

Research Article

Force/Position Hybrid Control of 6PUS-UPU Redundant Driven Parallel Manipulator Based on 2-DOF Internal Model Control

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To improve control performance of parallel manipulator, servo control is optimized according to 2-DOF control with Internal Model Control. Position loop of the controller is redesigned based on the original current loop and speed loop. The hybrid force/position control strategy on the basis of cross-coupling is proposed. With mechatronic cosimulation system, it is proved that the force/position hybrid control on the basis of 2-DOF Internal Model Control has better stability and position precision compared with the traditional PID control. The control precision and stability of the parallel manipulator are improved effectively in actual experiment. Two types of compliance operation including peg in hole and surface tracking are realized in 6PUS-UPU parallel manipulator and both have good applicable effect.

1. Introduction

Parallel manipulator is becoming increasingly popular in a large number of applications. It is a complex system with characteristics of multidegree of freedom, multi-input multioutput, high nonlinearity and strong coupling, and so forth. Control of parallel manipulator is very complex and researches mostly focus on kinematic and dynamic control. Dynamic control can meet the demands of high performance more than kinematic control. Dynamic feed forward control and computed torque control are common dynamic control methods [1–3]. Müller and Hufnagel [4] proposed the adaptive and singularity-free inverse dynamics models for control of parallel manipulators, Achim and Matthias [5] used the dynamics model as a feed forward on a handheld parallel mechanism to reduce the disturbance, and Farhadmanesh and Rastin [6] designed a new fuzzy model-based controller for complex dynamical systems with application to a 3-RRR spherical parallel manipulator.

Classic PID controller is widely used in various kinds of industrial fields for its simple structure and strong robustness. However, classic PID controller cannot meet the different performance requirements simultaneously. 2-DOF control

and Internal Model Control are introduced to improve the performance of parallel manipulator [7–10].

First, the servo control strategy of 6PUS-UPU parallel manipulator is analyzed. The PID control is combined with 2-DOF and Internal Model Control to redesign servo control loops of the parallel manipulator. Next the hybrid force/position control of parallel manipulator is proposed. Then the entire model of the 6PUS-UPU parallel manipulator is established, and the mechatronic cosimulation is carried out. Finally the control method is verified by actual prototype experiment.

2. Control Strategy of 6PUS-UPU Parallel Manipulator

On the basis of the original current loop and velocity loop, the position loop is redesigned to improve control precision and stability of the parallel manipulator.

2.1. Overview of 6PUS-UPU Parallel Manipulator. A novel 6-PUS/UPU parallel manipulator is shown in Figure 1, including the fixed platform, the moving platform, and connected

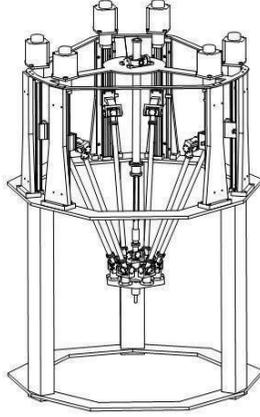


FIGURE 1: 6PUS-UPU parallel manipulator.

branches. The fixed platform and the moving platform are connected with six PUS (prismatic pair-universal pair-sphere pair) actuated branches and a passive UPU (universal joint-prismatic pair-universal joint) middle branch. Because one degree of freedom is constrained by the UPU branch, the moving platform only can achieve five degrees of freedom. The parallel manipulator is driven redundantly for its six actuated branches.

2.2. 2-DOF PID Control Based on IMC. For modern control systems, it is hoped to have good position tracking characteristics and good antidisturbance capacity simultaneously. Traditional control methods such as PID control belong to one degree of freedom control and only have one adjustable parameter. The control systems with one adjustable parameter are difficult to meet the requirement of good position tracking characteristics and good antidisturbance capacity. 2-DOF control is designed to solve the problem and two separate parameters are adjusted to have the two above-mentioned performances.

The servo control system of 6PUS-UPU parallel manipulator is composed of position loop, velocity loop, and current loop.

(1) Current loop is the innermost loop in the servo system. Current loop consists of the current controller, SPWM, filters, and other components. Proportional and integral controls are used in current controller to have the fastest response among the three loops. The transfer function of current controller is expressed as

$$G_i(s) = \frac{K_i(T_i s + 1)}{T_i s}, \quad (1)$$

where K_i is the proportional gain factor and $T_i = L/R$ is the integral gain factor.

