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Simulation of 6-DOF Parallel Robot for Coupling Compensation Method

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Abstract: In order to improve control performance and eliminate steady, a coupling compensation for 6-DOF parallel robot is presented. Taking dynamic load Tank Simulator as the research object, this study analyzes the coupling of 6-DOF parallel robot considering the degree of freedom of the 6-DOF parallel robot. The coupling angle and coupling velocity are derived based on inverse kinematics model. The performance revolving stability, accuracy and robustness of the proposed coupling compensation control scheme for 6-DOF parallel robot is analysed in theory and computer simulation. These simulations show that the coupling compensation can improve the control performance and eliminate the steady state errors of tank simulator.

Key words: Coupling compensation, screw theory, parallel robot, inverse kinematics

INTRODUCTION

Since, parallel structure is proposed by Stewart (1993), the 6-DOF parallel robot is one of the most popular cueing simulator mechanisms for its remarkable advantage over serial mechanisms (Huang *et al.*, 2005; Yang *et al.*, 2002), where a moving plate is connected to a base plate by six legs. The character of each leg influences the smoothness, accuracy and real-time of the moving plate. This perspective attracts a lot of research on error analysis and compensation.

Abdellatif and Heimann (2006) and Abdellatif *et al.* (2007) opened the discussion on the influence of Passive Joint Friction (PJF) in robot's dynamics and its impact on control performance Meng *et al.* (2002) proposed a direct-error-compensation method of measuring the error of a six-freedom-degree parallel mechanism CMM. Yang *et al.* (2010) developed PD control with gravity compensation for hydraulic 6-DOF parallel manipulator. Cleary and Arai (1991) analyzed the influence of moving plate by the length of each of the six legs. Wang *et al.* (2007) studied the coupling characteristics of large hydraulic Stewart Platform. Li *et al.* (2009) compensates the interference of Stewart Platform based on inverse dynamic model. Besides, researchers often use software to simulate the moving of parallel robot (Ma *et al.*, 2008; Iqbal *et al.*, 2008; Liu *et al.*, 2009). But there are few documents studied on the phenomenon of the coupling.

In this study, a coupling compensation is developed to improve the control performance including steady and moving precision via compensating each leg coupling errors. This study begins with a screw theory to analyze

the motion characters of 6-DOF parallel robot. Then the Plücker system of leg is built, considering the degree of freedom of the 6-DOF parallel robot and the coupling angle and coupling velocity are calculated by a closed-solution inverse kinematics. The performance including stability, precision and robustness of the 6-DOF parallel robot with coupling compensation is analysed in theory and simulation. The controller with coupling compensation is used to Tank Simulator to prolong its lifetime.

COUPLING ANALYSIS

With reference to Fig. 1, which represents the 6-DOF parallel robot structure here considered, it can be observed that the moving plate and the base plate are

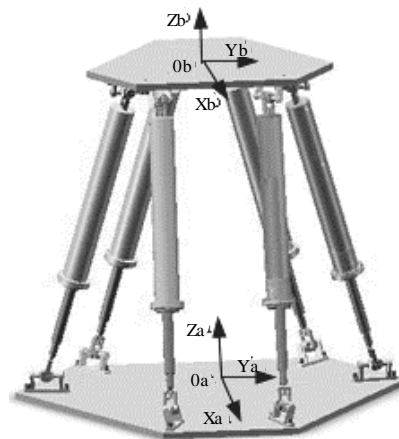


Fig. 1: Model of 6-DOF parallel robot

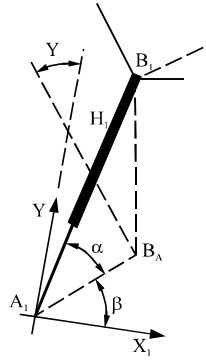


Fig. 2: Coordinate system of leg A1H1B1

combined with six legs which consist of upper gimbal, screw joint and lower gimbal. One of the combined legs is taken to analyze its coupling based on screw theory.

