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A double-loop structure in the adaptive generalized predictive control algorithm for control of robot end-point contact force

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ABSTRACT

Robot force control is an essential issue in robotic intelligence. There is much high uncertainty when robot end-effector contacts with the environment. Because of the environment stiffness effects on the system of the robot end-effector contact with environment, the adaptive generalized predictive control algorithm based on quantitative feedback theory is designed for robot end-point contact force system. The controller of the internal loop is designed on the foundation of QFT to control the uncertainty of the system. An adaptive GPC algorithm is used to design external loop controller to improve the performance and the robustness of the system. Two closed loops used in the design approach realize the system's performance and improve the robustness. The simulation results show that the algorithm of the robot end-effector contacting force control system is effective.

1. Introduction

Robot force control is an important topic in the area of robotic intelligent study. The research has great significance to enlarge robot application in industry [1,2]. The contact force control of the robot end-effector is a difficult problem at the area of robot force control. It has been a hot spot research in industrial control process. For robot, the end-effector is often required to make contact with environment. It will produce contact force when robot works in contact with task environment (such as spot welding, polishing or deburring) [3]. Force control is an important issue in order to guarantee certain process requisites and the quality of the final product [4–7]. This fact leads to the desire of controlling the interaction between the robot and the environment. Those contact forces should be properly controlled depending on the stiffness of the working objects and surfaces [8,9].

There are many high uncertainties when robot end-effector contacts with environment. It is important how the robot copes with dynamic uncertainties. Several force control laws were proposed to deal with the dynamics uncertainties [10–12]. However, most of these controllers have assumed that the model of the robot is exactly known. Recently, several approximate Jacobian controllers have been proposed to overcome the uncertainties. The proposed controllers do not require the exact knowledge of the robot model. However, Cheah found that the results are focusing on free motion control of robot where the robot end-effector is not in contact with the environment [13–15]. In order to expand the feasible applications of robots, several position and force controllers using approximate Jacobian have been proposed to overcome the uncertainties. These controllers do not need the exact knowledge of the robot model, but the results are limited to set point control or point-to-point control of robot manipulators [16,17].

An efficient solution to tackle this problem is to use a model based control scheme like predictive control. A model predictive control (MPC) algorithm in a force control scheme has been proposed [18]. The generalized predictive control (GPC) algorithm is easy to implement and robust with respect to modeling errors, uncertainties, and sensor noise. The GPC algorithm has been successfully used in many applications, e.g. non-minimum phase systems, open-loop unstable systems, and systems with variable or unknown dead time. In addition, the GPC algorithm can not only improve the convergence performance, but also reduce the computational complexity.

The actual design should take into consideration both the uncertainty of control equipment in productive process and control effect. There is a kind of engineering design theory that can quantitatively estimate the cost of feedback and take into account the phase information, that is the quantitative feedback theory (QFT), which is proposed by Horowitz and Sidi [19]. QFT was proposed for lumped systems in the early 1970s but its structure allows for various extensions, including the distributed systems. QFT is the robust controller design control theory based on the frequency domain response which allows the direct design

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to closed-loop robust performance and stability specifications. Amiri-M [20] found that the proposed technique was successfully applied to overcome the obstacles of non-linear robust control about SCARA (Selective Compliance Assembly Robot Arm) robots. The robot system modeling can produce a lot of uncertainty because of the limitation of structure knowledge, and the uncertainty will cause bad influence on the system performance. Quantitative feedback theory (QFT) and generalized predictive control (GPC) are two practical and effective control method to the uncertain system and have been widely used. So in consideration of the environmental rigidity of the system under the influence of model, GPC based on QFT is applied to the robot end-effector contact force control system. As a result, the majority of the proposed control schemes for robot contact tasks require exact knowledge about the kinematics in order to get good performance. This paper presents the control structure which not only eliminates the negative influence of the torque feedback and anti-jamming performances, but also resolves the robust design problem caused by uncertainty of model parameters effectively.

This paper is further organized as follows. Section 2 describes the mathematical model of the contact force with complicated surfaces. Section 3 presents the control approach that a generalized predictive control algorithm based on quantitative feedback theory design for robot end-point contact force system. Section 4 describes the results obtained with the different controller. It presents a brief discussion on the performance of the controller. Section 5 concludes the work with some remarks on the efficiency of the proposed controller.