The control objects of current loop are inverter and armature circuit. The inverter is a conversion circuit from DC to AC. In PMSM control system, SPWM voltage inverter

is used and considered as a first-order damp element. The transfer function of inverter is expressed as

$$G_{\text{inv}}(s) = \frac{K_n}{T_n s + 1}, \quad (2)$$

where K_n is control gain factor and T_n is time constant.

The armature circuit is considered as R - L model and its transfer function is expressed as

$$G_{rl}(s) = \frac{1}{R + Ls}, \quad (3)$$

where R is armature resistance and L is armature inductance.

In order to remove the noisy signal, a feedback filter is designed as a first-order damp element. The transfer function of the feedback filter is expressed as

$$G_{cf}(s) = \frac{K_{cf}}{T_{cf} s + 1}, \quad (4)$$

where K_{cf} is gain factor and T_{cf} is time constant.

The signal filter is designed to offset the delay caused by the feedback signal. Its transfer function is a first-order damp element and the transfer function is expressed as

$$G_{xi}(s) = \frac{1}{T_{cf} s + 1}. \quad (5)$$

In current loop, I_r is input current and I_m is output current.

(2) Velocity loop is used to improve the antidisturbance capacity by reducing error between output velocity and given velocity. PI control is used and its transfer function is expressed as

$$G_v(s) = \frac{K_v(T_v s + 1)}{T_v s}, \quad (6)$$

where K_v is proportional gain factor and T_v is integral gain factor.

Feedback filter is also needed in velocity loop and its transfer function is expressed as

$$G_w(s) = \frac{K_w}{T_w s + 1}, \quad (7)$$

where K_w is gain factor and T_w is time constant.

The signal filter is also added to offset the delay and its transfer function is expressed as

$$G_{xv}(s) = \frac{1}{T_w s + 1}. \quad (8)$$

In velocity loop, K_t is torque constant of the motor, J is inertia of the motor, T_e is torque of the motor, T_L is torque of the load, ω_r is input angular velocity, and ω_m is output angular velocity.

(3) Position loop is the outermost loop and is redesigned based on current loop and velocity loop. The block diagram of three servo loops is shown in Figure 2. In position loop, θ' is

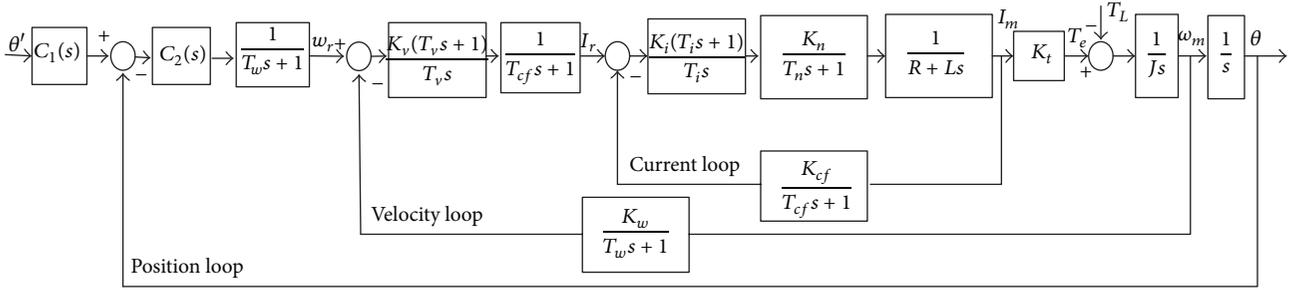


FIGURE 2: Block diagram of three control loops.

