Structural Analysis and Design of Robust Motion Controllers for High–Accuracy Positioning Systems

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Abstract

In this paper, a structural design method of robust motion controllers for high–accuracy positioning systems, which makes it possible to predict the performance of the whole closed–loop system, is proposed. First, a stabilizing control input is designed based on robust internal–loop compensator(RIC) for the system in the presence of uncertainty and disturbance. Next, using the structural characteristics of the RIC, disturbance attenuation properties and the performance of the closed–loop system determined by the variation of controller gains are analyzed. Through this analysis, in some specific applications, it is shown that if the control gain of RIC is increased by N times, the magnitude of error is reduced to its $1/N$. Finally, the proposed method is verified through experiments using a high–accuracy positioning system used in the semiconductor chip mounting devices.

1 Introduction

In designing a robust controller for a system in the presence of uncertainty, requirements can be classified into two major kinds. The first corresponds to robustness properties on the uncertainties including external disturbance, variations of the system parameters, modeling uncertainties, and *etc.*, and the second corresponds to performance specifications for given tasks. Till now, variety of advanced controller design methods have been proposed to meet these desired specifications. However since the modeling uncertainties and external disturbances cannot be exactly compensated, it is difficult to predict and tune the performances of the resulting closed system. This leads us to a development of the robust control laws which is aimed at predicting the performance of the whole closed loop system.

In this paper, a structural design method of robust motion controller for high–accuracy positioning systems, which makes it possible to predict the performance of the whole closed loop system, is proposed. The concepts is presented for SISO system, which gives us an intuition for the proposed design method. First, a stabilizing control input is designed based on Lyapunov redesign. And adopting the internal model following control, robust internal–loop compensator(RIC) is proposed. Next, using the structural characteristics of the RIC, we show disturbance attenuation characteristics and analyze the performance of the closed–loop system determined by the variation of controller gains.

2 Disturbance Attenuation Based on Lyapunov Redesign

Consider a system

$$\dot{y} = A(t)\,y + B(t)\,[u + d(t, y, u)] \tag{1}$$

where $A \in \mathbb{R}^{n\times n}$, $B \in \mathbb{R}^{n\times p}$, $y \in \mathbb{R}^n$ is the state, $u \in \mathbb{R}^p$ is the control input, and $d \in \mathbb{R}^p$ is the unknown disturbance that has bounded magnitude. A reference model of the system (1) can be taken as

$$\dot{y} = A_m(t)\,y + B_m(t)\,u. \tag{2}$$

(1) can be rewritten in terms of A_m and B_m

$$\dot{y} = A_m(t)\,y + B_m(t)\,[u + d_{eq}(t, y, u)]. \tag{3}$$

We assume that A_m, B_m, and d_{eq} are piecewise continuous in t and locally Lipschitz in y and u so that with any feedback control

$$u = u_r(t, y) \tag{4}$$

that is piecewise continuous in t and locally Lipschitz in y the closed–loop system will have a unique solution through every point $(t_0, y_0) \in [0, \infty) \times \mathbb{D}$, where $\mathbb{D} \subset \mathbb{R}^n$ is a domain that contain the origin. The functions A_m and B_m are known precisely, while the function d_{eq} is defined as the equivalent disturbance, that is an unknown function which lumps together various uncertain terms.

If we substitute the reference control input (4) into (2), we obtain the following reference closed–loop system

$$\dot{y} = A_m(t)\,y + B_m(t)\,u_r(t, y). \tag{5}$$

Suppose we have a continuously differentiable function $V(t, y)$ that satisfies the inequalities

$$\alpha_1(\|y\|) \le V(t, y) \le \alpha_2(\|y\|) \tag{6}$$

$$\frac{\partial V}{\partial t} + \frac{\partial V}{\partial y}[A_m(t)\,y + B_m(t)\,u_r(t, y)] \le -\alpha_3(\|y\|) \tag{7}$$

for all $(t, y) \in [0, \infty) \times \mathbb{D}$, where α_1, α_2, and α_3 are class $\mathcal{K}$ functions. And assume that with $u = u_r(t, y) + v$, the uncertain term d_{eq} satisfies the inequality

$$\|d_{eq}(t, y, u)\| \le \rho(t, y) + k\,\|v\|, \qquad 0 \le k < 1 \tag{8}$$

where $\rho : [0, \infty) \times \mathbb{D} \to \mathbb{R}$ is a nonnegative continuous function. Our goal is to show that we can design an additional feedback control $v = \gamma(t, y)$ such that the overall control

$$u = u_r(t, y) + \gamma(t, y) \tag{9}$$

stabilizes the actual system (3) in the presence of the uncertainty. The design $\gamma(t, y)$ is called *Lyapunov redesign* [1].

If we apply the control $u = u_r(t, y) + v$ to the system (3), then the closed–loop system

$$\dot{y} = A_m(t)\,y + B_m(t)\,u_r + B_m(t)\,[v + d_{eq}] \tag{10}$$

is a perturbation of the reference closed–loop system (5). Hence, the derivative of $V(t, y)$ along the trajectories of (10) is obtained as

$$\dot{V} \le -\alpha_3(\|y\|) + w^T v + w^T d_{eq} \tag{11}$$

where $w^T = \left[\frac{\partial V}{\partial y} B_m\right]$. Consequently, it is possible to choose v to cancel the effect of d_{eq} on $\dot{V}$.