2012 12th International Conference on Control, Automation and Systems
Oct. 17-21, 2012 in ICC, Jeju Island, Korea

On the Unified Approach to the Disturbance Observer

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Abstract: The purpose of the disturbance observer (DOB) in the dynamical system is to cancel out external disturbances from environment and inherent uncertainties in the plant through realizing the disturbance. Although a variety of different DOB structures has one common goal of rejecting disturbance, many variations in control structure are present owing to how to estimate the disturbance and how to cure signal distortion from modification. A unified approach to classify DOBs into model-based and non-model based DOBs is present. Several time-delayed DOBs as a non-model based DOB are derived from the ideal time-delayed DOB. Reconfiguration of the simplified time-delayed DOB turns out to be a high gain feedback control structure. The analysis of the time-delayed DOB with acceleration feedback shows that the overall open loop system becomes a nominal inertial system regardless of any second order plants under no time-delay condition. Practical issues are addressed and simulation examples are demonstrated to support the analysis.

Keywords: Disturbance observer, unified approach, time-delayed control.

1. INTRODUCTION

A disturbance observer (DOB) is one of advanced and practical control methods to deal with external disturbances as well as uncertainties in the dynamical system. Since implementation of DOB is so simple and cost effective, it is used mostly in practical control systems, typically in the motion control area.

DOB has attained its fame after successful demonstration of its performance when applying it to practical systems such as motion control systems [1-3] and position control in robotics [4,5]. The DOB structure proposed by Ohnishi for motion control systems is a model-based scheme [1]. DOB takes the position feedback, passes it through the inverse model of the plant, subtracts it from the control input to estimate the disturbance, and subtracts it from the control input again for the disturbance cancellation.

Taking advantage of the practical and simple structure of DOB with no cost, active research on designing a variety of modified versions of disturbance observers to reject disturbances has been carried out [6-17]. Differences in disturbance observer design appear in how to estimate disturbances in system models and how to cancel them out.

In general, the DOB structure has two parts: the inner loop observes and compensates for disturbances and the outer loop improves the system performance. The role of DOB as an inner loop controller is to estimate disturbances and cancel them out to help the outer loop controller to improve the tracking performance. This leads to the concept of two-degrees-of-freedom theory to design two controllers within the DOB structure [2,4]. Tomizuka has extended the two-degrees-of-freedom controllers by applying it to the digital motion control system [6]. DOB has been applied to control high speed disk drive system to improve positioning accuracy [7,8] and in H_∞ theory configuration [9]. DOB has been designed for non-minimum phase linear systems [10, 11].

DOB has been further extended to consider disturbances in nonlinear systems by addressing the robustness problems [12-15]. Acceleration control in association with DOB has been applied to motion control systems [16,17] and to the bilateral tele-operation system to compensate for the time-delay in communication channel [18].

Therefore, in the conventional DOB structure based on the inverse model to estimate disturbance as shown in Fig. 1, design of the filter $Q(s)$ is considered as the most important step for the performance. How to design the filter $Q(s)$ also provides plentiful DOB design methodologies as well.

The time-delayed control method is a non-model based approach of DOB design [19,20]. The time-delayed control method uses the difference of two consecutive samples at the time t-T and t, namely the previous and the current information of the system. It is assumed that the system dynamics do not change rapidly during one sampling time period T. The previous sampled information $u(t-T)$ is used as a system model to cancel out uncertainties.

Experimental studies for the position control of robot manipulators using the time-delayed control method are presented in [21]. The acceleration control with DOB is eventually one of time-delayed control scheme that uses acceleration information to estimate disturbance [17].

Although there are many DOB design in the literature, in this paper, a unified approach to classify DOB into two categories: an inverse model-based DOB scheme and a time-delayed DOB scheme. Starting from the ideal time-delayed DOB structure, several time-delayed DOB structures are reformulated and reconstructed. It is interesting to note that the simplified time-delayed DOB structure results in a high gain feedback control structure.