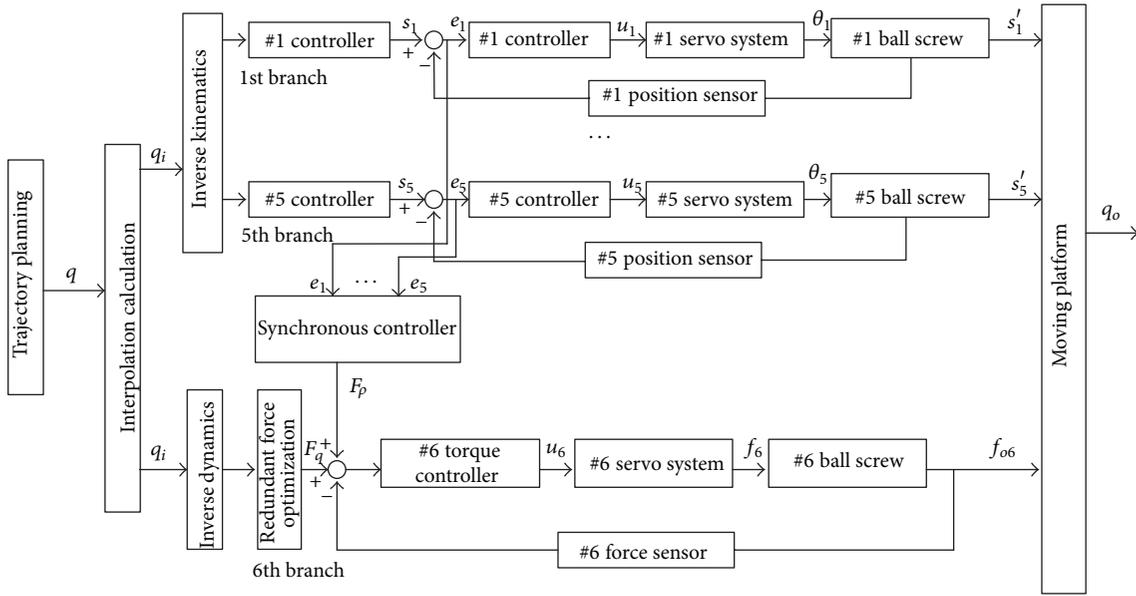


FIGURE 3: Force/position hybrid control.

input angle and θ is output angle; $C_1(s)$ and $C_2(s)$ are 2-DOF IMC controllers, respectively.

The mathematical models of $C_1(s)$ and $C_2(s)$ are expressed as

$$C_1(s) = \frac{3\lambda_1 s + 1}{3\lambda_2 s + 1}, \quad (9)$$

$$C_2(s) = \frac{(3\lambda_2 s + 1)(T_0 s + 1)}{3\lambda_2^2 s ((\lambda_2/3) s + 1)},$$

where λ_1, λ_2 are control parameters and T_0 is time constant.

2.3. Force/Position Hybrid Control Strategy. The force/position hybrid control of 6PUS-UPU parallel manipulator is proposed as shown in Figure 3. For five nonredundant branches, position control modes are used, and for the redundant branch force control mode is used.

The cross-coupling relationship between driving axes should be taken into consideration. The coupling position errors of five nonredundant branches from the 1st to the 5th branch in joint space are fed back to the 6th redundant driven branch. The coupling position errors are converted to the

force signal to make compensation in synchronous controller. So the position precision and torque balance of the parallel manipulator will be improved simultaneously.

It is assumed that the theoretical position of branch i is $s_i(t)$ and the actual position is $s'_i(t)$ at the time t . Then, the position error of the branch at the time t is as follows:

$$e_i(t) = s_i(t) - s'_i(t) \quad i = 1 \sim 5. \quad (10)$$

Only when the error of each branch is close to zero would the synchronous control be realized. Its variables $\xi_i(t)$ ($i = 1 \sim 10$) are defined as

$$\xi_i(t) = e_n(t) - e_m(t) \quad n = 1 \sim 4, m = (n + 1) \sim 5. \quad (11)$$

According to the minimum norm theory, the error of synchronous control is defined as

$$\rho(t) = \int_0^t \sqrt{\frac{1}{10} \sum_{i=1}^{10} \xi_i(w) dw}. \quad (12)$$

The driving force F_6 can be divided into two parts for the redundant driven branch. One is the driving force from

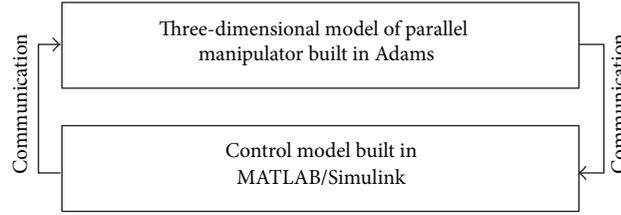


FIGURE 4: Structure of Adams and MATLAB cosimulation.

