DOI: https://doi.org/10.33103/uot.ijccce.22.3.4

Robust Sensor Fault Estimation for Control Systems Affected by Friction Force

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Abstract*— The paper presents an observer-based estimation of sensor fault for control systems affected by friction force. In such systems, the non-linearity of friction force leads to deteriorating sensor fault estimation capability of the observer. Hence, the challenge is to design an observer capable of attaining robust sensor fault estimation while avoiding the effects of friction. To overcome the highlighted challenge, an Unknown Input Observer (UIO) is designed to decouple the effects of friction as well as to estimate the state and sensor fault.The benefit of proposing UIO is to guarantee robust sensor fault estimation despite the highly non-linear disturbance in the form of friction. The gains of the UIO are computed through a single–step linear matrix inequality. Finally, an inverted pendulum simulation is presented to demonstrate the novel approach's performance effectiveness.*

Index Terms*—Robust fault estimation, Fault-Tolerant control, unknown input observer, Friction force, estimation/decoupling approach.*

I. INTRODUCTION

In real-world, huge systems may suffer from some failures, resulting in performance degradation and system instability. This increase the requirements to enhance control system safety and accuracy. It is important to know the beginning and development of the faults before they become serious and then compensate its effects from the closed-loop system or replace faulty components with fault-free (hardware redundancy). Fault-tolerant control is the process of accounting for faults acting within a control system in order to make the system insensitive to the faults, of which fault estimation and compensation control is one way [1] , [2] , [3] , [4].

By utilizing fault estimation, the Fault Tolerant Control (FTC) technique aims to overcome a number of challenges Fault Estimation (FE). FE is a fault diagnosis method that tells when and where the faults occur as well as provides information about the sizes and shapes of the faults. FTC and FE approaches have been shown in the control literature to show an important role in preserving system sustainability [5] , [6] , [7]. Information provided by FE is critical for online fault-tolerant control and real-time decision. FE designs are efficient except if they have perfect robustness against perturbations such as external disturbance, system uncertainty, friction force, acting on output measurements and state dynamics. Fault estimation can be realized by utilizing different observer techniques such as unknown input observers, that’s used to estimated / decoupling differents kinds of faults [8] , [9] , adaptive observers [10] , sliding mode observers, that’s used to compensated the effects of the faults [11] , [12] , [13] , [14] , and augmented system observers (including descriptor observers) [15] , [16] , [17] , [18].

Received 17/September/2021; Accepted 26/November/2021

 ISSN (Print) 1811-9212 ISSN (Online) 2617-3352

DOI: https://doi.org/10.33103/uot.ijccce.22.3.4

One of the methods in the literature to enhance FE robustness is the decoupling approach, It removes the perturbations/faults whose distribution matrix meets the matching rank condition from the estimate error dynamics [12].

Depending on the fault diagnostic method, within the FTC system, the fault signals can be estimated or decoupled [12].

This paper explains how to create a resilient FE/FTC model that can handle a wide range of time-varying faults. The system under consideration is a linear system with friction force and sensor faults.

Despite several studies, designing an FE observer for control systems with friction involves robustness challenges. The challenges are caused mainly by the non-linearity of friction force. Here, a new approach is nominated to deal with the FE problem in control systems with friction. Specifically, the friction force is viewed as a non-linear disturbance acting within the dynamic system. Then, regardless of the time behavior of friction, the effect is decoupled by exploiting the ability of UIO [19] , [20].

The contributes of this research are:

- A full-order (UIO) is presented to achieve FE. Full-order UIO is proposed in this study for time-varying sensor fault estimation in the state feedback case.
- To decouple the impacts of the friction force a new technique for FE/FTC design employing UIO has been proposed.

The structure of the paper is as follows: Section II. discusses the unknown input observer design (UIO) for a linear system affected by a sensor fault and friction force, as well as the LMI formulation for the UIO-based FTC design. The design of the active FTC controller is discussed in Section III. The simulation for this algorithm by using inverted pendulum with a cart as a friction force is demonstrated in Section IV. Section V. the conclusions.

II. THE DESIGN OF UIO FOR A LINEAR SYSTEM AFFECTED BY SENSOR FAULT AND FRICTION FORCE

The UIO for linear systems with sensor faults and friction force are introduced in this section. Ensure reliable fault estimation and in such systems is a difficult task. The required tasks can be accomplished using the new estimation/decoupling design technique. Consider the following linear system as shown in equation (1):

$$\begin{aligned} \dot{x}(t) &= Ax(t) + B\left[u(t) + f_{fric}(t)\right] \\ y(t) &= Cx(t) + F_s f_s(t) \end{aligned} \tag{1}$$

Where $x \in R^n, u \in R^m, y \in R^p$are the system state, input and output vectors, respectively. f_{fric} is the non-linear friction force applying on the system, and can be viewed as an actuator fault, $f_s \in R^l$ is the sensor fault, $A \in R^{n\times n}, B \in R^{n\times m}, C \in R^{p\times n}, F_s \in R^{p\times q}, wit\square\ q \le p < n$ and the matrices C is of full rank see *Fig. 1*. The pairs (A,B) and (A,C) are controllable and observable.

