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The study of model predictive control algorithm based on the force/position control scheme of the 5-DOF redundant actuation parallel robot

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HIGHLIGHTS

- Parallel robot is designed by force/position hybrid control structure.
- The model predictive control algorithm is applied to the parallel robot control.
- The algorithm can significantly improve the robustness of the robot.
- The influence of robot model mismatch and the uncertain disturbance is suppressed.

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ABSTRACT

Redundant actuated parallel robot is a multi-input and multi-output (MIMO) system which usually works in an uncertain environment. In this paper, the force/position hybrid control structure of 6PUS-UPU redundant actuation parallel robot is designed, and proportional–integral (PI) and model predictive control (MPC) cascade control strategies are used in the redundant branch of 6PUS-UPU redundant actuation parallel robot. The MPC algorithm is used in the current loop of the permanent magnet synchronous motor (PMSM) to restrain the motor parameter uncertainty and external disturbances influence on motor control. The MATLAB/ADAMS joint simulation method based on virtual 6PUS-UPU redundant actuation parallel robot prototype is used to test the performance of the proposed control strategy. The performance of proposed PI-MPC control strategy is compared with the traditional PI–PI control strategy. The simulation results show that the MPC controller can improve the tracking ability of the motor torque, guarantee the system robustness under the parameter variations and load disturbance environment.

1. Introduction

Parallel robot has high rigidity, high bearing capacity, high accuracy and good dynamic performance, which makes itself gradually develop into a manufacturing star in the field of numerical control processing. However, the parallel robot is an MIMO system and it works in an uncertain environment; there are many problems to be solved, such as the strong coupling of parallel robot between each branch, small work space, a large number of singular configuration, etc. These problems will result in large structure internal force, and the machine will be damaged. Redundant actuation as an effective solution is introduced. Redundancy in the parallel robot is divided into the movement redundancy and actuation redundancy [1–3], Movement redundancy means to add extra joints to increase the freedom of movement [4], while actuation redundant just increases the number of joints and cannot influence the degree of freedom of the machine. Comparing with the ordinary parallel robot, the parallel robot with redundant

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actuation can optimize the load distribution between the actuators, reduce the energy consumption of each independent actuator, avoid driving force mutation, and improve force transmission properties of homogeneity and the rigidity of the agency (active stiffness). Thus the parallel robot with redundant actuation can obtain a better dynamic performance, higher stiffness and greater carrying capacity [5,6]. In recent years, the redundant actuation parallel robot has widely been studied by many researchers. The authors of the work in [1–3] proposed the main functions of the redundant actuation to optimize some performance indexes, such as power, energy consumption and the internal forces. The authors of the work in [7–9] developed a method of the redundant actuation which can improve the dynamic performance. The author of the work in [10] proposed a novel 6PUS-UPU redundant actuation parallel robot. The author of the work in [11] proposed two methods to improve the position and force interaction control accuracy. The first approach is a position-based sliding mode impedance control which converts the target impedance into a desired position trajectory to be tracked, and the second one is established on the basis of a proportional–integral type of sliding function of the impedance measure error. The author of the work in [12] proposed a method in which both contact forces exerted by the manipulator and the position of the end-effector in contact with the surface are controlled.

The current loop control method of PMSM mainly uses PI regulator, hysteretic control, sliding mode variable structure control, etc. PI controller is a linear controller and the proportional gain can improve the dynamic performance of system. However, excessive gain will result in noise, overshoot and oscillation, which has a negative influence on the stability of system. It is very difficult to trade off between the rapid response and stability in practical applications. Hysteretic control offers quick responses, but this kind of control mode usually leads to large ripple of response. The switching frequency is not fixed and it is not suitable for high performance control cases. Sliding mode variable structure control method demonstrates a "chattering" problem [13–15]. The authors of the work in [16] introduced the differential feedback control into the PMSM servo system. The system offers a quick response speed and obviously suppresses well the overshoot. The authors of the work in [17] also did a similar research, but to some extent, the introduction of differential item could affect the system stability. The authors of the work in [18] used the feedforward method to compensate the cross coupling of the stator voltage, which fully realized the decoupling of the direct axis and quadrature axis (*dq* axis) in order to improve the current dynamic performance. The authors of the work in [19] developed the method of the voltage feedforward decoupling control of the current loop. The control performance of this method is influenced by the accuracy of the motor parameters and has poor robustness. The authors of the work in [20] developed a new predictive current control (PCC) for the PMSM drivers. The proposed control method obtains the same rapid torque dynamics as direct torque control (DTC) schemes, but it has smaller magnitude of ripples. The authors of the work in [21] developed a robust proportional–integral–derivative (PID) control scheme for the PMSM by using a genetic searching approach.