It supposes that the coupling does not exist in each screw joint of legs, which means the screw joint, as same as translational joint, has only one translational motion. The frame (X, Y, Z) located at the center of the lower gimbal is shown in Fig. 2. The lower gimbal A₁ contains two orthogonal rotational motion which are given in Plücker coordinates by:

$$\mathfrak{S}_1 = [1 \ 0 \ 0; 0 \ 0 \ 0] \quad (1)$$

$$\mathfrak{S}_2 = [0 \ 1 \ 0; 0 \ 0 \ 0] \quad (2)$$

The angle between the line of translational motion and the base plate is denoted by α , the angle between the X-axis and the line of A₁B₁ which is the projection of A₁B₁ is denoted by β . Thus, the translational motion of screw joint is given in Plücker coordinates by:

$$\mathfrak{S}_3 = [0 \ 0 \ 0; \cos\alpha \ \cos\beta \ \cos\alpha \ \sin\beta \ \sin\alpha] \quad (3)$$

The upper gimbal also contains two orthogonal rotational motions. Length of the leg A₁B₁ is denoted by L₁, γ stands for the angle between the line of the upper gimbal center joint and the opposing lower gimbal center joint. Thus, the two orthogonal rotational motion of the upper gimbal can be calculated in Plücker coordinates as follows:

$$\mathfrak{S}_4^1 = [-\sin\gamma \ \cos\gamma \ 0] \quad (4)$$

$$\begin{aligned} \mathfrak{S}_4^0 &= r \times \mathfrak{S}_4^1 = OB_1 \times \mathfrak{S}_4^1 \\ &= [-l \sin\alpha \cos\gamma \ -l \sin\alpha \sin\gamma \\ &\quad l \cos\alpha \cos\beta \cos\gamma + l \cos\alpha \sin\beta \sin\gamma] \end{aligned} \quad (5)$$

$$\mathfrak{S}_4 = [\mathfrak{S}_4^1; \mathfrak{S}_4^0] \quad (6)$$

$$\begin{aligned} \mathfrak{S}_5^1 &= \mathfrak{S}_4^1 \times \frac{r}{|r|} = [\sin\alpha \cos\gamma \ \sin\alpha \sin\gamma \\ &\quad -\cos\alpha \sin\beta \sin\gamma - \cos\alpha \cos\beta \cos\gamma] \end{aligned} \quad (7)$$

$$\begin{aligned} \mathfrak{S}_5^0 &= r \times \mathfrak{S}_5^1 = OB_1 \times \mathfrak{S}_5^1 \\ &= [-l \cdot \cos^2\alpha \cdot \sin^2\beta \cdot \sin\gamma - l \cdot \cos^2\alpha \cdot \sin\beta \cdot \\ &\quad \cos\beta \cdot \cos\gamma - l \cdot \sin^2\alpha \cdot \sin\gamma \quad l \cdot \sin^2\alpha \cdot \\ &\quad \cos\gamma + l \cdot \cos^2\alpha \cdot \sin\beta \cdot \cos\beta \cdot \sin\gamma + l \cdot \\ &\quad \cos^2\alpha \cdot \cos^2\beta \cdot \cos\gamma \quad l \cdot \sin\alpha \cdot \cos\alpha \cdot \cos\beta \cdot \\ &\quad \sin\gamma - l \sin\alpha \cos\alpha \sin\beta \cos\gamma] \end{aligned} \quad (8)$$

$$\mathfrak{S}_5 = [\mathfrak{S}_5^1; \mathfrak{S}_5^0] \quad (9)$$

Therefore, the screw system of leg A₁H₁B₁ is given as:

$$\mathfrak{S}_{A_1H_1B_1} = \begin{bmatrix} \mathfrak{S}_1 \\ \mathfrak{S}_2 \\ \mathfrak{S}_3 \\ \mathfrak{S}_4 \\ \mathfrak{S}_5 \end{bmatrix} \quad (10)$$

Thus the anti-screw system of leg A₁H₁B₁ has 1 DOF which is denoted by:

$$\mathfrak{S}_{A_1H_1B}^1 = [L \ M \ N \ P \ Q \ R] \quad (11)$$

where, P = 0, Q = 0. L, M, N can be expressed by R.

