CONTROL BY COMPENSATION OF NONLINEARITIES

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Keywords: Actuator nonlinearities, adaptive backstepping, adaptive control, adaptive inverse, backlash, dead-zone, feedback linearization, hysteresis, Lyapunov design, model reference design, neural network based inverse, nonlinearity inverse, PID control, pole placement design, stability, tracking.

Contents

Summary

A general adaptive inverse compensation approach is presented for control of plants with actuator imperfections caused by *nonsmooth* nonlinearities such as dead-zone, backlash, hysteresis and other piecewise-linear characteristics. An adaptive inverse is employed for compensating the effect of actuator nonlinearity with *unknown* parameters, and a linear feedback control law is used for controlling the dynamics of a linear or smooth nonlinear part following the actuator nonlinearity. State feedback and output feedback control designs are presented which all lead to linearly parameterized error models suitable for developing adaptive laws to update the inverse parameters. Neural networks and Fuzzy Logic can be also used to adaptively estimate the inverse of the actuator nonlinearity. This approach suggests that control systems with commonly-used linear or nonlinear feedback controllers such as those with model reference, PID, PD, pole placement, feedback linearization, backstepping or other control designs can be combined with an adaptive inverse for improving system tracking performance

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despite the presence of actuator imperfections.

1. Introduction

Adaptive control is a control methodology which provides adaptation mechanisms to adjust controllers for systems with parametric, structural and environmental uncertainties to achieve desired system performance. Payload variation or component aging causes parametric uncertainties, component failures leads to structural uncertainties, and external noises are typical environmental uncertainties. Such uncertainties often appear in control systems such as those in electrical, mechanical, chemical, aeronautical, and biomedical engineering.

Adaptive control of linear systems has been extensively studied. Systematic design procedures have been developed for model reference adaptive control, pole placement control, self-tuning regulators, and multivariable adaptive control. Robustness of adaptive control schemes with respect to modeling errors such as unmodeled dynamics, parameter variations and external disturbances has been a hot research topic. Recently adaptive controllers have been developed for nonlinear systems such as pure-feedback systems and feedback linearizable systems with sufficiently smooth nonlinearities.

Nonsmooth nonlinear characteristics such as dead-zones, backlash and hysteresis are common in actuators, such as mechanical connections, hydraulic servo-valves, piezoelectric translators, and electric servomotors, and also appear in biomedical systems. They are usually poorly known and may vary with time. They often severely limit system performance, giving rise to undesirable inaccuracy or oscillations or even leading to instability. The development of adaptive control schemes for systems with actuator imperfections caused by such nonlinearities has been a task of major practical interest.

Recently, an adaptive inverse approach has been developed to deal with systems with nonsmooth actuator nonlinearities. A typical control scheme consists of an adaptive inverse for compensating the effect of an unknown actuator nonlinearity such as a dead-zone, backlash, hysteresis, or a piecewise-linearity, and a state or output feedback design for a linear or nonlinear dynamical system. The adaptive inverse approach has been unified for adaptive output feedback control of linear systems with unknown actuator or/and sensor dead-zone, backlash and hysteresis, based on a model reference control method for systems with stable zeros.

Several other methods have also been used for dead-zone or hysteresis compensation control. Essentially, these methods apply to systems with non-smooth nonlinearities present at the input or at the output. A two-layered fuzzy logic controller consisting of fuzzy logic based pre-compensator followed by a fuzzy PD controller can be used. This controller is robust to variations in dead-zone nonlinearities. A class of integral, hysteretic control influence operators has been derived for the representation of structural systems exhibiting hysteresis due to active materials. The hysteretic influence operator is defined in terms of a probability distribution that describes the concentration of a particular hysteresis kernel. Once the hysteretic operators are identified, their feedforward approximate inverses are built to compensate them in adaptive control

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schemes. An adaptive fuzzy logic pre-compensator has been for proposed for dead-zone compensation in nonlinear systems. The classification property of fuzzy logic systems is used for offsetting the dead-zone that has a strong dependence on the region in which the argument occurs. Different control algorithms for hard disk drives (HDDs) have also been designed and evaluated for friction modeling, estimation and compensation. Model-free control design approaches based on neural networks and fuzzy systems are developed to deal with dynamical systems with actuator nonlinearities.

