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Predictive active disturbance rejection control for processes with time delay

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ABSTRACT

Active disturbance rejection control (ADRC) has been shown to be an effective tool in dealing with real world problems of dynamic uncertainties, disturbances, nonlinearities, etc. This paper addresses its existing limitations with plants that have a large transport delay. In particular, to overcome the delay, the extended state observer (ESO) in ADRC is modified to form a predictive ADRC, leading to significant improvements in the transient response and stability characteristics, as shown in extensive simulation studies and hardware-in-the-loop tests, as well as in the frequency response analysis. In this research, it is assumed that the amount of delay is approximately known, as is the approximated model of the plant. Even with such uncharacteristic assumptions for ADRC, the proposed method still exhibits significant improvements in both performance and robustness over the existing methods such as the dead-time compensator based on disturbance observer and the Filtered Smith Predictor, in the context of some well-known problems of chemical reactor and boiler control problems.

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1. Introduction

Active disturbance rejection control (ADRC) was first conceived by Han in 1995 [2], 1998 [3], and was fully articulated in 2009 [1]. Han demonstrated with his penetrating insight and computer simulations, and later validated by others in various theoretical studies [4–6], that both the unknown plant dynamics and the external disturbances can be accurately estimated in real time, based on the input-output signals of the plant. Such estimation is used to reduce the plant to a canonical, integral form where a control solution is readily available. In doing so, a highly effective solution was born for processes that are nonlinear, time-varying, and full of uncertainties, both internal and external. With such uniqueness in design concept, ADRC provides excellent solutions to many pressing engineering problems; see for example [7–12].

As a new control design framework, ADRC solutions are still growing and they are not without limitations. For example, much of the success of ADRC has been achieved with systems with little or no dead time [13], and processes with long time delays still pose a great challenge. This paper strives to meet this challenge.

Processes with time delay are difficult to control because delay introduces extra phase lag leading to reduced stability margins and putting a stringent limit on the bandwidth. Therefore, specific analysis techniques and design methods must be developed to adequately address the presence of delays. Concerned with this very problem in the context of ADRC, Han suggested the following three methods [1]: (1) Transfer function approximation of the delay; (2) Input prediction; and (3) Output prediction.

In the first method, first-order lag or Padé approximation can be used to approximate the delay term, essentially treating the process as a higher order system without delay [14]. With this method, both stability robustness and performance are improved for a multi-variable process with time delay in the input. However, the controller bandwidth and observer bandwidth are still quite limited, leading to sluggish transient and disturbance rejection response.

The second method of predicting the control signal is not easily done, unless the accurate model information and future set point information are given, making it quite limited as a practical solution.

In this paper we adopt a strategy based on the third method suggested by Han, by using a prediction method to obtain the delay-less output feedback, similar to the idea of the Smith Predictor (SP), leading to a predictive ADRC solution that is able to handle long time-delays in the process. Such approach overlaps somewhat with the existing literature on disturbance-observer based control design for processes with a time delay. A disturbance-observer in the Dead-time compensators (DTC) is presented in [15] and analyzed in [16,17], showing that the method is applicable to both stable and unstable systems. The modified versions of this structure were presented in

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[18–21], where more complex algorithms and tuning rules are described to deal with integral plants with delay. The main distinguishing factor between these methods and the proposed one is whether or not the disturbance model is required: the existing methods do, the proposed doesn't. Another difference is that the ADRC based approach is more tolerant of the uncertainties in both plant dynamics and external disturbances, as shown in this paper.

The rest of the paper is organized as follows. First, the concept of ADRC is introduced in Section 2, the proposed structure is introduced in Section 3, and then some numerical examples are tested in Section 4. Stability analysis using classical control theory in frequency domain is given in Section 5, followed by some application examples in Section 6. Finally, concluding remarks are given in Section 7.

2. Active disturbance rejection

Active disturbance rejection is a unique design concept that aims to accommodate not only external disturbances but also unknown internal dynamics in a way that control design can be carried out in the absence of a detailed mathematical model, as most classical and modern design methods require. To illustrate the basic idea, consider an ADRC design for a second order system without time delay described as:

$$\ddot{y}+a_1\dot{y}+a_0y=b(u+w), \tag{1}$$

where u and y are the input and output of the plant, respectively. The external disturbance is w. a_1, a_0, and b are system parameters. In the ADRC design, (1) is rewritten as:

$$\ddot{y}=bu+f, \tag{2}$$

where $f=bw-a_1\dot{y}-a_0y$. The function $f(\cdot)$ is a general nonlinear, time-varying dynamic representing the total disturbance including both internal (unknown dynamics) and external (disturbance) uncertainties. The key idea is to extend the state definition of f, which allows us to estimate it in real time using the state observer. With the state vector defined as $X=\begin{bmatrix} x_1 & x_2 & x_3\end{bmatrix}^T=\begin{bmatrix} y & \dot{y} & f\end{bmatrix}^T$, (2) is rewritten in the state space form as:

$$\begin{cases} \dot{X}=AX+Bu+E\dot{f} \\ y=CX \end{cases}, \tag{3}$$

where $A=\begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 0 & 0 & 0\end{bmatrix}$, $B=\begin{bmatrix} 0 \\ b \\ 0\end{bmatrix}$, $C=\begin{bmatrix} 1 \\ 0 \\ 0\end{bmatrix}^T$ and $E=\begin{bmatrix} 0 \\ 0 \\ 1\end{bmatrix}$.