In the same manner, each of the leg has one constraint motion, the degrees of freedom of the moving plate is no more than 6. The result does not match with actual situation. While the anti-screw system of leg A₁H₁B₁ has a rotational motion along the line of A₁B₁ when R = 0. It supposes that coupling exists in legs moving, the constraint of leg is released. Thus the moving plate has three translational motions and three rotational motions. Therefore, the coupling exists in each leg indeed.

COUPLING COMPENSATION

There are two frames describing the motion of the moving plate: an inertia frame (X_a, Y_a, Z_a) located at the center of the base plate and a body frame (X_b, Y_b, Z_b) located at the center of the moving plate with Z_b-axis pointing outward (Fig. 1). The length vector of the *i*th leg is calculated as:

$$L_i^A = B_i^A - A_i^A, \quad i = 1, \dots, 5 \quad (12)$$

where, A_i^A is the position of the lower joint A_i in the inertia frame, B_i^A is the position of the upper joint B_i in the inertia frame.



Fig. 3: One Leg of the 6-DOF parallel robot

$$B_1^A = {}^A T_B \cdot B_1^B \quad (13)$$

where, ${}^A T_B$ is the transformation matrix from the body frame (X_b, Y_b, Z_b) to the inertia frame (X_a, Y_a, Z_a) , B_1^B is the position of the upper joint B_1 in the plate body frame.

The leg can rotate around the axis of gimbal, while the upper part of the leg is sliding inside the lower part by an actuating force. This motion is considered by two frames: a leg fixed frame (X_{mi}, Y_{mi}, Z_{mi}) located at the joint A_i with the Z_{mi} -axis parallel to the length vector of leg and X_{mi} -axis parallel to the rotational axis of lower gimbal in outward, the leg body frame (X_{mi}, Y_{mi}, Z_{mi}) located at the same point with X_{mi} -axis parallel to the rotational axis of upper gimbal as shown in Fig. 3.

$$Z_{mi} = \frac{L_i^A}{|L_i^A|} \quad (14)$$

$$X_{mi} = \frac{Z_{mi} \times G_{mi}^A}{|Z_{mi} \times G_{mi}^A|} \quad (15)$$

where, G_{mi}^A is the installation vector of the upper gimbal in the inertia frame, $G_{mi}^A = {}^A T_B G_{mi}^B$, G_{mi}^B is the installation vector of the upper gimbal in the plate body frame.

$$Z_{mi} = Z_{mi} \quad (16)$$

$$X_{mi} = \frac{Z_{mi} \times G_{mi}^A}{|Z_{mi} \times G_{mi}^A|} \quad (17)$$

where, G_{mi}^A is the installation vector of the lower gimbal in the inertia frame.

There are 2 DOF between the leg fixed frame (X_{mi}, Y_{mi}, Z_{mi}) and the leg body frame (X_{mi}, Y_{mi}, Z_{mi}) : one

translational motion along Z_{mi} -axis and one rotational motion around Z_{mi} -axis. The coupling angle ψ_i is then calculated as:

$$|\psi_i| = \arccos \frac{X_{mi} \cdot X_{mi}}{|X_{mi}| |X_{mi}|} \quad (18)$$

where, ψ_i is positive number when $X_{mi} \times X_{mi}$ have the same direction with L_i^A , otherwise ψ_i is negative number.

The angular velocity ω_s of coupling is given as:

$$\begin{aligned} \omega_s &= \dot{\psi}_i \\ &= \frac{M}{|X_{mi}| |X_{mi}| \sqrt{1 + \left(\frac{X_{mi} \cdot X_{mi}}{|X_{mi}| |X_{mi}|} \right)^2}} \end{aligned} \quad (19)$$

where,

$$M = \frac{\left(\frac{v_{bi}^A}{|L_i^A|} \times G_{mi}^A + Z_{mi} \times J G_{mi}^B \right) X_{mi} \cdot \frac{X_{mi}}{|L_i^A|} (v_{bi} \times G_{mi}^A)}{|Z_{mi} \times G_{mi}^A|} + \frac{X_{mi}}{|Z_{mi} \times G_{mi}^A|}$$

J is the Jacobian matrix of the general velocity of the moving plate to the velocity of the upper attachment points.