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 ISSN (Print) 1811-9212 ISSN (Online) 2617-3352

DOI: https://doi.org/10.33103/uot.ijccce.22.3.4

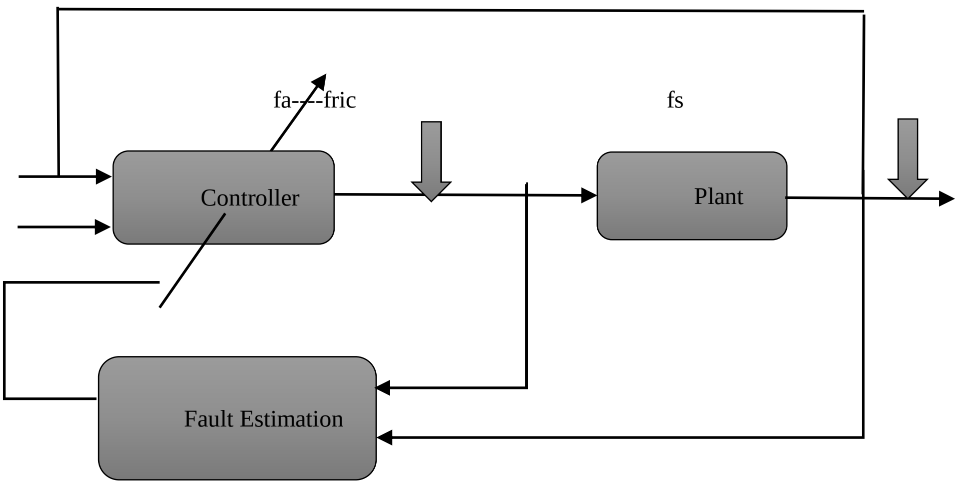

FIG. 1. A FTC WITH FAULT ESTIMATION TO THE SENSOR FAULT FOR CONTROL SYSTEMS AFFECTED BY FRICTION FORCE.

The system is transformed to manage sensor faults by creating a new state $x_s \in R^p$, which is defined as $\dot{x}_s = -A_s x_s + A_s y$, where $-A_s$ is a stable matrix with proper dimensions. The following is a description of the new system as shown in equation (2):

$$\begin{gathered} \dot{x}_n = A_n x_n + B_n\left[u + f_{fric}\right] + F_{sn} f_s \\ y_n = C_n x_n \end{gathered} \tag{2}$$

Where $x_n = \begin{bmatrix} x \\ x_s \end{bmatrix}$, $A_n = \begin{bmatrix} A & 0 \\ A_s C & -A_s \end{bmatrix}$, $B_n = \begin{bmatrix} B \\ 0 \end{bmatrix}$, $C_n = \begin{bmatrix} C & o \\ 0 & I_p \end{bmatrix}$, $F_{sn} = \begin{bmatrix} 0 \\ A_s F_s \end{bmatrix}$.

Obviously, $x_n \in R^{\bar{n}}, \bar{n} = n + p$ is the state vector that includes the system states, in order to use the developed actuator FE methods for sensor fault problems, as shown in the construction of a system (2).

The derivative of f_s with respect to time is assumed is be norm bounded function i.e., $\|\dot{f}_s\| \leq f_1 , w\square ere\ 0 \leq f_1 < \infty$.

The next UIO is consider to estimate the augmented state x_n as shown in equation (3)

$$\begin{gathered} \dot{z} = Mz + Ju + Ly_n + F\hat{f}_s \\ \hat{x}_n = z + Hy_n \end{gathered} \tag{3}$$

Where $z, \hat{x} \in R^{\bar{n}}$ indicate the observer system state and its state estimate respectively. The design matrices M, J, L, F and H are of the suitable dimensions.

The state dynamic error is defined as follows in equation (4):

$$e_x = x_n - \hat{x}_n = x_n - z - HC_n x_n = (I_{\bar{n}} - HC_n)x_n - z = Tx_n - z \tag{4}$$

Denote $T = I_{\bar{n}} - HC_n$, $L = L_1 + L_2$, $F = T * F_{sn}$, $and\ A_1 = TA_n$, so that

$$\begin{gathered} \dot{e}_x = (A_1 - L_1 C_n)e_x + (A_1 - L_1 C_n - M)z + (TB_n - J)u + [(A_1 - L_1 C_n)H - L_2]y_n \\ +TB_n f_{fric} + TF_{sn} e_{fs} \end{gathered} \tag{5}$$

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Conditions required for the error system's stability (5) are (6), (7), and (8).

$$A_1 - L_1 C_n - M = 0 \tag{6}$$
$$TB_n - J = 0 \tag{7}$$
$$(A_1 - L_1 C_n)H - L_2 = 0 \tag{8}$$

The state estimation error is reduced to equation (9)

$$\dot{e}_x = M e_x + T F_{sn} e_{fs} \tag{9}$$

It is worthy noting that the free design parameters (H, J, L_1, L_2) are utilized to achieve equations (6-8) to make the dynamic error (9) only affected by e_{fs}. Hence, if the M is Huriwitz, the error (e_x)converges to a small region around zerogoverned by the fault estimation error.

Note that the dynamic error is related to e_{fs} only, then the error tends to zero if the M is Huriwitz and estimation converges to zeros.

Knowing that $e_y = y_n - \hat{y}_n$ and based on equation of y_n in (2), the following relationship is obtained as shown in equation (10):

$$\begin{aligned} e_y &= C e_x \\ \dot{e}_y &= C \dot{e}_x \end{aligned} \tag{10}$$

The formula chosen to estimate the sensor fault is as follow in equation (11):

$$e_{fs} = \hat{f}_s - f_s \tag{11}$$

In the case of time varying sensor faults, the derivative of e_{fs} is due to $\dot{f}_s \neq 0$, as shown in (12)

$$\dot{e}_{fs} = \dot{\hat{f}}_s - \dot{f}_s \tag{12}$$

The friction force can be decoupled, and to do these the following assumptions must be made.

