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Model-free development of control systems for a multi-degree-of-freedom robot☆

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ABSTRACT

For a multi-degree-of-freedom (MDOF) robot, its dynamics model is very complex, and there are many contained terms. Moreover, with the increase of the degree-of-freedom (DOF), the number of the terms contained in the dynamics equation increases geometrically, and the dynamics equation has the characteristics of highly nonlinear and serious coupling, therefore, it is difficult to achieve the accurate and efficient control. In particular, when the uncertain factors such changes in the load, friction and disturbance are considered, the problems of control are more obvious. To deal with these problems, the two model-free intelligent control systems are designed in this paper: (1) The adaptive sliding mode control (ASMC) system; (2) the fuzzy neural network control (FNNC) system. For the ASMC, the consumed time is shorter, and the efficiency is higher, but the control accuracy is relatively poorer. However, for the FNNC, the control accuracy is relatively higher, but the consumed time is longer, and the efficiency is poorer. In order to give full play to the advantages of the two intelligent control systems, the ASMC and the FNNC are combined to form the adaptive sliding mode-fuzzy neural network control (ASM-FNNC) system, which the priority is given to the ASMC, and the error thresholds are set, when the control error exceeds the thresholds, switch to the FNNC. Finally, the proposed control scheme is applied to a six DOF robot, to verify its effectiveness.

1. Introduction

In practical situation, it is very difficult or even impossible to establish the accurate dynamics model of a MDOF robot, which is a typical nonlinear mechanical system. Moreover, the information of the external random disturbances may also not be well known, when one deals with a time-variant complex robot system [1–10]. Therefore, the control methods based on the accurate dynamics model are not advisable [11,12], and it is necessary to design a intelligent control strategy with adaptive capability and robustness, to ensure the precise and stable control.

To achieve the goals, some model-free control methods have been proposed. Depraetere et al. [13] compared the model-free control method with the model-based control method for the time optimal hit control of a badminton robot, and the advantages and disadvantages were discussed, which shows that the model-free control method is worthy to be studied. Zadeh et al. [14] presented a novel model-free approach for the optimal control of a PUMA 560 robot manipulator based on the particle swarm optimization, and demonstrated the good control effect. A model-free reinforcement learning technique was proposed by Distante et al. [15] to solve the problems of target identification and grasping, which didn't require the accurate target model. Without the detailed information of the dynamics model of a robot, Wang et al. [16] studied a model-free sliding mode control system based on the time-delay estimation, which shown the high precision, fast convergence, and good stability. The time-delay estimation technique was used again by Jin et al. [17], and a model-free robust adaptive controller without the dynamics model parameters was designed for a humanoid robot with flexible joints, its robustness and high accurate were demonstrated by experiments. And a new model-free method was investigated to assist the assisting robot's cyclical movements in [18]. Ge et al. [19] designed a decentralized model-free controller and a centralized model-free controller for a single-link flexible smart materials robot to make up the shortcomings of the model uncertainties and truncations, and suppress the residual vibration. Without the models of the actuator, body material, and the accurate information of the friction mechanisms, Vikas et al. [20] presented a novel model-free learning-based control method for a soft robot, which could easily calculate the control sequences. To provide a model-free learning controller for a complex robot system with the

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external disturbances and the modeling uncertainties, Lee and Choi [21] studied an adaptive neurocontroller. However, according to the previous studies, for the model-free control methods, the stability and robustness are the problems that need to be perfected.

Among the modern model-free control methods, many researchers have been attracted by the advantages of the sliding mode control (SMC) [22] and the fuzzy control (FC) [23].

In recent years, because of the capability to deal with uncertainties, good transient performance and fast response, more and more scholars have paid attention to the sliding mode control techniques [24,25]. However, the large chattering and high-frequency dynamics may be caused by these control methods. In order to overcome these drawbacks, some researchers took nonlinear systems with uncertain disturbances as the research objectives to study the problems of chattering and high-frequency dynamics. In [26–29], the boundary-layer methods are introduced, which need to balance between the robustness and chattering, and the priori knowledge of the disturbances and the dynamics model is required to guarantee the adaptive capability and robustness, but the priori knowledge may be difficult obtained. To make up for the deficiencies of these methods, the passivity-based control, the robust Lyapunov stability-based control, and the combination of adaptive and sliding mode control were investigate in [24,25,30–32]. Among which, to control a simple flexible robot without knowing the exact dynamics models, the passivity-based control approaches were proposed in [31,32], which the implementation was relatively easy, but these control approaches couldn't provide readily quantifiable performance measures. In addition, the robust Lyapunov stability-based control as shown in [30] could know the asymptotic behavior of the solution without solving the dynamics model, but a reasonable Lyapunov positive definite function with a negative definite time derivative must be found, and the chattering of robot couldn't always effectively suppressed. Moreover, the combination of adaptive and sliding mode control methods without knowing the bound of disturbances were presented in [24,25], however, severe problems of adaptability and robustness were shown.

Therefore, although the adaptive sliding mode controls have the advantages of high computational efficiency and quick response, the control accuracy and the vibration stability aren't so satisfactory. Especially, for the MDOF robot system with uncertain disturbances, the adaptive capability and robustness are more difficult to guarantee.

