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Estimation of Unknown Disturbances in Gimbal Systems

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Abstract. This paper presents a method for the estimation of unknown disturbances for high precision gimbal systems. Alternative to the classical methods of model inversion and filtering, we employ an asymptotically stabilizing controller which achieves the estimation process even in the presence of unstable zeros. The architecture provides an input equivalent disturbance which can be thought to capture all real disturbances in the system as well as virtual ones such as unmodelled dynamics and nonlinearities. The proposed method is illustrated on a 2-axis gimbal system where system identification is followed by the design on an integral linear quadratic regulator as the stabilizing controller which forms the base of the disturbance observer. It is seen that a random unknown disturbance is estimated successfully in the presence of additional gyro noise.

Introduction

Estimation of disturbances is an important topic of interest in gimbal systems due its high potential to improve the stabilization precision and in many such systems, disturbance compensation is the main issue to handle. Various methods have been proposed so as to estimate and observe unknown disturbances [1,6].Among these methods, inverse dynamics approach is the most common and widespread disturbance estimation method in literature [7,10]. This approach has been validated in numerous cases; however, the inverse dynamic approach in estimating unknown disturbances cannot be utilisedon plants that have unstable zeros. Another solution to the stated problem is using Kalman filters and many state and parameter estimation work using Kalman filters exist in literature [11, 14]. In addition, there have been efforts to estimate input disturbances instead only; by this approach it is not necessary to differentiate the measured output to estimate the disturbances [15].

The estimation methods mentioned above can be used to estimate the exact parameters of the system and external disturbances; however, most of them have some disadvantages for gimbal systems in practice. Firstly, it is assumed that measurements are accurate in each processing time and there is no measurement noise. Secondly, the state feedback observer, which used in estimation of input disturbance, needs analytic feedback gain calculation and hence the operation time of estimation is much longer. Thirdly, the disturbance observer, which is solely based on disturbance injected to the rotor as torque, may fail due to the existence of other types of disturbances. These methods depend on the disturbance model or type. Lastly, disturbance estimation based on Kalman filter has long operation time as well. In precise control of gimbals, operational time of the disturbance observer is the primary focus.

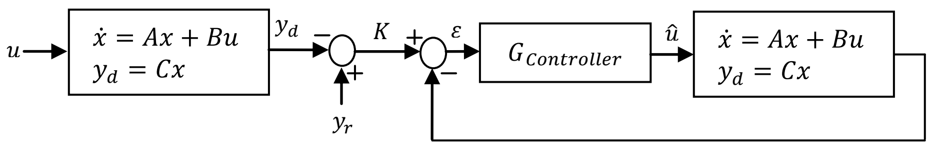

Fig. 1. The architecture of the proposed disturbance estimator

In this paper, a fast and precise estimation method for gimbal systems is proposed to overcome the problems mentioned above. The main objective of this disturbance estimator is to estimate all external disturbances by an asymptotically stable system with a fast response. The rest of the paper is organized as follows: First, the definition of equivalent input disturbance is given. Then, the mathematical model for disturbance estimation is presented. Finally, an empirical example is included to illustrate the success of the proposed technique for gimbals system.

Definition of Equivalent Input Disturbance

In this section, an equivalent input disturbance system is defined. Definition of the linear time-invariant model is shown in Eq. 1.

$$\dot{x_0} = Ax_0 + Bu + B_d T_d$$
$$y_0 = Cx_0 \quad (1)$$

Where $A \in \mathbb{R}^{n\times n}, B \in \mathbb{R}^{n\times 1}, B_d \in \mathbb{R}^{n\times n_d}$, and $C \in \mathbb{R}^{1xn}$. By the meaning of different dimensions on B andB_d, number of disturbances and their applied points may vary. However, if all types and numbers of disturbances are represented as disturbances on the input channel, then the equivalent plant model is as given in Eq. 2.

$$\dot{x} = Ax + B(u + T_{ed}) = Ax + Bu + BT_{ed}$$
$$y = Cx \quad (2)$$

If $y = y_0$, then the disturbance T_{ed} is called the equivalent input disturbance of the disturbanceT_d.