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In addition, the time-delayed DOB with acceleration feedback shows that the plant with DOB becomes a nominal inertial system, $1/s^2$, regardless of any second order plants if no time-delay is assumed. This advantage becomes worthwhile to reinvestigate the time-delayed control method further although it has still the stability problem due to the time-delay. In the framework of a time-delayed DOB structure, practical issues are addressed and simulation studies are conducted to demonstrate the feasibility of the analysis.

2. DESIGN AND ANALYSIS OF TIME-DELAYED DOB

2.1 Inverse Model-Based DOB

The structure of the inverse model-based DOB is simple and can be constructed without adding any extra cost. To estimate the disturbance $D(s)$, the inverse model of the plant, $1/G_m(s)$ is required as shown in Fig. 1. Equations (1)-(3) are the corresponding structural equation of the DOB of Fig. 1.

$$Y(s) = G(s)U(s) + G(s)D(s) \quad (1)$$

$$\hat{D}(s) = \frac{1}{G_m(s)}Y(s) - U(s) \quad (2)$$

$$U(s) = \overline{U}(s) - \hat{D}(s) \quad (3)$$

where $\overline{U}(s)$ is the reference control input, $\hat{D}(s)$ is the estimated equivalent disturbance of the disturbance $D(s)$, and $G_m(s)$ is the model of the plant $G(s)$.

Combining equations (1), (2), and (3) yields the output Y(s) of which disturbance effect is eliminated, but control performance is much dependent upon the accuracy of the model, $G_m(s)$.

$$Y(s) = G_m(s)\overline{U}(s) \quad (4)$$

Therefore, control action from the controller can be delivered to the plant as desired with one condition that the exact modeling $G_m(s) = G(s)$ is required, and the inverse model should exist and be stable. In reality, however, it is quite difficult to satisfy the conditions.

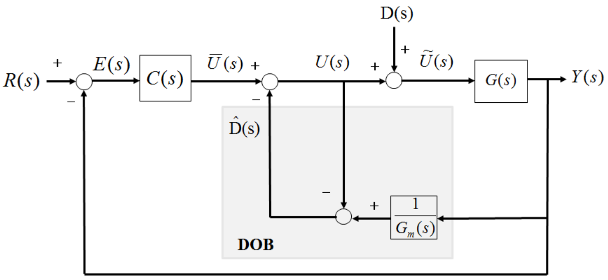

Fig. 1 Inverse model-based DOB structure

Important characteristics of the inverse model-based DOB structure are summarized as below.

i) Inverse model is required.
ii) $G_m(s)$ should be proper and minimum phase.
iii) $1/G_m(s)$ should be realizable.
iv) The disturbance is estimated by DOB as $\hat{D}(s) = \frac{1}{G_m(s)}Y(s) - U(s) = \hat{\tilde{U}}(s) - U(s) = \Delta\hat{U}(s)$.

2.2 Inverse Model-Based DOB with Q filter

The modeling error can be adjusted by modifying the disturbance estimation through a filter $Q(s)$ as shown in Fig. 2. The disturbance estimation $\hat{D}(s)$ is modified through the filter $Q(s)$ as

$$\hat{D}(s) = Q(s)\tilde{D}(s) \quad (5)$$

where $\tilde{D}(s) = (\frac{1}{G_m(s)}Y(s) - U(s))$.

Then the output becomes

$$Y(s) = \frac{G_m(s)G(s)}{\Delta_I(s)}\overline{U}(s) + \frac{G_m(s)G(s)(1-Q(s))}{\Delta_I(s)}D(s) \quad (6)$$

where $\Delta_I(s) = G_m(s) + (G(s) - G_m(s))Q(s)$.

To cancel out the disturbance effect in (6), $|Q(s)| \approx 1$ is desired so that we have

$$Y(s) \approx \frac{G_m(s)G(s)}{G_m(s) + (G(s) - G_m(s))Q(s)}\overline{U}(s) \approx G_m(s)\overline{U}(s) \quad (7)$$

In (7), we see that the modeling error term, $G(s) - G_m(s)$ appears in the denominator, which means that the tracking performance by the controller can be degraded due to the modeling error.