Assumption 1: $rank\ (C_n B_n) = rank\ (B_n)$.

Assumption 2: $t\square e\ pair\ (C_n, A_n)\ is\ detectable$, Cn is full rank

Assumption 3: invariant zeros of $(A_n,\ F_{sn}, C_n)$ lie in open Left Half Plane (LHP).

Assumption 1 ensure that the term of the friction force in equation (5) is solvable, and it has a unique solution is as in equation (13)

$$H = B_n[(C_n B_n)^T (C_n B_n)]^{-1} (C_n B_n)^T \tag{13}$$

So, assumption 2 ensures that Hurwitz local matrices exist (M).

The goal then is to calculate the gains M, J, L to ensure robust performance by decoupling the effect of the friction force in equation (5)

Lemma 1: the following inequality in (14) holds for a scalar μ>0 and a symmetric positive definite (spd) matrix P:

$$2x^T y \leq \frac{1}{\mu} x^T P x + \mu y^T P^{-1} y \quad\quad x, y\ \in R^{\bar{n}} \tag{14}$$

Theorem 1: if P>0, Q>0 are symmetric positive definite matrices, and a matrix F that satisfy the following conditions [21] as in (15) and (16)

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$$P(A_1 - L_1C_n) + (A_1 - L_1C_n)^T P = -Q \tag{15}$$

$$(TF_{sn})^T P = FC \tag{16}$$

Then the sensor fault estimation using the integral and the preoperational is as following (17)

$$\dot{\hat{f}}_s = -\Gamma F(\dot{e}_y + \sigma e_y) \tag{17}$$

The learning rate is represented by the symmetric positive definite matrix Γ. Substituting $e_y = Ce_x$ in (17) gives the following term in (18)

$$\dot{\hat{f}}_s = -\Gamma FC(\dot{e}_x + \sigma e_x) \tag{18}$$

Remark 1: To improve the traditional technique so that time-varying faults can be taken into account while using the UIO observer, then the sensor fault estimation using the integral and the preoperational terms is proposed, It helps to improve the speed which sensor fault estimate may be done.

Lemma 2: If and only if assumptions 1-3 are true, the conditions (15)-(16) hold.

Theorem 2: if there exist symmetric positive definite matrices P>0, G>0, Γ>0 matrices H and Y,and a scalar σ satisfying the following LMI constraint, the UIO modul in (3) is stable and the H∞ performance is secured as shown in (19):

$$\begin{bmatrix} PA_1 + A_1{}^T P - YC_n - C_n{}^T Y^T & -\left(\frac{1}{\sigma}\right)(PA_1 - YC_n)^T (TF_{sn}) \\ * & -2\left(\frac{1}{\sigma}\right)(TF_{sn})^T P (TF_{sn}) + (1/(\sigma\mu))G \end{bmatrix} < 0 \tag{19}$$

Where $Y=PL_1$, and * indicates the symmetric elements in a symmetric matrix.

Proof: For the following function, the observer gains should meet Lyapunov's conditions of the next equation to create a stable estimation error dynamic for (19) as in (20):

$$V(e_x) = e_x{}^T P e_x + (1/\sigma) e_{fs}{}^T \Gamma^{-1} e_{fs} \tag{20}$$

The time derivative of (20) gives the following equation in (21)

$$\dot{V}(e_x) = e_x{}^T P \dot{e_x} + \dot{e_x}{}^T P e_x + \frac{1}{\sigma} e_{fs}{}^T \Gamma^{-1} \dot{e}_{fs} + \frac{1}{\sigma} \dot{e}_{fs}{}^T \Gamma^{-1} e_{fs} \tag{21}$$

Knowing that $e_{fs}{}^T \dot{e}_{fs} = \dot{e}_{fs}{}^T e_{fs}$, the following derivative Lyapunov function can be obtained in (22):

$$\begin{aligned} \dot{V}(e_x) &= e_x{}^T P \dot{e_x} + \dot{e_x}{}^T P e_x + 2\frac{1}{\sigma} e_{fs}{}^T \Gamma^{-1} \dot{e}_{fs} \\ &= e_x{}^T P\left[(A_1 - L_1C_n)e_x + TF_{sn}e_{fs}\right] + \left[(A_1 - L_1C_n)e_x + TF_{sn}e_{fs}\right]^T P e_x \\ &\quad + 2\frac{1}{\sigma} e_{fs}{}^T \Gamma^{-1}\left[-\Gamma FC\left((A_1 - L_1C_n)e_x + TF_{sn}e_{fs} + \sigma e_x\right) - \dot{f}_s\right] \end{aligned} \tag{22}$$

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$$= e_x{}^T\left[PA_1 + A_1{}^T P - YC_n - C_n{}^T Y^T\right]e_x - 2\frac{1}{\sigma}e_{fs}{}^T(TF_{sn})^T P(A_1 - L_1C_n)e_x - 2\frac{1}{\sigma}e_{fs}{}^T(TF_{sn})^T P(TF_{sn})e_{fs} - 2\frac{1}{\sigma}e_{fs}{}^T\Gamma^{-1}\dot{f}_s$$