In actual application, because of the influence of the temperature and other uncertain factors, some parameters of the system model can be changed and result in the model mismatch, which bring huge influence on the control performance of the whole system. The above control methods could not deal with it. So we propose a model predictive control algorithm in this paper.

MPC was proposed in the 1970s, which has been the most widely used multivariable control algorithm in the chemical process industries and other research areas. MPC is suitable for many kinds of problems, and demonstrates the advantages especially when dealing with the problems subject to [22]: (1) a large number of manipulated and controlled variables, (2) constraints imposed on both the manipulated and controlled variables, (3) change control objectives and/or equipment (sensor/actuator) failure, (4) time delays. MPC uses the online rolling optimization and feedback correction strategy. The online rolling optimization strategy can compensate the uncertainty influence caused by model mismatch and interference so as to improve the control effect of the system [23–25]. After a series of future control variables are determined by the optimization, MPC uses the detected error between actual output and the model prediction output to realize feedback correction to remedy the defect. So the states of the controlled plant are prevented from deviating from the ideal states because of the model mismatch or environment interference. At the next sampling time, the detected actual output modifies the MPC output. And then a new optimization is performed. This method can overcome the uncertainty of the system, improve the robustness of the system [26–28]. The authors of the work in [29] compared the Forced Machine Current Control (FMCC) with the Model Predictive Direct Torque Control (MPDTC) and Model Predictive Direct Current Control (MPDCC) for MV induction motor drives. The authors of the work in [30] developed the Model Predictive Direct Speed Control (MP-DSC), which overcomes limitations of cascaded linear controllers. The authors of the work in [31,32] developed an MPC scheme to control the speed of a PMSM drive system. The performance of the proposed controller is compared with a classical PI controller and tested by MATLAB/ADAMS simulation platform. The results show that more accurate tracking performance of the PMSM has been obtained.

For PMSM current loop control problem, we introduce the MPC algorithm to the motor control of 6PUS-UPU redundant actuation parallel robot in this paper. The algorithm can avoid the uncertain impact problems effectively, such as the motor parameters time-varying and load disturbance, and it can also track the reference input quickly without overshoot.

In this paper, PMSM space voltage vector control simulation platform is built, and MPC strategy is used in the redundant branch of 6PUS-UPU redundant actuation parallel robot. The performance of MPC controller and PI controller are compared, and the results of simulation demonstrate that MPC controller has the better robustness property than PI controller. MPC controller can improve the force tracking ability of 6PUS-UPU redundant actuation parallel robot, guarantee the robustness of 6PUS-UPU redundant actuation parallel robot under the parameter variations and load disturbance environment.

This paper is organized as follows. In Section 2, we analyze the dynamic model of the 6PUS-UPU redundant actuation parallel robot, and obtain the dynamic mode by KANE method. In Section 3, 6PUS-UPU redundant actuation parallel robot force/position hybrid control structure and control design are presented. We build the PMSM predictive control model, and the redundant branch control strategy is designed using PI–PI strategy and PI-MPC strategy respectively. In Section 4, we build the PMSM space voltage vector control simulation platform using the simulink of MATLAB. Then we perform the simulations and present the simulation results. In Section 5, a conclusion is drawn.

2. Dynamics modeling

The dynamics modeling of 6PUS-UPU redundant actuation parallel robot will be introduced in this part on the basis of the results of Refs. [10,33]. The modeling process includes velocity analysis, the angular velocity analysis, the constraints analysis and Kane equation.