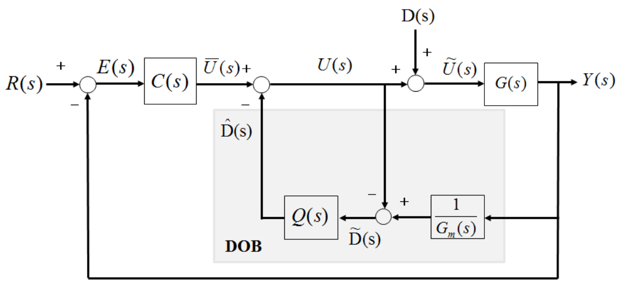

Fig. 2 Structure of Inverse model based DOB with Q filter

Important characteristics of the inverse model based DOB structure with Q filter are:

i) Inverse model is required.
ii) $G_m(s)$ should be proper and minimum phase.
iii) $1/G_m(s)$ should be realizable.
iv) Q(s) filter is needed to be designed appropriately.
v) The estimation of disturbance is filtered by Q(s) filter as $\hat{D}(s) = Q(s)(\hat{\tilde{U}}(s) - U(s)) = Q(s)\Delta\hat{U}(s)$.

In (6), it is clear that *Q(s)* is the important element which determines the performance of DOB. The gain of *Q(s)* must be a unit gain in order to reject the disturbance and to transform the characteristics of the plant to the model. The filter *Q(s)* is suggested to be a low pass filter.

In the inverse model-based DOB, several issues are raised. Firstly, the plant model may not be accurate. In reality, it is a difficult task to model accurately. Secondly, the inverse model of the plant may not be realized in the proper function for the stability.
Lastly, sensor noise is still present in the system.

2.3 Ideal Time-delayed DOB

To ease the problem of the difficulty of realizing the model of a plant, a time-delayed disturbance observer is presented to be a good candidate. In the ideal time-delayed DOB, the disturbance is realized by subtracting the previous control input $u(t-T)$ from the current control input $u(t)$, namely $\hat{d}(t)=u(t)-u(t-T)$ as shown in Fig. 3.

It is true that this approach is not actually implementable since we do not have access to $\tilde{U}(s)$ except for some cases that can measure the signal by using sensors explicitly. In Laplace transform of the disturbance estimation, $\hat{d}(t)$, we have

$$\hat{D}(s)=\tilde{U}(s)-U(s)e^{-sT}=D(s)+U(s)(1-e^{-sT}) \tag{8}$$

where T is the sampling time and s is the Laplace operator.

The output is represented as

$$Y(s)=\frac{G(s)}{\Delta_D(s)}\bar{U}(s)+\frac{(1-e^{-sT})G(s)}{\Delta_D(s)}D(s) \tag{9}$$

where $\Delta_D(s)=1+(1-e^{-sT})$. Equation (9) suggests that the time delay should be zero in order for the controller to eliminate the disturbance effect. Then we have the disturbance rejection.

$$Y(s)=G(s)\bar{U}(s) \tag{10}$$

Thus, if the sampling time is selected to be fast enough, this results in minimizing the effect of a disturbance term.

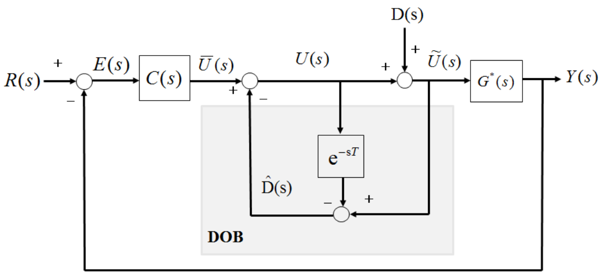

Fig. 3 Ideal time-delayed DOB structure

Important characteristics of the ideal time-delayed DOB structure are:

i) Plant model is NOT required.
ii) Measurement of $\tilde{U}(s)$ is must be available.
iii) Phase delay effects should be taken care of.
iv) The estimation of disturbance is

$$\hat{D}(s)=D(s)+U(s)(1-e^{-sT}).$$

Note that the estimate of the disturbance approximates the actual disturbance when the time-delay is minimal.

$$\hat{D}(s)\approx D(s) \tag{11}$$

2.4 Time-delayed DOB with Delayed Acceleration Feedback

Here we have the second order dynamic system which is a single-input single-output system.

