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Research article

Enhanced extended state observer-based control for systems with mismatched uncertainties and disturbances☆

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ABSTRACT

This paper presents an enhanced Extended State Observer (ESO)-based control strategy to deal with the disturbance attenuation problem for a class of non integral-chain systems subject to non-linear mismatched uncertainties and external disturbances. The proposed control strategy does not assume the integral-chain form and it is formed by a state-feedback plus a dynamic disturbance compensation term, which is designed to reject the disturbance effect in the system output. From a theoretical point of view, the proposed strategy is reduced to the conventional ESO when the integral chain form and the matched condition hold. In this sense, this paper is presented as an extension of the ESO principles to cover a wider class of systems. The theoretical results show that the internal zero-dynamics plays an important role in ESO-based control design. Also, the closed-loop stability is analyzed and some numerical simulations show the effectiveness of the proposal in comparison with previous ESO-based techniques.

1. Introduction

Disturbance rejection is a fundamental topic in control theory [1]. Many control systems are normally affected by unmeasurable external disturbances and/or unmodeled internal nonlinearities which may degrade the closed-loop control performance [2]. Due to the increasing interest in high precision control, the use of disturbance estimation techniques, which are capable of attenuating those uncertainties, are often useful in the controller design. The final objective is that the control operation should not be influenced by those internal or external uncertainties [3].

Many Disturbance Observer Based Control (DOBC) methods, such as the Disturbance Observer (DOB) [4,5], the Equivalent Input Disturbance (EID) [6,7], the Uncertainty and Disturbance Estimator (UDE) [8–10] or the Extended State Observer (ESO) [11,12], among others, have been developed with this main purpose. Their principal ideas are: (i). to obtain a disturbance estimation through the plant input-output measurements and (ii). to select a control action which, by means of the disturbance estimation, attenuates its effect. A detailed DOBC review can be found in the recent survey paper [1].

Although many results in DOBC have been developed for systems satisfying the so-called matched condition, there are fewer results concerning systems with mismatched uncertainties as pointed out in [3,13,14]. In fact, it is mentioned in [13] that "the disturbance-based feed-forward control for systems with mismatched disturbances is a longstanding unresolved problem". Indeed, it is found that in many practical systems such as magnetic levitation [15], flight control systems [16] or permanent magnet synchronous motor systems [17], the disturbance does not affect the system in the same channel than the control action. This motivates the development of DOBC techniques capable of dealing with mismatched uncertainties.

The aforementioned DOBC techniques employ some kind of plant information for disturbance observation and control design. The ESO is the one that uses the less information as only the system relative degree should be known [18]. For that reason, the ESO has become very popular in recent years. It is the core of the Active Disturbance Rejection Control (ADRC) [18,19] and many studies providing theoretical analyses [20–23], or practical applications [24–27], have been proposed. As the knowledge of the relative degree is its unique requirement, it is natural to doubt about what kind of plant information needs to be really considered for control design [13,28]. However, the original ESO assumes that the plant is expressed in the Conventional Integral Chain Form (CICF) satisfying the matched condition [3,12]. Therefore, its applicability is restricted to systems which, directly or by means of a change of variable, can be expressed in the CICF. In this sense, the

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advantage of requiring the less plant information for control design is contrasted with the limitation of expressing the system in the CICF for analysis purposes. Performing such transformation is not always easy as it is mentioned in [18,19,29], specially if the system has zero-dynamics. Therefore, motivated by the successful results of the ESO, it was recently pointed out in [13] that it is imperative to develop ESO-based control techniques for systems without assuming the CICF.

One of the major results in this area is presented in [13], where a novel Generalized Extended State Observer (GESO) is proposed in order to extend the ESO principles to a class of systems with mismatched uncertainties that are not expressed in the CICF. Concretely, in [13], a disturbance compensation gain is designed to reject the disturbance from the system output in steady-state, while the disturbance, f, is assumed to satisfy $\lim_{t\to\infty}\dot{f}=0$. Other works in which the CICF is not assumed have been recently developed. In [28] an ADRC is designed for the same system considered in [13] but assuming the matched condition. In that work, it is shown that the knowledge of the inner plant dynamics led to better control performance. In [30] it is shown how the system considered in [13] can be reduced to the CICF if the plant does not have zeros. In [31], the GESO is applied to control a cart-pendulum system.

This paper aims to apply the ESO principles to control a class of non integral-chain systems subject to non-linear mismatched uncertainties. The proposed control strategy does not assume the integral-chain form and it is formed by a state-feedback plus a dynamic disturbance compensation term. This strategy is able to attenuate an uncertainty whose k_d+1 time-derivative is bounded (being k_d a positive integer unequivocally determined by the internal system structure); and it is able to reject an uncertainty satisfying $\lim_{t\to\infty}f^{(k_d+1)}(t)=0$. Some simulation results show that the disturbance attenuation is enhanced with this strategy in comparison with the previous ones. Also, from a theoretic point of view, this scheme can be interpreted as an extension of the GESO-based control presented in [13] in which the requirement of steady-state is avoided; or as an extension of the conventional ESO in which the requirements of the CICF and the matched condition are eliminated. This paper also shows that the knowledge of the internal zero-dynamics plays an important role in ESO-based control design.

The rest of the paper is structured as follows. In Section 2 the system under consideration is presented and the GESO-based control law is recalled. Section 3 contains the main results. First, the proposed ESO-based control law is defined in general terms. Then, in Section 3.1, an analysis in order to obtain the explicit expression of the required control action so that the effect of the mismatched uncertainty is removed from the system output is performed. The closed-loop stability is analyzed in Section 3.2 and some examples to show the feasibility of the proposal are shown in Section 4. Finally, the conclusions and future works are drafted in Section 5.