From Lemma 1, it obtained the following equation as in (23)

$$-2\frac{1}{\sigma}e_{fs}{}^T\Gamma^{-1}\dot{f}_s \leq \frac{1}{\sigma\mu}e_{fs}{}^T G e_{fs} + \frac{\mu}{\sigma}\dot{f}^T\Gamma^{-1}G^{-1}\Gamma^{-1}\dot{f}_s \leq \frac{1}{\sigma\mu}e_{fs}{}^T G e_{fs} + \frac{\mu}{\sigma}f_1{}^2\lambda_{max}(\Gamma^{-1}G^{-1}\Gamma^{-1}) \quad (23)$$

Substitution equation (23) into (22), can obtain the equation (24):

$$\dot{V}(e_x) = \begin{bmatrix} e_x \\ e_{fs} \end{bmatrix}^T \begin{bmatrix} PA_1 + A_1{}^T P - YC_n - C_n{}^T Y^T & -\left(\frac{1}{\sigma}\right)(PA_1 - YC_n)^T(TF_{sn}) \\ * & -2\left(\frac{1}{\sigma}\right)(TF_{sn})^T P(TF_{sn}) + (1/(\sigma\mu))G \end{bmatrix} \begin{bmatrix} e_x \\ e_{fs} \end{bmatrix} + \varepsilon \quad (24)$$

Where $\varepsilon = \frac{\mu}{\sigma}f_1{}^2\lambda_{max}(\Gamma^{-1}G^{-1}\Gamma^{-1})$.

Next, it will look at how to solve the conditions in Theorem 1. It is easy to solve the inequality (19) by using the LMI toolbox, but the solving difficulty is increased by equation (16). In fact, it is a major problem to solve (16) and (19) simultaneously. Fortunately, it can transform (16) in Theorem 1 to the following optimization problem [21].

Minimize ψ subject to (19) and (25)

$$\begin{bmatrix} \psi^I & (TF_{sn})^T - FC \\ ((TF_{sn})^T - FC)^T & \psi^I \end{bmatrix} > 0. \quad (25)$$

III. THE DESIGN OF THE ACTIVE FTC CONTROLLER

A general form of fault estimation based FTC controller input is shown in equation (26):

$$u = Kx \quad (26)$$

By using the pole-placement method, the nominal controller gain K is got.
By substituting (26) into (1), the closed-loop system will be as in (27):

$$\begin{aligned} \dot{x} &= (A + BK)x + Bf_{fric} \\ y_c &= y_n - F_s\hat{f}_s \end{aligned} \quad (27)$$

Where y_c is the output for the system without sensor fault and $\hat{f}_s = [0\ I_q]$ is the sensor fault estimate.

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IV. SIMULATION RESULTS

This section provides a practical model of the inverted pendulum with the cart as a control system impacted by a friction force. By using force control on the cart, a transmission belt connects the cart to a drive wheel controlled by a DC-motor, which in the vertical plane, this turns the pendulum into a vertical position. The non-linear mathematical model equations are illustrated below in (28) [19], [22]:

$$\begin{gathered}(M+m)\ddot{x}_r + F_x\dot{x}_r + m\left(\ddot{\theta}cos\theta - \dot{\theta}^2 sin\theta\right) = u - f_{fric}(\dot{x}_r),\\ J\ddot{\theta} + F_\theta\dot{\theta} - mlgsin\theta + ml\ddot{x}_r cos\theta = 0\end{gathered} \tag{28}$$

Wherex_r and θ are the cart position and the pendulum angle. Table I lists the specific the values for the system parameters. The non-linear equations of motion have been linearized around the equilibrium point $\dot{x}_r = \dot{\theta} = \theta = 0$.

TABLE I. THE INVERTED PENDULUM SYSTEM'S PARAMETER VALUES

	M	m	J	l	F_x	F_θ	g
Values	3.2	0.535	0.062	0.365	6.2	0.009	9.807
Units	kg	kg	$kg.m^2$	m	kg/s	$kg.m^2$	m/s^2

The discontinuous Stribeck friction model is used to simulate the friction force operating on the cart is as in (29) [19].

$$f_{fric} = g(x_r)Sign(x_r), \qquad Sign(x_r) \in \begin{Bmatrix} \{-1\} & if\ x_r < 0 \\ \{-1,1\} & if\ x_r = 0 \\ \{1\} & if\ x_r > 0 \end{Bmatrix} \tag{29}$$

$g(x_r) = F_c + (F_s - F_c)exp(-|x_r|/v_s)^{\delta}$, F_c and F_s represent the Coulomb and static friction levels, whereas v_s and $\delta > 0$ represent the Stribeck velocity and shaping parameters, respectively. The values of the parameters that used in the simulation are as follow:

$$F_c = 25\,, \quad F_s = 30\,, \ \ v_s = 0.15ms^{-1} \ \ and\ \delta > 2$$

These results correlate to the signal input u and measurements y in the system triple. The measurements (cart position, pendulum angular position, and cart velocity) duplicate the laboratory system measurements.

$$A = \begin{bmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & -1.9333 & -1.9872 & 0.0091 \\ 0 & 36.9771 & 6.2589 & -0.1738 \end{bmatrix}$$

$$B = \begin{bmatrix} 0 \\ 0 \\ 0.3205 \\ -1.0095 \end{bmatrix}, \quad C = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix}, \quad E = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0.1 \end{bmatrix}, \quad F_s = \begin{bmatrix} 0 \\ 0.1 \\ 0 \end{bmatrix}$$

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Three simulation cases are used with the structure of FE and FTC design to demonstrate the effectiveness of the suggested control mechanism. i.e., case 1 for the inverted pendulum in the absence of sensor faults and friction force and case 2 for the same system withsensor faults, and case 3 with sensor faults and friction force.The system model was implemented using MATLAB.