$$m\ddot{y}(t)+d(t)=u(t) \tag{12}$$

where *m* is a mass, *y(t)* is the output, and *d(t)* includes other dynamical terms including disturbance, and *u(t)* is the control input. A simple way to estimate *d(t)* is to use the previous information of the system dynamics, which is known as a time-delayed control method.

$$\hat{d}(t)=u(t-T)-\hat{m}\ddot{y}(t-T) \tag{13}$$

where T is a sampling time and $\hat{m}$ is an estimated mass. Therefore, the desired control input becomes

$$\begin{aligned} u(t)&=\hat{m}\bar{u}(t)+\hat{d}(t)\\ &=\hat{m}\bar{u}(t)+u(t-T)-\hat{m}\ddot{y}(t-T)\end{aligned} \tag{14}$$

Note that the time-delayed control is named after using previously sampled information for the current control input as in (14).

From the Laplace transform of (14), the control input can be described as

$$U(s)=\frac{\hat{m}}{1-e^{-sT}}(\bar{U}(s)-s^2e^{-sT}Y(s)) \tag{15}$$

The complete control block diagram is shown in Fig. 4.

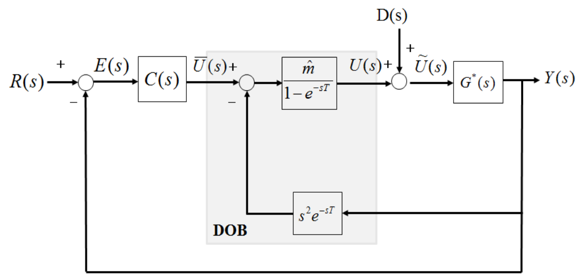

Fig. 4 Time-delayed DOB with delayed acceleration feedback

The closed loop transfer function is obtained by

$$Y(s)=\frac{\hat{m}G^*(s)C(s)R(s)}{1-e^{-sT}+\hat{m}s^2e^{-sT}G^*(s)+\hat{m}G^*(s)C(s)}+\frac{G^*(s)(1-e^{-sT})D(s)}{1-e^{-sT}+\hat{m}s^2e^{-sT}G^*(s)+\hat{m}G^*(s)C(s)} \quad (16)$$

Note from (16) that the fast sampling time guarantees the stability and the disturbance effect is eliminated. Fig. 5 shows a further simplified structure of Fig. 4. Note that the transfer function $G_T(s)$ becomes a simple inertial system, namely $1/\hat{m}s^2$ under the condition of $|e^{-sT}|=1$ and no phase delay.

$$G_T(s)=\frac{G^*(s)}{1-e^{-sT}+\hat{m}s^2e^{-sT}G^*(s)}=\frac{1}{\hat{m}s^2} \quad (17)$$

Then Fig. 4 becomes disturbance free and model free control structure as shown in Fig. 5. The mass model $\hat{m}$ is further cancelled by the controller, the resultant plant $G_T(s)$ becomes $1/s^2$, which is a nominal inertial system of double integrators with the cancellation of $\hat{m}$ as shown in Fig. 6. This means that controllers can be easily designed to satisfy performance specifications regardless of any second order plants.

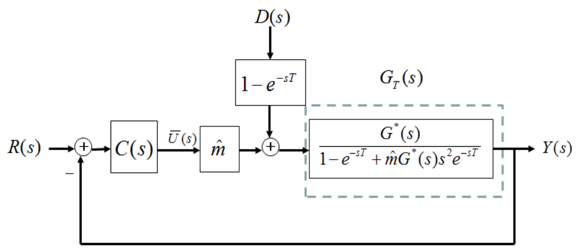

Fig. 5 Simplified structure of Fig. 4

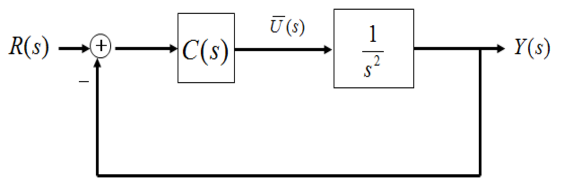

Fig. 6 Ideal resultant control structure

2.5 Time-delayed DOB with Acceleration Feedback

Consider the case of direct measurement of the acceleration signal from an accelerometer for the nominal second order plant such that