Mathematical Model of Disturbance Estimator

The architecture of the proposed disturbance estimator is given in Fig. 1. The estimator uses two kinds of system models. Below,state-space system models that are under equivalent disturbance and with no disturbances are defined in Eq. 3 and in Eq. 4 respectively.

$$\dot{x} = Ax + Bu + BT_{ed}$$
$$y_r = Cx \quad (3)$$

$$\dot{x} = Ax + Bu$$
$$y_d = Cx \quad (4)$$

Here, to estimate the disturbance T_{ed}, the difference between y_d and y_r is calculated in Eq. 5.

$$y_r - y_d = C\left[\int_0^\infty (Bu + BT_{ed} + Ax)dt - \int_0^\infty (Bu + Ax)\, dt\right] \quad (5)$$

The simplified form of Eq. 5 is given in Eq. 6.

$$K = C\int_0^\infty (BT_{ed})dt \quad (6)$$

where K is the difference betweeny_d and y_r.In Fig. 1,ε is the error of the disturbance estimator system, $G_{Controller}$ is the controllerwhose output $\hat{u}$estimates the equivalent disturbanceT_{ed}. It is assumed that the $G_{Controller}$ makes the plant in Eq. 4 asymptotically stable so that the error ε converges to zero, that is

$$\varepsilon = K - y_d = C\left[\int_0^\infty (BT_{ed} - B\hat{u} - Ax)dt\right] \to 0\,. \quad (7)$$

If $C \neq 0$ this implies that the integrand also converges to zero, hence

$$BT_{ed} - B\hat{u} - Ax \rightarrow 0$$

$$\hat{u} + \frac{B^T}{B^T B} Ax \rightarrow T_{ed} \tag{8}$$

for $B \neq 0$. To summarize, the equivalent disturbance T_{ed} can be estimated as in Eq. 8 under the following assumptions:

i) $B \neq 0, C \neq 0$.

ii) $x$is measured or can be observed. (i.e. (C, A) is observable.)

iii) $G_{Controller}$asymptotically stabilizes the plant in Eq. 4.

By this approach, all disturbances between the real system and the linear model can be estimated as an equivalent disturbance. In addition, the real system's nonlinear behavior can also be captured in T_{ed}. Thus, the proposed disturbance observer is flexible and addresses many drawbacks of classical disturbance observers mentioned in the introduction section. The next section presents a numerical example showing the proposed disturbance observer in action.

Numerical Example for A 2-axis Gimbal System

Validation of the proposed disturbance estimator on a 2-axis gimbals system is made as shown in Fig. 2. The actual photos of the system as well as the exact parameters for the system and controllers cannot be provided due to the confidential military nature of the project; therefore the results will be illustrated as plots only.