CASE 1: SIMULATION IN THE ABSENCE OF SENSOR FAULT AND FRICTION FORCE (IDEAL LINEAR SYSTEM)

The system without faults and friction force is considered in this scenario. The simulation results for the given initial values for such a system are seen in the figures below. *Fig. 2* shows the error dynamic of the states. *Fig. 3* described the actual states and the estimated states. And, finally, *Fig. 4* depicts the system's control input.

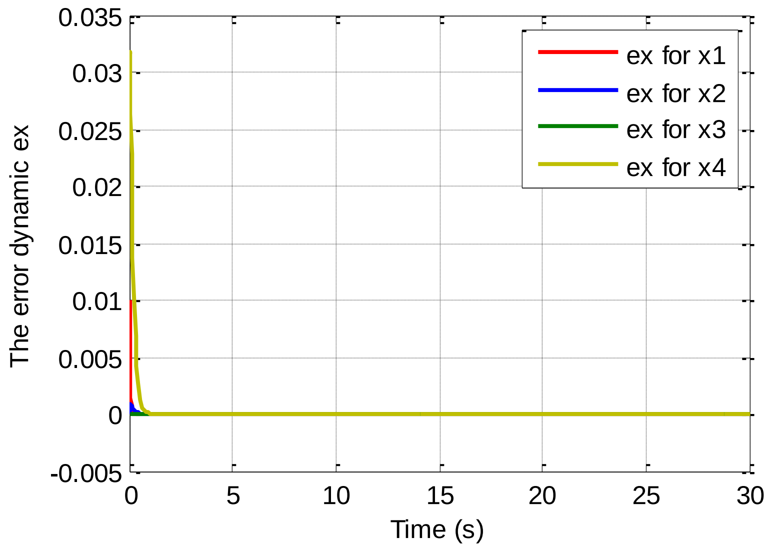

FIG. 2. THE ERROR DYNAMIC USING THE UIO WITHIN FTC FOR IDEAL SYSTEM.

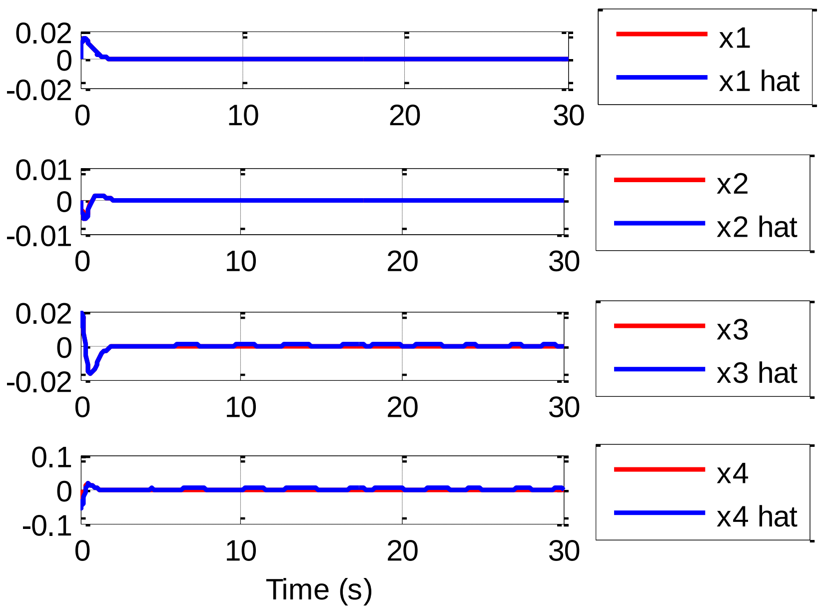

FIG. 3. THE X AND ESTIMATED X USING THE UIO WITHIN FTC FOR IDEAL SYSTEM.

Received 17/September/2021; Accepted 26/November/2021
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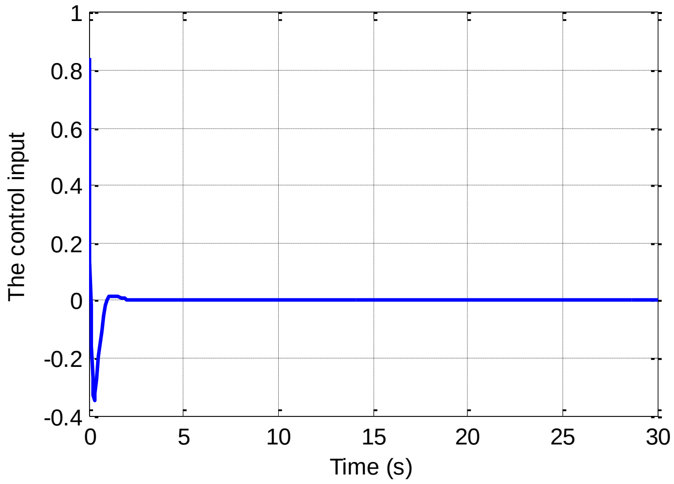

FIG. 4. THE CONTROL INPUT USING THE UIO WITHIN FTC FOR IDEAL SYSTEM.

CASE 2: SIMULATION IN THE PRESENCE OF SENSOR FAULT

The sensor fault will be chosen as a step signal, and it's started at a time of 10 sec as present in *Fig. 5*. The results in *Fig.* 6 show how the UIO structure-based FE design work in the presence of sensor faults to estimate the effect of sensor faults and how the error dynamic changes as a result of the sensor fault.