$$G(s)=\frac{1}{ms^2+bs+k} \quad (18)$$

The control input is given by

$$U(s)=\bar{U}(s)-(\tilde{U}(s)-U(s)e^{-sT}) \quad (19)$$

where $\tilde{U}(s)=\hat{m}s^2Y(s)$. Then the control input becomes

$$U(s)=\frac{\bar{U}(s)-\hat{m}s^2Y(s)}{1-e^{-sT}} \quad (20)$$

Combining (20) with the output Y(s) yields the closed loop equation

$$Y(s)=\frac{\hat{m}C(s)R(s)+(1-e^{-sT})D(s)}{(1-e^{-sT})(ms^2+bs+k)+\hat{m}s^2+\hat{m}C(s)} \quad (21)$$

Note that $|e^{-sT}|=1$, (21) becomes

$$Y(s)=\frac{\hat{m}C(s)R(s)}{\hat{m}s^2+\hat{m}C(s)} \quad (22)$$

If PD controller is used, (22) becomes

$$Y(s)=\frac{\hat{m}(K_d s+K_p)R(s)}{\hat{m}s^2+\hat{m}(K_d s+K_p)} \quad (23)$$

Regardless of the inertia model, (23) is further simplified as

$$Y(s)=\frac{K_d s+K_p}{s^2+K_d s+K_p}R(s) \quad (24)$$

This means that the control structure given in Fig. 7 leads to the closed loop equation (24) regardless of any second order systems under the assumption that the inertia model is exactly same as the plant.

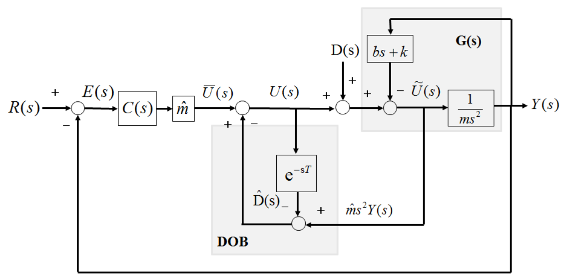

Fig. 7 TD DOB with direct acceleration measurement

The control structure described in Fig. 7 is comparable to that of Fig. 3. Therefore, for any second order systems, the time-delayed DOB becomes a transfer function of (24) under the assumption of an exact model. Only one condition for the stability and performance is the fast sampling time that guarantees a minimal phase delay. In the practical point of view, minimizing time-delay, or equally minimizing phase delay is feasible with the current hardware technology.

3. SIMULATION STUDIES

For simulation studies, four different second order plants are tested. The control structure described in Fig. 7 is used for the plants. The time-delay is set to 0.01 second which is considered as one sample delay.

1) Plant 1 : $G(s) = 1/s^2$

First, the double integrator system is tested. The double integrator system is known to be difficult to be stabilized in many DOB structures due to its marginal stability. PD controllers are designed first to satisfy the tracking performance. Then disturbances are intentionally added to the system to test the DOB.

Fig. 8 shows the step response of the double integrator system when the time-delay is set to 0.01 seconds. The step response is distorted due to disturbances up to 5 seconds. After 5 seconds, DOB is turned on. We clearly see from Fig. 8 that DOB reduces the disturbance effect.

2) Plant 2 : $G(s) = 1/(s^2 + 2s + 10)$

The second plant is tested. Since the same PD controller is used, there is a steady state error before DOB is turned on as shown in Fig. 9. After DOB is on at 5 seconds, disturbance is minimized as well as the steady state errors.

3) Plant 3: $G(s) = 1/(s^2 + 10)$

The same simulation is conducted for the plant. As shown in Fig. 10, both disturbance effect and steady state errors are reduced after DOB is turned on.

4) Plant 4 : $G(s) = 1/(2s^2 + 2s + 10)$

The last plant is tested. The step response under the disturbance is shown in Fig. 11. DOB works well after 5 seconds.