2. Problem statement

Let us consider the following class of uncertain non-linear systems [13]:

$$\begin{cases} \dot{x}=Ax+B_u u+B_f f\big(x,\omega(t),t\big),\\ y=Cx \end{cases} \tag{1}$$

where $x=[x_1,\ldots,x_n]^T$; $A\in\mathbb{R}^{n\times n}$; $B_u\in\mathbb{R}^n$; $B_f\in\mathbb{R}^n$; and $f(\cdot)\colon\mathbb{R}^n\times\mathbb{R}\times\mathbb{R}_{\geq 0}\to\mathbb{R}$ is an uncertain possibly non-linear function. For the sake of simplicity, let us denote $f\triangleq f\big(x,\omega(t),t\big)$.

The traditional ESO is proposed for systems which are expressed in the CICF, that is, with

$$A=\begin{bmatrix}0&1&0&\cdots&0\\0&0&1&\cdots&0\\\vdots&\vdots&\vdots&\ddots&\vdots\\0&0&0&\cdots&1\\0&0&0&\cdots&0\end{bmatrix},\quad B_u=\begin{bmatrix}0\\0\\\vdots\\0\\b\end{bmatrix},\quad B_f=\begin{bmatrix}0\\0\\\vdots\\0\\1\end{bmatrix},$$
$$C=\begin{bmatrix}1&0&0&\cdots&0\end{bmatrix}. \tag{2}$$

On the other hand, the GESO deals with system (1) with arbitrary structure [13]. The control law proposed therein is given by

$$u=K_x\hat{x}+k_G\hat{f} \tag{3}$$

where

$$k_G=-\left[C(A+B_uK_x)^{-1}B_u\right]^{-1}C(A+B_uK_x)^{-1}B_f \tag{4}$$

is the disturbance compensation gain, K_x is the feedback gain, and $\hat{x}$, $\hat{f}$ are estimations of x, f, respectively, which are obtained by constructing the following GESO:

$$\begin{bmatrix}\dot{\hat{x}}\\ \dot{\hat{x}}_{n+1}\end{bmatrix}=\begin{bmatrix}A & B_f\\ 0_{1\times n} & 0\end{bmatrix}\begin{bmatrix}\hat{x}\\ \hat{x}_{n+1}\end{bmatrix}+\begin{bmatrix}B_u\\0\end{bmatrix}u+L(y-C\hat{x}), \tag{5}$$

being, $L\in\mathbb{R}^{n+1}$ the observer gain and $\hat{x}_{n+1}\triangleq\hat{f}$.

Remark 1. The GESO is reduced to the traditional ESO when the matrices are given by (2).

Remark 2. If K_x, L are chosen such that the system and the observer closed-loop matrices are Hurwitz, then, the bounded stability of (1) under (3)–(5) is guaranteed under the assumption of boundedness of f and $\dot{f}$, [13].

In general, the control law (3)–(5) removes the effect of f from the system output in steady state if $\lim_{t\to\infty}\dot{f}(t)=0$. In this paper, a further extension of (3) is proposed. First, an analysis is performed in order to show that, under perfect disturbance estimation, a dynamic disturbance rejection term can be designed such that f is completely rejected from the system output without the need of imposing the steady-state requirement. Then, the closed-loop system stability when observation errors are considered is analyzed.

Definition 1. The next definitions are made:

(i) $\bar{A}\triangleq A+B_uK_x$.
(ii) $z_{u,j}\in\mathbb{C}$, $j=1,\ldots,m_u$, with $z_{u,j}\neq z_{u,j+1}$, $\forall j$, denotes the zeros in the triplet $(\bar{A},B_u,C)$.
(iii) $n_{u,j}\in\mathbb{N}$ denotes the multiplicity of $z_{u,j}$.
(iv) The zeros $z_{u,j}$, and their respective multiplicities $n_{u,j}$, are divided into: minimum phase zeros, $z_{u_m,j}$, $n_{u_m,j}$, $j=1,\ldots,m_{u_m}$; non-minimum phase zeros, $z_{u_{nm},j}$, $n_{u_{nm},j}$, $j=1,\ldots,m_{u_{nm}}$; and zeros at the imaginary axis, $z_{u_0,j}$, $n_{u_0,j}$, $j=1,\ldots,m_{u_0}$; satisfying $m_u=m_{u_m}+m_{u_{nm}}+m_{u_0}$.
(v) The total number of zeros in the triplet $(\bar{A},B_u,C)$ is denoted by $m_u^{tot}=\sum_{i=1}^{m_u}n_{u,i}$. And, in the same way: $m_{u_m}^{tot}=\sum_{i=1}^{m_{u_m}}n_{u_m,i}$, $m_{u_{nm}}^{tot}=\sum_{i=1}^{m_{u_{nm}}}n_{u_{nm},i}$ and $m_{u_0}^{tot}=\sum_{i=1}^{m_{u_0}}n_{u_0,i}$; are the total number of minimum phase zeros, non-minimum phase zeros and zeros at the imaginary axis, respectively.
(vi) The same notation defined in **(ii)**, **(iii)**, **(iv)** and **(v)** is used for the triplet $(\bar{A},B_f,C)$ by replacing the subindexes 'u' by 'f'.

Also, the next assumptions are considered.

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