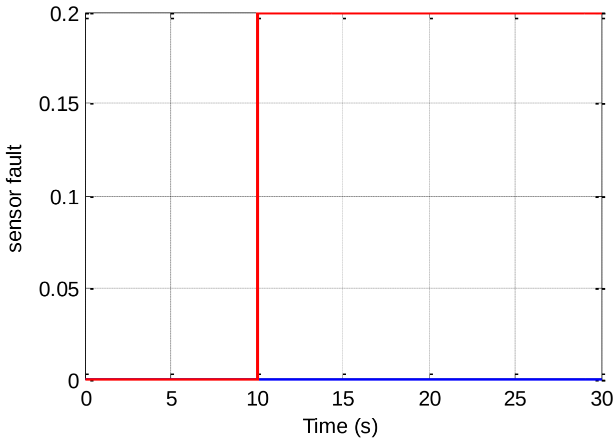

FIG. 5. THE SENSOR FAULT THAT AFFECTS THE SYSTEM OUTPUT AT TIME 10 SECOND.

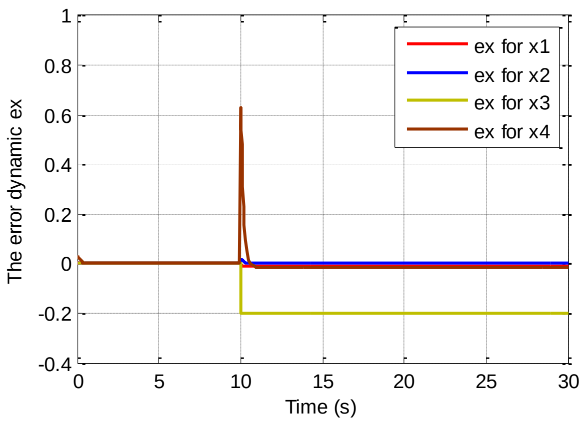

FIG. 6. THE ERROR DYNAMIC USING THE UIO WITHIN FTC FOR CONTROL SYSTEM AFFECTED BY SENSOR FAULTS.

Received 17/September/2021; Accepted 26/November/2021

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Then, using the UIO, the sensor fault can be estimated, as seems in *Fig.* 7, the estimated sensor fault is extremely near to the actual one, that's mean that the observer is worked perfectly to estimated the faults.

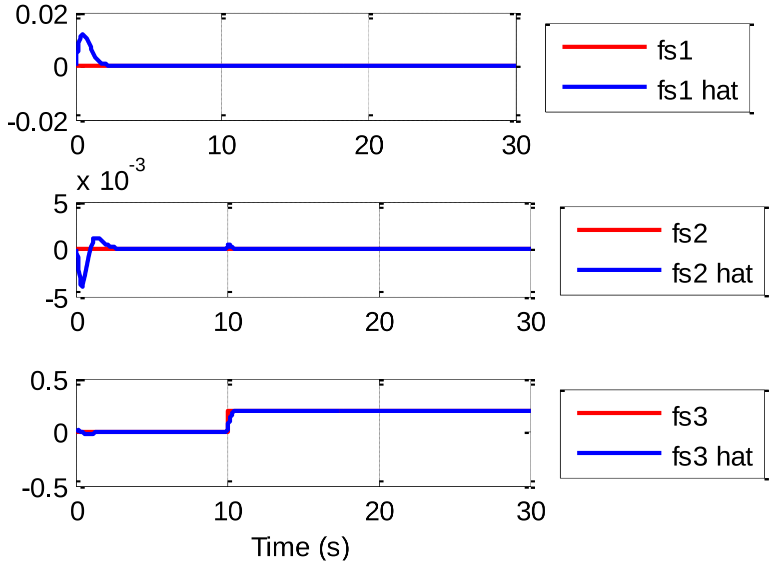

FIG. 7. THE SENSOR FAULT AND ITS ESTIMATION USING THE UIO WITHIN FTC FOR CONTROL SYSTEM AFFECTED BY SENSOR FAULTS.

Fig. 8 and *9* described the actual states and the estimated states, and the control input.

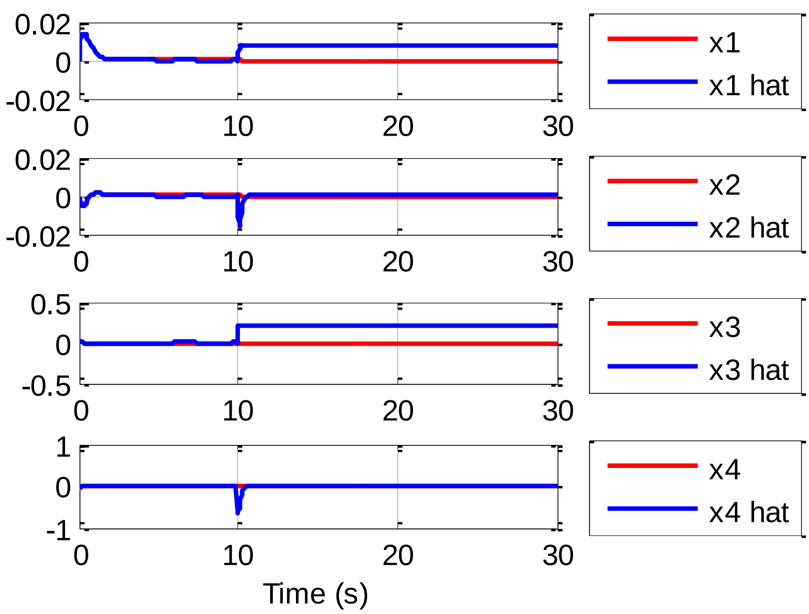

FIG. 8. THE X AND ESTIMATED X USING THE UIO WITHIN FTC FOR SYSTEM EFFECTED BY SENSOR FAULT.