The difference of the i th leg between practice and theory Δ_i is computed as:

$$\Delta_i = \frac{\psi_i}{2\pi} \cdot Da \quad (20)$$

where, Da is the screw-pitch.

Therefore, the practical length of the i th L_i is given as:

$$L_{ii} = l_i + (\Delta_i - \Delta_{pi}) \quad (21)$$

where, Δ_{pi} is the difference of the i th leg between practice and theory in the previous moving plate position.

RESULTS

Model simulation is a simple and effective to verify proposed method or system that many researchers used (Aqel, 2006; Eker *et al.*, 2002). This study takes Tank Simulator which base on 6-DOF parallel robot as the simulation model. Each leg of the 6-DOF parallel robot has an upper part sliding inside a lower part to imitate the physical feeling of driving a Tank for the three translational motions (surge, sway and heave) and the three rotational motions (pitch, roll and yaw). Coupling compensation has been used in order to guarantee

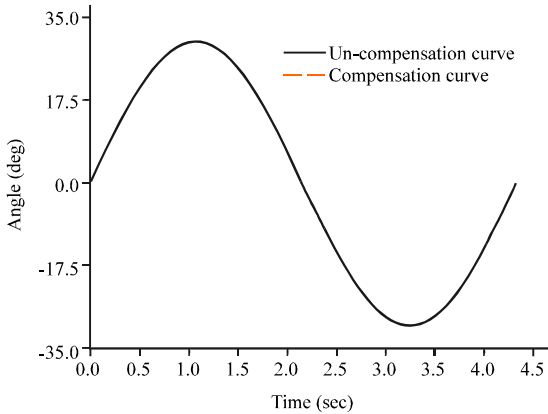


Fig. 4: Rotational angle on Z-axis

Table 1: Parameters of the tank simulator

Symbol	Description	Value
Rb (m)	Radius of the movable plate	0.4
Ra (m)	Radius of base plate	0.8
β (°)	Joint angles of upper plate	[40, 80, 160, 200, 280, 320]
α (°)	Joint angles of base plate	[20, 100, 140, 220, 260, 340]
H (m)	Center height of Tank Simulator	1.4
m (t)	Payload of Tank Simulator	2

against numerical problems in the solution process. All parameters of the 6-DOF parallel robot configuration and the initial conditions, which are kept invariable during the simulation, refer to Table 1.

It investigates two controlling curves (the compensation controlling curves and the un-compensation controlling curves) to test the precision of the coupling compensation. Taking the actuator velocity which makes the moving plate of rotated around Z_a-axis to make the sinusoidal motion which amplitude is 30° as the input of 6-DOF parallel robot model, this study analyzes performance of Tank Simulator. Without the coupling compensation, 6-DOF parallel robot generates an extra moving on the direction of Z-axis. Rotated angle with coupling compensation and without coupling compensation of Z-axis is shown in Fig. 4. Besides, Fig. 5 and Fig. 6 show the translational velocity and acceleration on Z-axis.

From the experiment results, it is obvious that the motion on command direction according to preconceived track with accurate amplitude and period, but the 6-DOF parallel robot generate an extra moving along with Z-axis which can causes vibration of Tank Simulator that can not neglect. All coordinate values, especially the Z coordinate value, decreased dramatically after the coupling compensation of 6-DOF parallel robot. The variation of moving velocity on Z-axis after the compensation was tends to zero; acceleration has decreased from 225 mm sec⁻² to almost zero. In the same