The essence of the adaptive inverse approach is that, upon an adaptation transient, the inverse cancels the effects of the unknown nonlinear characteristic so that a significant improvement of accuracy and performance is achieved with *control algorithms* rather than with more expensive components without imperfections. There are many new technical issues for utilizing such an approach: system modeling, parameterization of inverse models, output matching control, fixed inverse compensation, adaptive inverse compensation, reduced-order control, continuous-time inverse control, discrete-time inverse control, hybrid inverse control, implicit inverse, explicit inverses, gradient-type adaptive designs, Lyapunov-type adaptive designs.

In this chapter, we describe how such an adaptive inverse approach can be combined with popular control methods such as pole placement, PID, model reference and how it can be applied to multivariable or nonlinear dynamics with actuator nonlinearities. In Section 2, we present a general parameterized actuator nonlinearity model illustrated by a dead-zone characteristic. In Section 3, we propose a parameterized inverse for compensating the actuator nonlinearity, illustrated by a dead-zone inverse. In Section 4, we design state feedback adaptive inverse control schemes, while in Section 5, we develop a general output feedback adaptive inverse control scheme. In Section 6, we present three output feedback designs: model reference, pole placement, and PID as examples of the general control scheme of Section 5. In Section 7, an output feedback adaptive inverse control scheme for plants with unknown dynamics with unknown input nonlinearity is presented. We also present feedback adaptive inverse control schemes in Section 8 for multivariable linear plants with actuator nonlinearities, using adaptive parameter update laws based on a coupled estimation error model or a Lyapunov design, and in Section 9 for smooth nonlinear dynamics with nonsmooth actuator nonlinearities, using feedback linearization and an adaptive basckstepping design. In Section 10, we present an adaptive inverse control scheme using an output tracking controller and a neural network based inverse compensator for systems with smooth nonlinear dynamics and unknown nonsmooth actuator nonlinearities. In Section 11, we present an illustrative example to show the damaging effect of actuator backlash nonlinearity on performance of a feedback system with a PI controller, and the desirable compensation ability of an adaptive backlash inverse in improving system performance in the presence of an uncertain backlash characteristic.

2. Plants with Actuator Nonlinearities

Consider the plant with a nonlinearity $N(\cdot)$ at the input of a linear part $G(D)$:

$$y(t) = G(D)[u](t),\ u(t) = N(v(t)), \tag{1}$$

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where $N(\cdot)$ represents an actuator uncertainty, such as a dead-zone, backlash, hysteresis or piecewise-linear characteristic, with *unknown* parameters, $v(t)$ is the applied control, $u(t)$ is not accessible for either control or measurement, and $G(D)$ is a rational transfer function either in continuous time (when D denotes either the Laplace transform variable or the time differentiation operator : $D[x](t)=\dot{x}(t)$) or in discrete time (when D denotes either the z-transform variable or the time advance operator: $D[x](t)=x(t+1)$), for a unified presentation. The case when $G(D)$ is replaced by a nonlinear dynamics is considered in Section 9.

The control objective is to design an adaptive compensator to compensate the effect of the uncertain actuator nonlinearity $N(\cdot)$ so that a commonly-used control scheme for the linear part $G(D)$ can be used to ensure desired system performance. To achieve such an objective, there are two key tasks: one is the clarification of the class of actuator nonlinearities for which such compensators can be developed, and the other is the design of adaptive laws which can effectively update the compensator parameters. In this section, we fulfil the first task by presenting a parameterized nonlinearity model suitable for adaptive compensation schemes to be developed in the next sections.