Received 17/September/2021; Accepted 26/November/2021
 ISSN (Print) 1811-9212 *ISSN (Online) 2617-3352*

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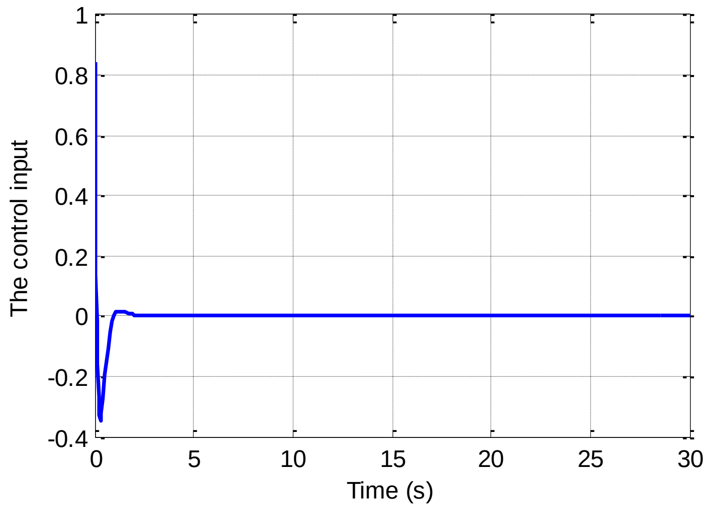

FIG. 9. THE CONTROL INPUT FOR SYSTEM EFFECTED BY SENSOR FAULT.

CASE 3: SIMULATION FOR A SYSTEM AFFECTED BY SENSOR FAULT IN THE PRESENCE OF FRICTION FORCE

The robustness problems that come with FE design, when the system is effected by a sensor fault in the presence of friction force are examined in this section.

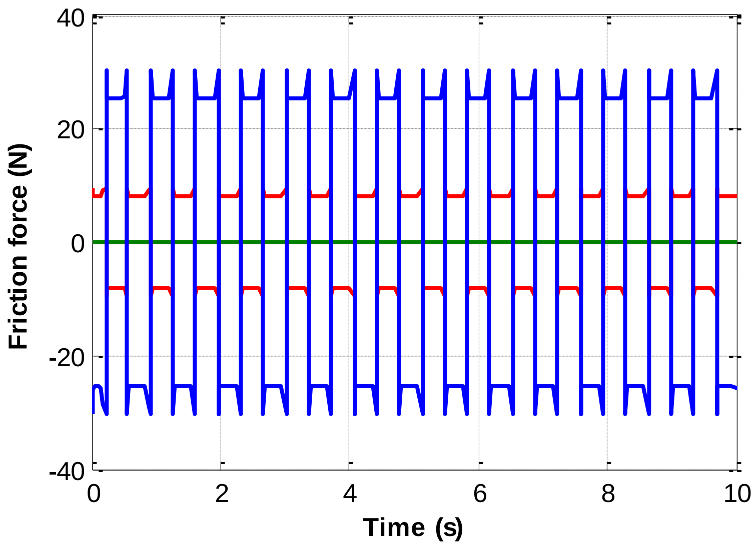

FIG. 10. THE FRICTION FORCE FOR THE CONTROL SYSTEM WITH FS = 30 N.

Consequently, the unpredictable time behavior of the friction force and the high level of non-linearityimpose robustness challenges on using estimation/decoupling approach of sensor faults and friction force with UIO.

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 ISSN (Print) 1811-9212 ISSN (Online) 2617-3352

DOI: https://doi.org/10.33103/uot.ijccce.22.3.4

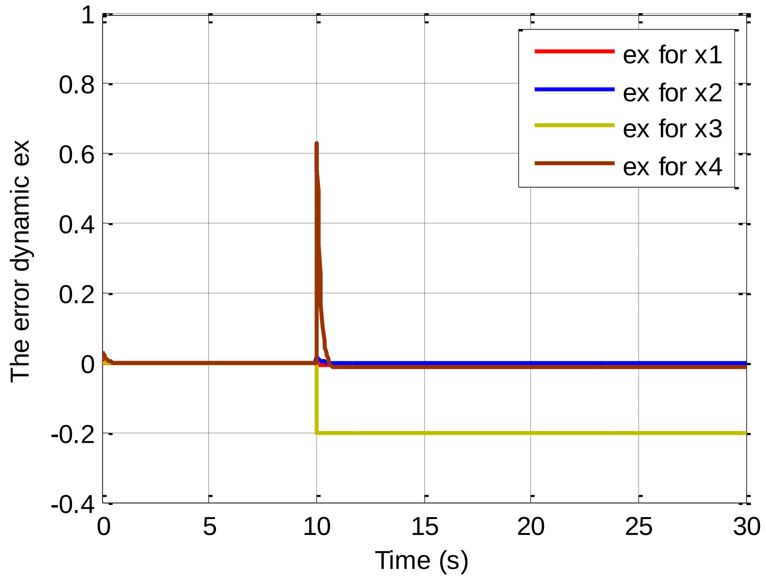

FIG. 11. THE ERROR DYNAMIC USING THE UIO FOR A SYSTEM WITH SENSOR FAULTS AND AFFECTED BY FRICTION FORCE.