Note that the total disturbance $f(\cdot)$is defined as the extended state x_3 that is augmented to the original second order system. According to (3), a linear extended state observer (ESO) is constructed as:

$$\begin{cases} \dot{Z}=AZ+Bu+L(y-\hat{y}) \\ \hat{y}=CZ \end{cases}, \tag{4}$$

where $Z=\begin{bmatrix} z_1 & z_2 & z_3\end{bmatrix}^T$ is the observer state vector which provides an estimation of the system state vector X. $L=\begin{bmatrix} l_1 & l_2 & l_3\end{bmatrix}^T$ is the observer gain vector; $\hat{y}$ is the estimation of output. Most importantly, the ESO provides z_3, an estimation of the total disturbance. The idea of ADRC, as in Fig. 1, is to actively estimate $f(\cdot)$ and then cancel it with the control signal, thereby reducing the problem to controlling an integral plant.

The ADRC control law is given as:

$$u=(k_1()r-z_1+k_2(\dot{r}-z_2)-z_3)/b_o \tag{5}$$

where k_1 and k_2 are controller gains, r is the reference signal, and b_o is the estimation of b.

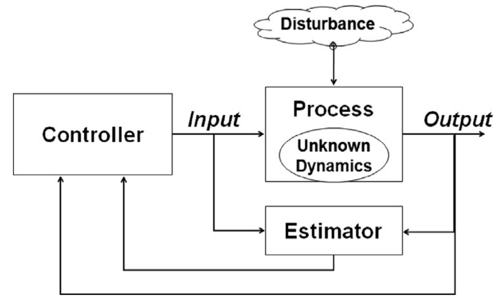

Fig. 1. Active disturbance rejection control scheme.

In a plant with input time delay l_p, the estimated output and the plant output, which is delayed, were not synchronized in ESO and Eq. (4) becomes:

$$\begin{cases} \dot{Z}(t) &= AZ(t)+Bu(t)+L[y(t-l_p)-\hat{y}(t)] \\ \hat{y}(t) &= CZ(t) \end{cases} \tag{6}$$

More generally, consider a plant that is single-input single-output, nth-order, nonlinear, uncertain, and with time delay; its input $u(t)$ and output $y(t)$ are governed by:

$$y^{(n)}=f(y,\dot{y},\ldots,y^{(n-1)},w,u)+b\times u(t-l_p) \tag{7}$$

where $f(\cdot)$ is again the total disturbance to be estimated and cancelled. The state space form of (7) is:

$$\begin{cases} \dot{X}(t-l_p)=A_gX(t-l_p)+B_gu(t-l_p)+E_g\dot{f} \\ y(t-l_p)=C_gX(t-l_p) \end{cases} \tag{8}$$

with:

$$X=\begin{bmatrix} X_1 \\ X_2 \\ \vdots \\ X_n\end{bmatrix},\ A_g=\begin{bmatrix} 0 & 1 & 0 & \ldots & 0 \\ 0 & 0 & 1 & \cdots & 0 \\ \vdots & \ddots & 0 & \ddots & \vdots \\ \vdots & \ddots & \ddots & \ddots & 1 \\ 0 & 0 & \cdots & \cdots & 0\end{bmatrix},\ B_g=\begin{bmatrix} 0 \\ \vdots \\ 0 \\ b \\ 0\end{bmatrix},$$

$$E_g=\begin{bmatrix} 0 \\ \vdots \\ 0 \\ 1\end{bmatrix},\ C_g=\begin{bmatrix} 1 & 0 & \cdots & 0\end{bmatrix}$$

To obtain the estimation of total disturbance $\hat{f}(\cdot)$ using the ESO in its standard form, we have:

$$\begin{cases} \dot{Z}(t)=A_gZ+B_gu(t)+L(y(t-l_p)-\hat{y}(t)) \\ \hat{y}(t)=C_gZ \end{cases} \tag{9}$$

where $Z=\begin{bmatrix} z_1 & z_2 & \cdots & z_{n+1}\end{bmatrix}^T$. Clearly the observer error $y(t-l_p)-\hat{y}(t)$ is misaligned time wise, which can lead to ESO instability.

For the plant with no delay, i.e. $l_p=0$, the standard design of ADRC can be stated as follows. Define ω_0 as the observer bandwidth, the ESO gain vector L can be chosen as:

$$L=\begin{bmatrix} \beta_1\omega_0 & \beta_2\omega_0^2 & \cdots & \beta_{n+1}\omega_0^{n+1}\end{bmatrix}^T, \tag{10}$$

such that the polynomial $s^{n+1}+\beta_1s^n+\cdots+\beta_ns+\beta_{n+1}$ is Hurwitz. Note that the ESO gains in (10) can be chosen so that all its eigenvalues are placed at $-\omega_0$, the observer bandwidth, which makes ESO easy to tune. With a well-tuned ESO, $z_{n+1}=\hat{f}(\cdot)\approx f(\cdot)$, the control law

$$u=(-\hat{f}(\cdot)+u_0)/b_o \tag{11}$$