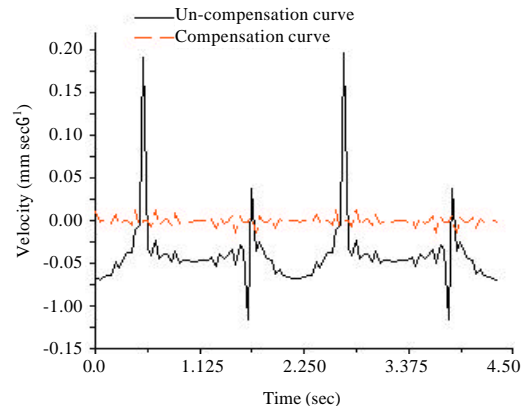


Fig. 5: Moving speed of Z-axis

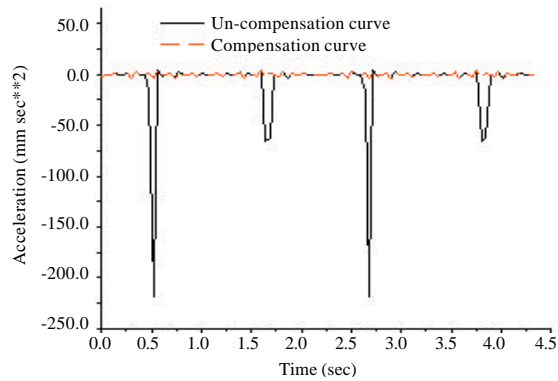


Fig. 6: Moving acceleration of Z-axis

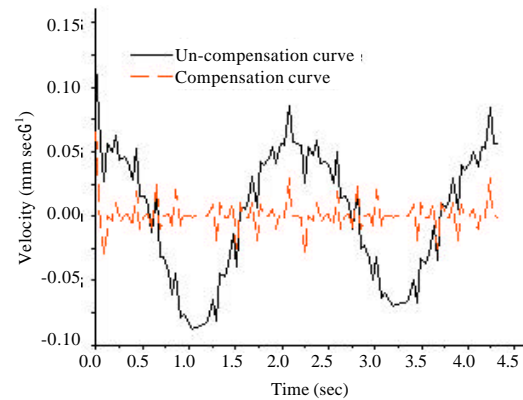


Fig. 7: Movement distance on X-axis

manner, taking the rotation of X-axis or Y-axis as the research process, the translational error on X-axis or Y-axis decreased dramatically. Movement distance on X-axis and Y-axis are shown as Fig. 7 and Fig. 8. After considering the coupling compensation of the controller,

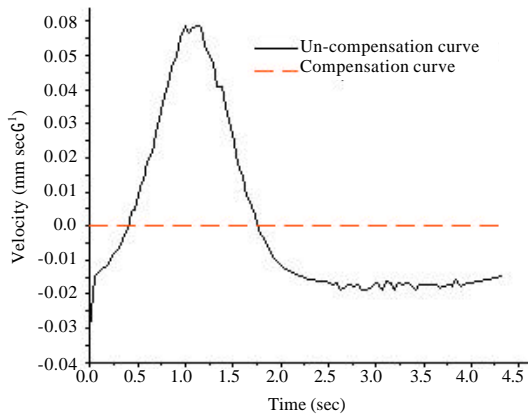


Fig. 8: Movement distance on Y-axis

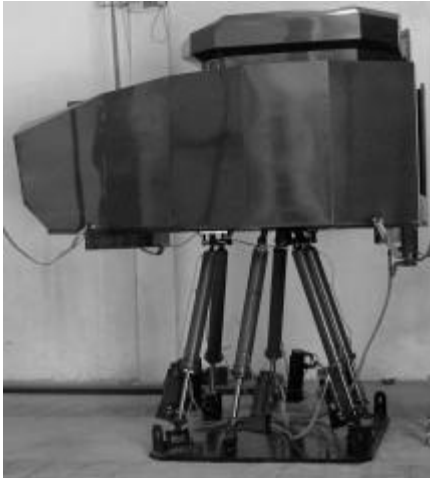


Fig. 9: Photo of Tank Simulator test prototype

the vibration of Tank Simulator (Fig. 9) has decreased and the stability has improved. Therefore the lifetime of the Tank Simulator can be prolonged.

CONCLUSIONS

In this study, the motion of 6-DOF parallel robot is studied base on screw theory. The following conclusions can be drawn:

- Due to analysis of the legs of 6-DOF parallel robot model, there exists coupling between the six degrees of freedom. In this study, it builds the coupling velocity and acceleration. Besides, the coupling compensation is proposed to optimize the moving track

- Mechanism-model combined motion method which is presented in this study considers the influence of the motion controller and actuator that can improves the reliability and authenticity of 6-DOF parallel robot
- Experimental results show that the precision can be increased by the coupling compensation. It eliminates jitter in the motion that can prolong life of Tank Simulator

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