the optimized inverse redundant torque F_q and the other is the driving force from the compensation of synchronous control error F_ρ . The total driving force is defined as

$$F_6 = F_q + F_\rho. \quad (13)$$

By means of computing torque method, the relationship between the redundant driving force and the coupling errors can be expressed as

$$F_\rho = m_6 \rho''(t) + c_6 \rho'(t) + g \rho(t), \quad (14)$$

where m_6 , c_6 , and g are mass, coefficient of Coriolis force, and gravitational acceleration of the 6th branch; $\rho'(t)$ and $\rho''(t)$ are velocity error and acceleration error of synchronous control.

Eventually, the hybrid control with position and force is realized effectively.

3. Mechatronic Cosimulation

3.1. Cosimulation Principle. The 3D model of the parallel manipulator is established in Adams and the control model of the parallel manipulator is established in Simulink module of MATLAB. The mechanical model is combined with the control system of the parallel manipulator to realize mechatronic cosimulation.

The cosimulation diagram between Adams and MATLAB is shown in Figure 4.

The major step is shown in Figure 5.

3.2. Examples of Cosimulation. As shown in Figure 6, 3D model of the parallel manipulator is established in Adams. MOTION_1 to MOTION_5 are added as position driver of five nonredundant branches and FORCE is added as force driver of the redundant branch.

The control models of nonredundant branches and the redundant branch are established in Simulink module of MATLAB. Position control is adopted in five nonredundant branches and force control is used in the redundant branch. The parameters in relevant transfer function mentioned above are listed in Table 1.

The given trajectory is a major arc of 200 mm radius in cosimulation. The output response of the moving platform is shown in Figure 7.

In Figure 7, the output of the moving platform with 2-DOF IMC is closer to the theoretical value than the traditional control and the accuracy of tracking position is improved effectively.

TABLE 1: Parameters list.

Parameter	Data
λ_1	0.018
λ_2	0.15
T_0	0.01475 s
J	0.000188 kg·m ²
K_v	0.015
T_v	5 s
K_w	1
T_w	0.01 s
K_i	1
T_i	0.00208 s
K_{cf}	1
T_{cf}	0.00016 s
K_n	4.43
T_n	0.0001 s
R	1.3 Ω
L	0.0027 H

4. Experiment and Application

The self-developed prototype of 6PUS-UPU parallel manipulator is shown in Figure 8.

In the experiment, the trajectory is from the starting point (0, 0, 0), through the point (-100, -100, 0), to the final point (100, 100, 0).

The two experiments were done in PID control mode and hybrid synchronous control mode, respectively. The actual trajectories of the moving platform are measured by the laser interferometer. By comparing the data, the errors of the hybrid control can be reduced by about 15% compared to PID control mode.

As shown in Table 2, the output torque peak in two control modes of five nonredundant branches is recorded by oscilloscope. The torque peak of the hybrid synchronous control can be reduced by about 10% compared with PID control mode and the output torques are balanced.

Based on this, two types of actual compliance operation are realized in 6PUS-UPU parallel manipulator. As shown in Figure 9, peg in hole (a) and surface tracking (b) both have good effects.

5. Conclusion

The control method combining 2-DOF control and Internal Model Control was optimized. On the basis of current loop

TABLE 2: Output torque peak table (rounded, unit: Nm).

Control mode	Branch one	Branch two	Branch three	Branch four	Branch five
PID control	485	2830	3891	3590	1381
Synchronous control	440	2516	3463	3265	1207

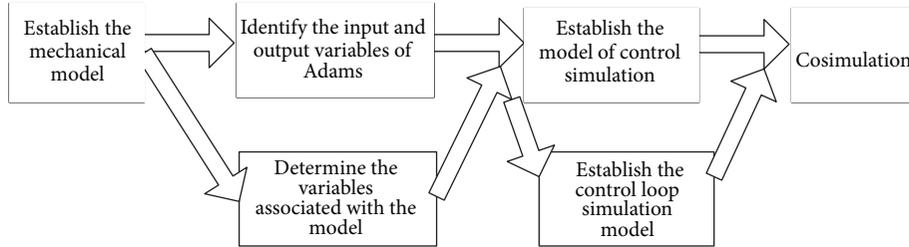


FIGURE 5: Flowchart of cosimulation.