Fortunately, we find that the fuzzy system is a good tool to solve the above problems, and the reduction of chattering may be realized without sacrificing the adaptive capability and the robustness by combining the sliding mode control and the fuzzy control. In this direction, the fuzzy sliding mode control methods have been applied to some robot systems [33–37], which shown the good effect of the chattering attenuation with the adaptive capability and the robustness. And many fuzzy techniques have been applied to the model-free control in the field of robotics. To estimate and compensate the uncertainty, an adaptive fuzzy controller was designed by Fateh et al. [38,39]. Huang and Lee [40] developed a stable self-organizing fuzzy controller without the mathematical model to guarantee the accurate trajectory control of a robot. In [41], the fuzzy control strategy was used to tune the PID gains, which could improve the response speed and handle the actual constraints. In addition, because of the learning ability and adaptivity, neural network technique is suitable to solve the complex nonlinear problems, based on the advantages of neural network technique, Fei et al. [42–45] designed some adaptive sliding mode control strategies for nonlinear dynamic systems, which achieved good results. Combining the fuzzy control and neural network, Wai and Lee [9] and Wai and Chen [46] investigated a model-free intelligent control system, which could guarantee the stable trajectory control and no need the prior information. As the references [9,46] shown, the neural networks and the fuzzy inference systems don't require the mathematical models and have the ability to approximate nonlinear systems.

It can be seen from the major contribution of the existing works, the ASMC and the FNNC are undeniably two excellent model-free control methods, and have achieved some achievements in the field of simple mechanical control system. However, the ASMC and the FNNC have the obvious shortcomings respectively. For the ASMC, its control accuracy is not very high, and the chattering phenomenon is inevitable, which is disadvantage to the stable and safe operation; for the FNNC, according to the control requirement, the continuous learning process is required to adjust the connection weights, biases, membership functions and fuzzy rules, etc., which lead to the slow response and low control efficiency.

In particular, when the control objective is a MDOF robot, which the dynamics model is very complex, and there are many contained terms. Moreover, with the increase of the DOF, the number of the terms contained in the dynamics equation increases geometrically, and the dynamics equation has the characteristics of highly nonlinear and serious coupling, it is difficult to achieve the accurate and efficient control. Further, when the uncertain factors such changes in the load, friction and disturbance are considered, the problems of control are more serious, and the shortcomings of ASMC and FNNC will be more obvious, neither the ASMC nor the FNNC can complete the control task alone perfectly.

Therefore, to guarantee the accurate, stable and efficient control for a MDOF robot according to the error thresholds and the actual control requirements, it is a deserve topic to study that make the best of the advantages of the two excellent model-free control methods (the ASMC and the FNNC), and avoid the shortcomings.

In this paper, we design a intelligent control system the ASM-FNNC with the ASMC and FNNC, which enjoys the advantages of both the ASMC and FNNC, and then, through experiments, the feasibility and reliability of our study are verified.

The remainder of this paper is organized as follows: Section 2 presents the dynamics model of the typical robot system, the intelligent control systems of the ASMC and the FNNC are designed in Section 3, Section 4 analyzes the stability of the ASMC and the FNNC, Section 5 demonstrates the validity of the approach by experiments, and the conclusions and contributions of this work are drawn by Section 6.

2. Dynamics model of robot

Based on the previous studies, the generalized dynamics model of robot can be expressed as [47]

$$\boldsymbol{M}\ddot{U} + \boldsymbol{C}\dot{U} + \boldsymbol{G} + \boldsymbol{\delta} = \boldsymbol{\tau} - \tau_f \quad (1)$$

where $\boldsymbol{M}$ is the generalized mass matrix, which is symmetric positive definite; $\boldsymbol{C}$ is the generalized damping matrix, which contains the Coriolis force and centrifugal force; $\boldsymbol{G}$ is the generalized gravity; $\boldsymbol{\delta}$ is the uncertain disturbance caused by the modeling error and the external disturbance; $\boldsymbol{\tau}$ is the generalized input torque; $\ddot{\boldsymbol{U}}$ and $\dot{\boldsymbol{U}}$ are the elastic acceleration and elastic velocity; τ_f is the friction model, and

$$\tau_f = \boldsymbol{f}_{cs} + \nu\dot{\boldsymbol{U}} \quad (2)$$

where $\boldsymbol{f}_{cs} = (\boldsymbol{f}_c + (\boldsymbol{f}_s - \boldsymbol{f}_c)\exp(-|\dot{\boldsymbol{U}}/\dot{\boldsymbol{U}}_s|^{\kappa}))\mathrm{sgn}(\dot{\boldsymbol{U}})$, $\boldsymbol{f}_c$ is the coulomb friction moment, $\boldsymbol{f}_s$ is the static friction moment, $\dot{\boldsymbol{U}}_s$ is the Stribeck velocity, κ is the empirical parameter, ν is the viscous friction coefficient.

The dynamics model of robot have the following properties:

Property 1. $\boldsymbol{M}$ is bounded, and

$$0 < \lambda_{\min}(\boldsymbol{M}) \le \|\boldsymbol{M}\| \le \lambda_{\max}(\boldsymbol{M}) \quad (3)$$

where $\lambda_{\min}(\boldsymbol{M})$ and $\lambda_{\max}(\boldsymbol{M})$ are the minimum eigenvalue and the maximum eigenvalue of $\boldsymbol{M}$.

Property 2. $\boldsymbol{C}(\boldsymbol{U},\ \xi)\upsilon = \boldsymbol{C}(\boldsymbol{U},\ \upsilon)\xi,\ \forall\ \boldsymbol{U},\ \xi,\ \upsilon \in \boldsymbol{R}^n$

$$0 < C_{\min}\ \|\dot{\boldsymbol{U}}\|^2 \le \|\boldsymbol{C}\dot{U}\| \le C_{\max}\ \|\dot{\boldsymbol{U}}\|^2,\ \forall\ \boldsymbol{U},\ \dot{\boldsymbol{U}} \in \boldsymbol{R}^n \quad (4)$$

where $C_{\min}$ and $C_{\max}$ are the positive constants.