - J_s^\ominus J_s^{\ominus+})J_s J_s^+)e_q, \quad (12)$$

where K_G and K_E are mutual independent scalar gains, $e_q = [e_{q1}, e_{q2}, e_{q3}]^T$ is the difference of the relevant joints movement between the master and the slave.

Experiment result analysis

As shown in Figure 5 and Figure 6, they are respective the normalized force feedback curve of applying the conventional p-f force feedback control strategy and the position constraint space control strategy when the slave's slider at the bottom of the chain 1 and the chain 2 are obstructed by the obstacle simultaneously.

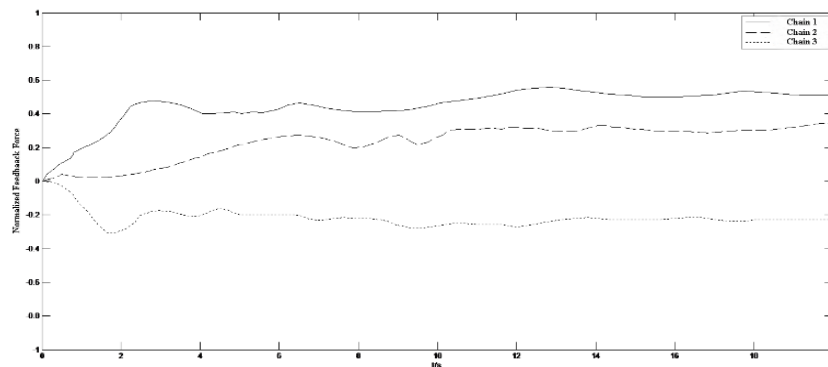


Fig.5 Applying the conventional p-f force feedback control strategy

Obviously, in the situation where the conventional p-f control strategy is utilized, the three chains also bear feedback force when the chain 1 and the chain 2 are obstructed by the obstacle simultaneously, resulting in the illusion that the three branches are all hindered by obstacle, cannot correctly respond to the real situation.

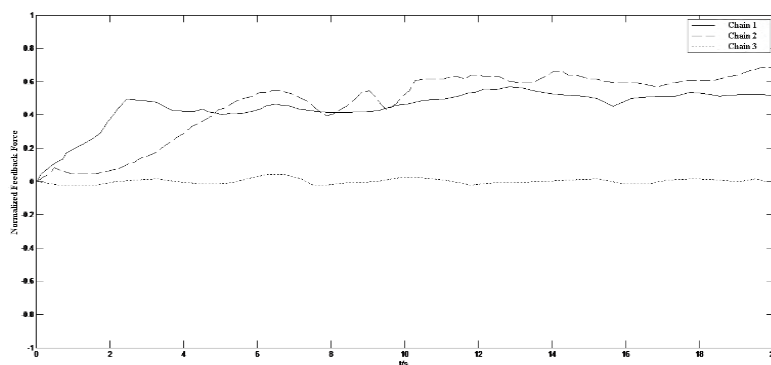


Fig. 6 Applying the position constraint space control strategy

Conclusion

In this paper, a decoupled three translational degree of freedom joystick for tele-operation is designed, and the force feedback experiment is carried out and the results show the effectiveness of the position constraint space control strategy.

Acknowledgment

The authors are grateful for partial support from The National Research Foundation for the Doctoral Program of Higher Education of China under Grant No. 20130061110009.

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