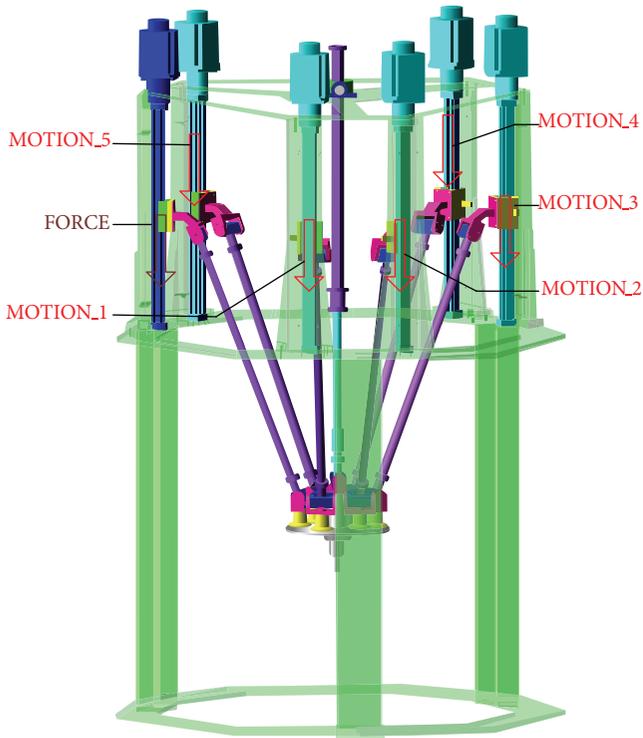


FIGURE 6: 3D model in Adams.

and velocity loop, position loop was redesigned to improve stability and position precision simultaneously. Based on cross-coupling, the force/position hybrid control of parallel manipulator is realized. Mechatronic cosimulation and the experiment of 6PUS-UPU parallel manipulator were carried out and both high stability and good position precision are verified. It is effective for peg in hole and surface tracking by actual operation and it should be also applicable to glass cleaning, egg grasping, component assembly, space docking, and so forth.

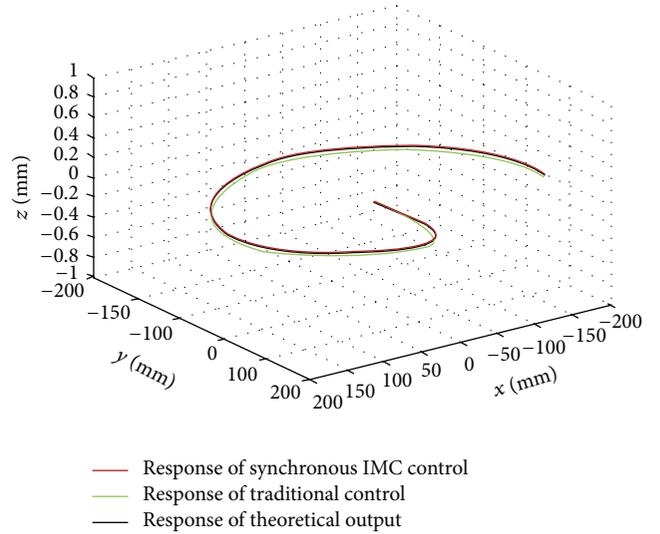
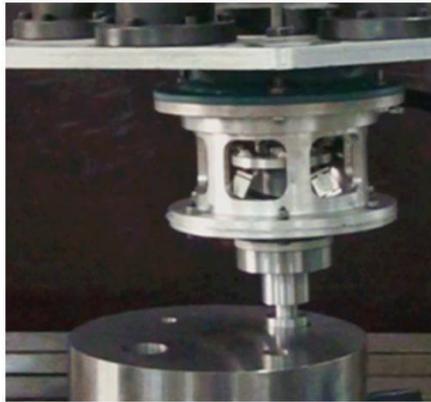


FIGURE 7: 3D comparison chart of output response.



FIGURE 8: The prototype of 6PUS-UPU parallel manipulator.



(a) Peg in hole



(b) Surface tracking

FIGURE 9: Application of 6PUS-UPU parallel manipulator.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

Acknowledgments

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