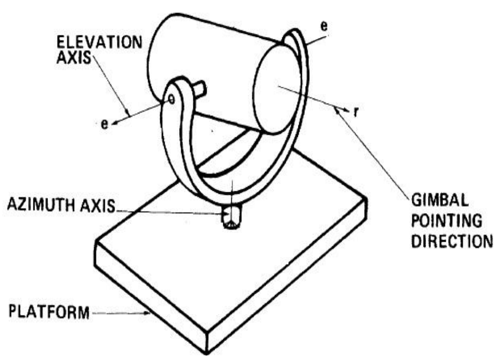

Fig. 2

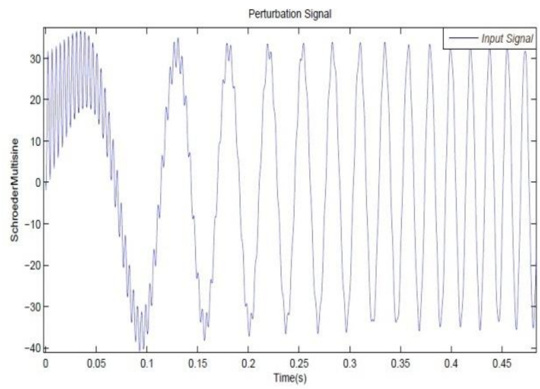

Fig. 3

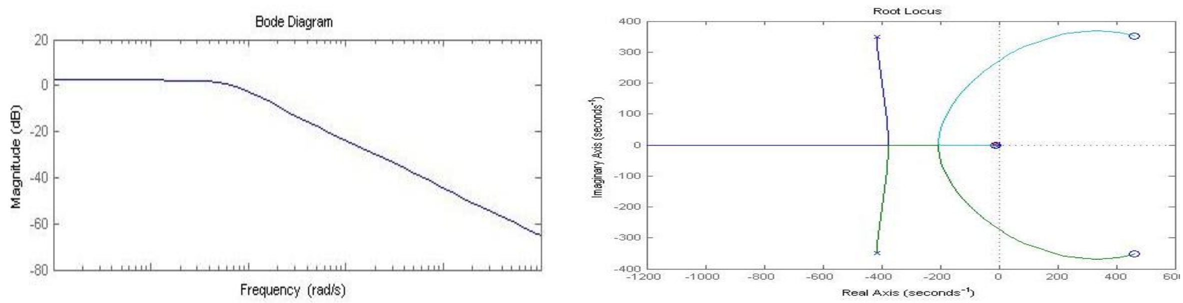

Fig. 4

For simplicity, the disturbance estimator is demonstrated only for the elevation axis in this paper; the designs for other axes follow similarly. The elevation axis has a direct-drive DC motor for which the design and validation procedure is carried out in the following steps:

Step1: Getting the system model with real-time system identification.

Step2: Design of the controller ($G_{Controller}$) which makes the plant obtained in Step1asymptotically stable.

Step3: Using the proposed observer architecture in the previous section to estimate disturbances.

Step1. In this step, black box system identification is applied to the gimbal, the schematic illustration of which is given in Fig. 2.

Direct-drive motor is driven by an input torque signal, namely Schroeder Multisine Signal, as shown in Fig. 3. Gyro signal for elevation axis is selected as the output signal of the black box system. By using $MATLAB^{®}$ System Identification Toolbox, a fourth order state-space black box system was obtained. This system's bode plot and root locus diagrams are shown in Fig. 4., from where it is seen that the plant has two unstable zeros.

Step2. The employed controller $G_{Controller}$ is a Linear Quadratic Regulator (LQR) (see Anderson and Moore (2007)) with integral action to achieve tracking. The plant is revisedby adding this integral error term in Eq. 9 and the control input $\hat{u}$is calculated by the LQR method asshown in Eq. 10.

$$\begin{bmatrix} \dot{x} \\ \dot{\varepsilon} \end{bmatrix} = \begin{bmatrix} A & 0 \\ -C^T & 0 \end{bmatrix} \begin{bmatrix} x \\ \varepsilon \end{bmatrix} + \begin{bmatrix} B \\ 0 \end{bmatrix} u + \begin{bmatrix} 0 \\ 1 \end{bmatrix} K \tag{9}$$

$$\hat{u} = -\widehat{K}_{optimal,gains} x + VK \tag{10}$$

where$\varepsilon = \int_0^t (K - y_d)dt$ is the additional integral state variable, $\widehat{K} = R^{-1}B^T P$ is theoptimal gain vector for state regulation and $V = -(C^T(A - B\widehat{K})^{-1}B)^{-1}$ is the feedforward action which compensates steady-state error of the system.P is the solution of Ricatti Equation shown in Eq. 11.The proposed controller guarantees asymptotical stability.

$$A^T P + PA - PBR^{-1}B^T P + Q = 0 \tag{11}$$

Step3. The proposed architecture is shown in Fig. 5. For the estimation process, an unknown disturbance signal shown in Fig. 6 is employed. The proposed architecture's response with actual disturbance is given in Fig. 7. In this estimation process, a MATLA$B^{®}$/Simulink based xPC target machine is employed. In this experiment the gyro also has a low magnitude noise. As seen in Fig. 7, the disturbance is estimated successfully in real-time, with only a low delay (30 ms) due to the system dynamics.