2. System model

Robots are no longer confined to the structured factory environments but work on well-designed automation tasks. They are now expected to function, particularly in a largely autonomous manner, in unstructured, dynamic and uncertain environments. With the rapid development of robot, the structure and performance of the robot end-effector are various. When the robot end-effector contacts with the environment, the dynamic characteristics of force generation are related to the environmental stiffness, the dynamic characteristics of the robot end-effector and the transducer. In order to explain the end-effector work process more clearly, Fig. 1 gives the model of the end-effector control system. Driving mechanism, that is actuator, controls end-effector up and down, left and right sides to achieve the given control task. The force of the end-effector processing is fed back through the force sensor during the movement. The force error is obtained by comparing the force with the desired value, i.e. the accurate value. According to the force error, the designed controller conveys the regulative controlled variable to the actuator, and then carries out its tracking expected force value. The stiffness of external environment which the robot end-effector contacts with can be simplified as a stiffness coefficient k_e, and the relative damping is denoted by C in the mechanism (see Fig. 1). We only think about the force control toward one dimensional positive direction, as shown x direction in Fig. 1. So it only needs to get the transfer function of end-effector in this direction. According to [24], the end-effector in all directions can be decoupled into different second order transfer function forms as in Eq. (1).

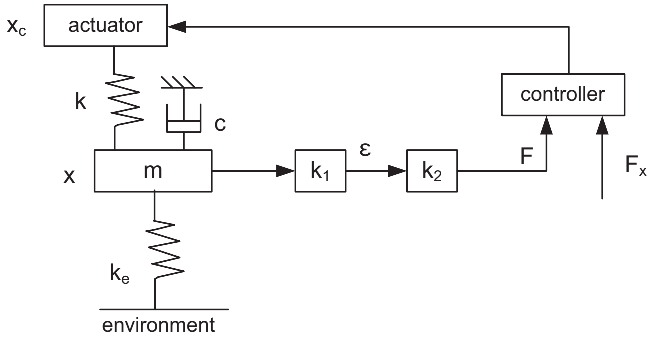

Fig. 1. The structural diagram of the contact force system.

$$G(s)=\frac{\Delta x(s)}{\Delta x_c(s)}=\frac{k}{ms^2+cs+k}=\frac{d}{s^2+as+d} \tag{1}$$

where $d=k/m$, $a=(c/m)m$, c and k are the equivalent mass, equivalent damping and equivalent stiffness of the robot end-effector respectively. $\Delta x_c(s)$ and $\Delta x(s)$ are the change of displacement. When the robot performs position control in the movement space, the robot shows nonlinear dynamic characteristics. And when the robot is in contact with the external environment, the change of movement in the contact direction should be slow, ignoring the nonlinear dynamic characteristics of the system caused by F and making $G(s)$ denote the characteristics of contacting with the outside world.

For analyzing the robot end-effector contact force system, it needs to study the end-effector equivalent stiffness k, the equivalent mass m and equivalent damping c. With the robot end-effector equivalent stiffness k, we can get

$$k=\frac{F}{x} \tag{2}$$

where F is the subjected force of the actuator, x is the strain processed by the actuator because of the stiffness restrictions.

$$x=\frac{Fl^3}{3EI},\ k=\frac{3EI}{l^3} \tag{3}$$

where E is the elastic modulus of the robot end-effector, I is the moment of inertia of cross section on the rotation shaft, l is the length of the end-effector. In order to obtain the equivalent quality m of the end-effector, we need to solve the inherent frequency ω_n of the end-effector. Thus, m is

$$m=\frac{k}{\omega_n^2} \tag{4}$$

If the end-effector is regarded as a Bernoulli–Euler beam, the approximate inherent frequency ω_n is obtained according to the energy principle of the vibration system. The implementation of the method can result in the uncertainty of the model parameter, which needs to set its scope because of the specific circumstances. According to the characteristics of Bernoulli–Euler beam, we can get the equation of the kinetic energy T of the end-effector and the equation of elastic potential energy V.

$$T=\frac{1}{2}\int_0^l \rho A\left(\frac{\partial w}{\partial t}\right)^2 dx \tag{5}$$

$$V=\frac{1}{2}\int_0^l EI\left(\frac{\partial w}{\partial t}\right)^2 dx \tag{6}$$

where A is the cross-section area of Bernoulli–Euler beam, ρ is the density of end-effector material, ω is the static deflection function of beam element. $W(x)$ is the static deflection curve when the beam is under stress when $\omega(x,t)=W(x)\cdot\ \sin(\omega_n t+\varphi)$.

$$W(x)=-\frac{Px^2}{6EI}(3l-x) \tag{7}$$

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