Nonlinearity Model. Dead-zone, backlash, hysteresis, and piecewise-linear characteristics are representatives of an actuator nonlinearity $N(\cdot)$. These nonlinear characteristics have break points so that they are nondifferentiable (nonsmooth) but they can be parameterized. Their parameterized models can be unified as

$$u(t)=N(v(t))=N(\theta^{*};v(t))=-\theta^{*T}\omega^{*}(t)+a^{*}(t), \qquad (2)$$

where $\theta^{*}\in R^{n_\theta}(n_\theta\geq 1)$ is an unknown parameter vector, and $\omega^{*}(t)\in R^{n_\theta}$ and $a^{*}(t)\in R$ whose components are determined by the signal motion in the nonlinear characteristic $N(\cdot)$ and therefore may be also unknown.

A Dead-Zone Example. To illustrate the nonlinearity model (2), let us consider a dead-zone characteristic $DZ(\cdot)$ with the input-output relationship:

$$u(t)=N(v(t))=DZ(v(t))=\begin{cases} m_r(v(t)-b_r) & \text{if } v(t)\geq b_r \\ 0 & \text{if } b_l<v(t)<b_r \\ m_l(v(t)-b_l) & \text{if } v(t)\leq b_l, \end{cases} \qquad (3)$$

where $m_r>0$, $m_l>0$, $b_r>0$, and $b_l<0$ are dead-zone parameters.

Introducing the indicator function $\chi[X]$ of the event X :

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$$\chi[X] = \begin{cases} 1 \text{ if } X \text{ is true} \\ 0 \text{ otherwise} \end{cases} \tag{4}$$

we define the dead-zone indicator functions

$$\chi_r(t) = \chi[u(t) > 0] \tag{5}$$

$$\chi_l(t) = \chi[u(t) < 0]. \tag{6}$$

Then, introducing the dead-zone parameter vector and its regressor

$$\theta^* = (m_r, m_r b_r, m_l, m_l b_l)^T \tag{7}$$

$$\omega^*(t) = (-\chi_r(t)v(t), \chi_r(t), -\chi_l(t)v(t), \chi_l(t))^T \tag{8}$$

we obtain (2) with $a^*(t) = 0$ for the dead-zone characteristic (3).

For a parameterized nonlinearity $N(\cdot)$ in (2), we will develop an adaptive inverse as a compensator for compensating $N(\cdot)$ with unknown parameters.

3. Parameterized Inverses

The essence of the adaptive inverse approach is to employ an inverse

$$v(t) = \widehat{NI}(u_d(t)) \tag{9}$$

to compensate the effect of the unknown nonlinearity $N(\cdot)$, where the inverse characteristic $\widehat{NI}(\cdot)$ is parameterized by an estimate θ of θ^*, and $u_d(t)$ is a desired control signal from a feedback law. The key requirement for such an inverse is that its parameters can be updated from an adaptive law and should stay in a pre-specified region needed for implementation of an inverse. In our designs, such an adaptive law is developed based on a linearly parameterized error model and the parameter boundaries are ensured by parameter projection.

Inverse Model. A desirable inverse (9) should be parameterizable as

$$u_d(t) = -\theta^T(t)\omega(t) + a(t) \tag{10}$$

for some known signals $\omega(t) \in R^{n_\theta}$ and $a(t) \in R$ whose components are determined by the signal motion in the nonlinearity inverse $\widehat{NI}(\cdot)$ such that $v(t)$, $\omega(t)$ and $a(t)$

are bounded if $u_d(t)$ is. The error signal due to an uncertain $N(\cdot)$ is

$$d_n(t) = \theta^{*T}(\omega(t) - \omega^*(t)) + a^*(t) - a(t), \qquad (11)$$

which should satisfy the conditions that $d_n(t)$ is bounded, $t \geq 0$, and that $d_n(t) = 0, t \geq t_0$, if $\theta(t) = \theta^*, t \geq t_0$, and $\widehat{NI}(\cdot)$ is correctly initialized: $d_n(t_0) = 0$.