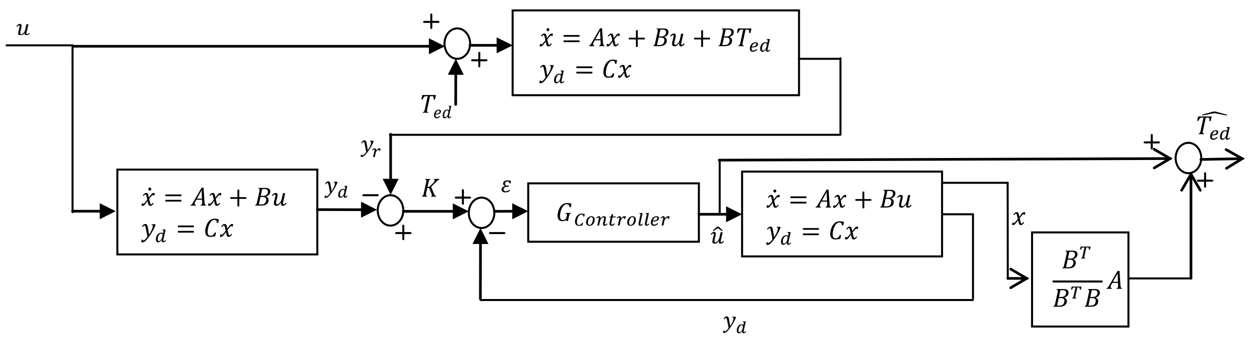

Fig. 5

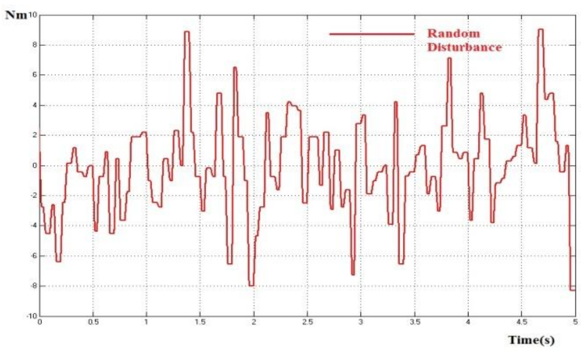

Fig. 6

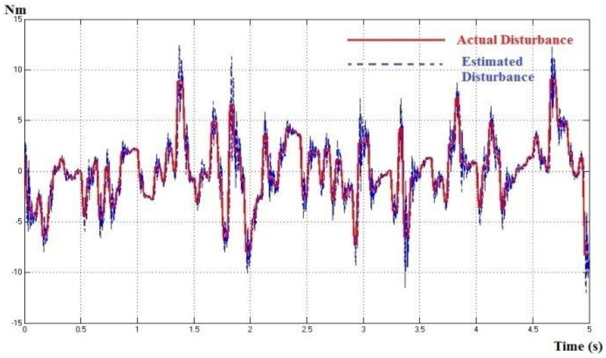

Fig. 7

Conclusions and Future Works

In this paper a method was considered for the estimation of disturbances in gimbal systems for high precision control. The disturbance is estimated by comparing the real and predicted outputs through a stabilizing controller, the input of which provides an estimate for the input equivalent disturbance, which represents all disturbances in the system as well as nonlinearities and unmodelled dynamics. The presented approach works for plants with unstable zeros as well, which provides an advantage over traditional filtered inverse dynamics designs. The proposed method was tested on an actual 2-axis gimbal system with unstable zeros and it was seen that even under gyro noise the unknown disturbance was estimated successfully.

Future research directions include extending the proposed approach to wider classes of systems, augmenting controller design to the process and testing on different experimental platforms.

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