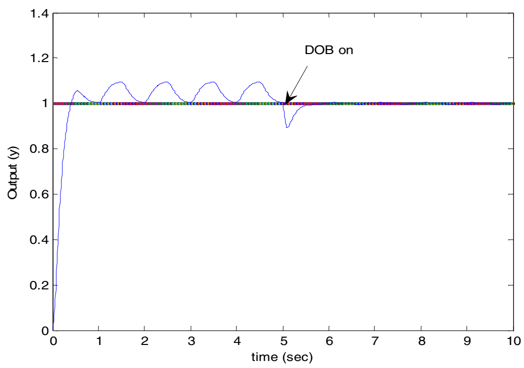

Fig. 8 Step response of $G(s) = \frac{1}{s^2}$ no delay in acceleration

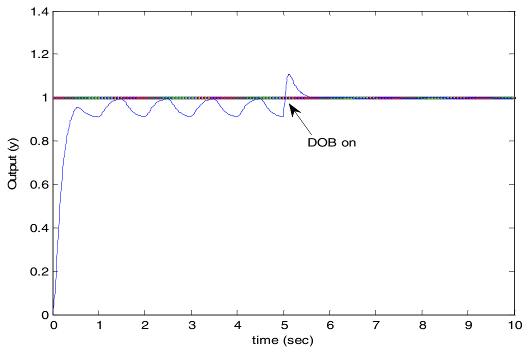

Fig. 9 Step response of the plant $G(s) = \frac{1}{s^2 + 2s + 10}$

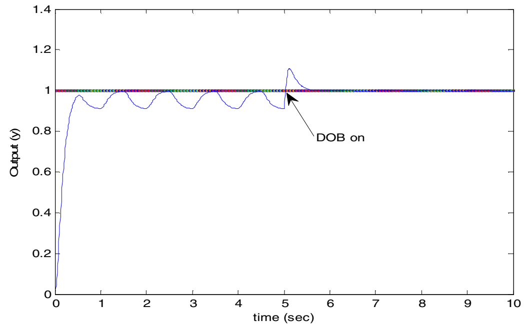

Fig. 10 Step response of the plant $G(s) = \frac{1}{s^2 + 10}$

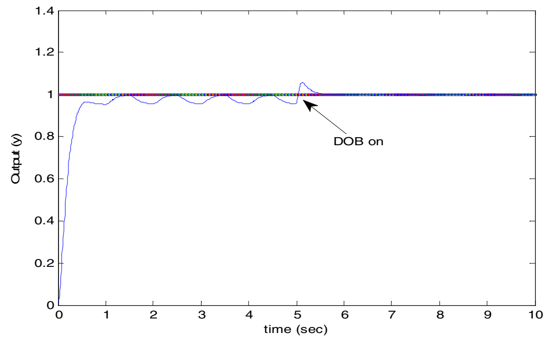

Fig. 11 Step response of the plant $G(s) = \frac{1}{2s^2 + 2s + 10}$

From all step results of several plants, we can conclude that the proposed TD DOB method minimizes disturbance effectively, and even minimizes the steady state errors.

4. CONCLUSION

This paper reformulates DOBs into a unified form so that the structure among several DOBs can be easily distinguished. The time-delayed control method is reconfigured as a non model-based DOB and several structures are presented. Only one condition required for the time-delayed DOB is that the sampling time should be fast enough such that the phase delay is minimal. TD DOB Scheme is eventually a same control structure except the way of acceleration feedback.

The TD DOB has two major drawbacks: a requirement of acceleration estimation and the stability due to a time-delay. Using accelerometer sensors allows the direct estimation of acceleration from the sensor without a delay. This simplifies a problem. Another problem is the use of the delayed information to form a control input. This can be solved by the current hardware technology.

Acknowledgement

This research has been partially supported by Korea Research Fund (KRF 2011-0027055), an abroad research program of Research Foundation of Chungnam National University, and the center for autonomous intelligent manipulation (AIM) for service robots of the MKE (The Ministry of Knowledge Economy), Korea, under the Human Resources Development Program for Convergence Robot Specialists support program supervised by the NIPA (National IT Industry Promotion Agency) (NIPA-2011-C7000-1001-0003).

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