Inverse Examples. The inverses for a dead-zone, backlash, hysteresis, and piecewise-linearity have such desired properties. Here we use the dead-zone inverse as an illustrative example. Let the estimates of $m_r b_r, m_r, m_l b_l, m_l$ be denoted as $\widehat{m_r b_r}, \widehat{m_r}, \widehat{m_l b_l}, \widehat{m_l}$, respectively. Then the inverse for the dead-zone characteristic (3) is described by

$$v(t) = \widehat{NI}(u_d(t)) = \widehat{DI}(u_d(t)) = \begin{cases} \frac{u_d(t) + \widehat{m_r b_r}}{\widehat{m_r}} & \text{if } u_d(t) > 0 \\ 0 & \text{if } u_d(t) = 0 \\ \frac{u_d(t) + \widehat{m_l b_l}}{\widehat{m_l}} & \text{if } u_d(t) < 0. \end{cases} \qquad (12)$$

For the dead-zone inverse (12), to arrive at the desired form (10), we introduce the inverse indicator functions

$$\widehat{\chi_r}(t) = \chi[v(t) > 0] \qquad (13)$$

$$\widehat{\chi_l}(t) = \chi[v(t) < 0] \qquad (14)$$

and the inverse parameter vector and regressor

$$\theta = (\widehat{m_r}, \widehat{m_r b_r}, \widehat{m_l}\, \widehat{m_l b_l},)^T \qquad (15)$$

$$\omega(t) = (-\widehat{\chi_r}(t)v(t), \widehat{\chi_r}(t), -\widehat{\chi_l}(t)v(t), \widehat{\chi_l}(t))^T. \qquad (16)$$

Then, the dead-zone inverse (12) is

$$\begin{aligned} u_d(t) &= \widehat{m_r}\widehat{\chi_r}(t)v(t) - \widehat{m_r b_r}\widehat{\chi_r}(t) + \widehat{m_l}\widehat{\chi_l}(t)v(t) - \widehat{m_l b_l}\widehat{\chi_l}(t) \\ &= -\theta^T\omega(t) \end{aligned} \qquad (17)$$

that is, $a(t) = 0$ in (10). It follows from (7), (8), (11) and (16) that

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$$\begin{aligned} d_n(t) &= \theta^{*T}\omega(t)\chi[u(t)=0] \\ &= -m_r\chi[0<v(t)<b_r](v(t)-b_r) \\ &\quad - m_l\chi[b_l<v(t)<0](v(t)-b_l) \end{aligned} \tag{18}$$

which has the desired properties that $d_n(t)$ is bounded for all $t \geq 0$ and that $d_n(t)=0$ whenever $\theta=\theta^*$. Furthermore, $d_n(t)=0$ whenever $v(t)\geq b_r$ or $v(t)\leq b_l$, that is, when $u(t)$ and $v(t)$ are outside the dead-zone, which is the case when $\widehat{b_r} \stackrel{\Delta}{=} \frac{\widehat{m_r b_r}}{\widehat{m_r}} \geq b_r$ and $\widehat{b_l} \stackrel{\Delta}{=} \frac{\widehat{m_l b_l}}{\widehat{m_l}} \leq b_l$.

Control Error: It is important to see that the inverse (10), when applied to the nonlinearity (2), results in the control error

$$u(t)-u_d(t)=(\theta-\theta^*)^T\omega(t)+d_n(t), \tag{19}$$

which is suitable for developing an adaptive inverse compensator. For the adaptive designs to be presented in the next sections, we assume that the inverse block (9) has the form (10) and $d_n(t)$ in (11) has the stated properties. We should note that the signals $a^*(t)$ in (2) and $a(t)$ in (10) are non-zero if the nonlinearity $N(\cdot)$ and its inverse $NI(\cdot)$ have inner loops as in the hysteresis case.

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