By using the design procedure, it shows from *Fig. 11* how the error dynamic affected by sensor fault in the existence of the friction force.

Since the advantage of the UIO is to estimate the sensor fault and decoupling the friction force. The sensor fault and its estimation can be seen in *Fig. 12*.

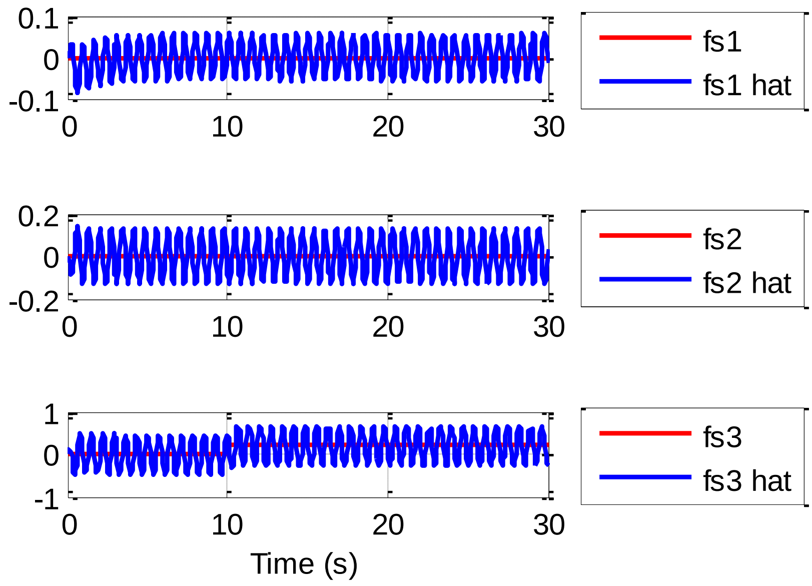

FIG. 12. THE SENSOR FAULT AND ITS ESTIMATION IN THE PRESENCE OF THE FRICTION FORCE.

Received 17/September/2021; Accepted 26/November/2021
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Finally, *Fig.* 13 illustrates the control input of the system that is affected by sensor fault in the presence of the friction force.

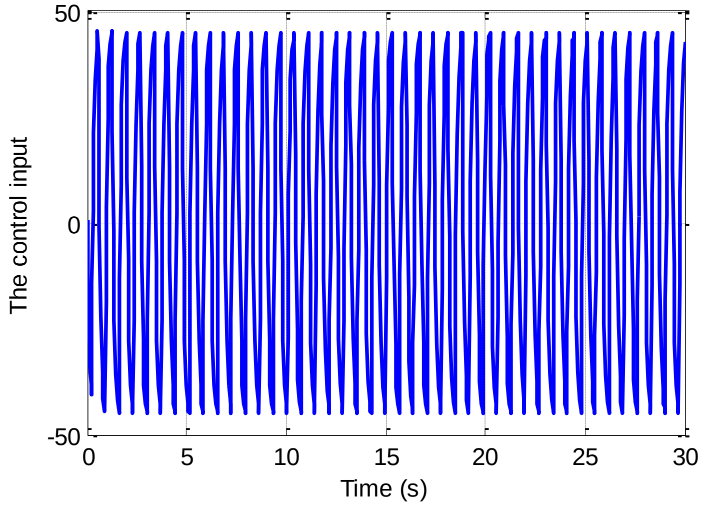

FIG. 13. THE CONTROL INPUT FOR SYSTEM EFFECTED BY SENSOR FAULT AND FRICTION FORCE.

V. CONCLUSIONS

This paper discover a new estimation/decoupling approach for a control system with sensor fault and friction force, the robustness challenges correlated with the UIO observer.

Most researchers consider the friction force as an unknown influence on the system, friction decoupling for a mechanical system can be considered as a specific application of a FE observer design.

And, by compared this paper with the work of (R. J. Patton, D. Putra, and S. Klinkhieo, 2010), which developed two methods to compensate the non-linear friction force effects, it can show that it can be decoupling the effects of the friction force and minimize the disturbance in order to estimate the sensor fault and then compensated it, without the need for design complexity and put different stability analysis, The results are well-suited to real-time use.

The results indicate the UIO's robustness and suggest such a technique provide a superior fault estimation and decoupling.

UIO has been presented as a solution to these challenges. The proposed UIO's advantage is that it may be used to estimate sensor faults also while decoupling the effects of friction and reducing the observer's order.

REFERENCES

[1] M. S. Shaker, "Active fault-tolerant control of nonlinear systems with wind turbine application," no. October, 2012.
[2] J. Lan, "Robust model-based fault estimation and fault-tolerant control: Towards an integration," 2017.
[3] J. Lan and R. J. Patton, *Robust Integration of Model-Based Fault Estimation and Fault-Tolerant Control*. 2021.
[4] M. Sami and R. J. Patton, "Active fault tolerant control for nonlinear systems with simultaneous actuator and sensor faults," *Int. J. Control. Autom. Syst.*, vol. 11, no. 6, pp. 1149–1161, 2013.
[5] J. Lan and R. J. Patton, "Integrated Design of Fault-Tolerant Control for Nonlinear Systems Based on Fault Estimation and T-S Fuzzy Modeling," *IEEE Trans. Fuzzy Syst.*, vol. 25, no. 5, pp. 1141–1154, 2017.

Received 17/September/2021; Accepted 26/November/2021

DOI: https://doi.org/10.33103/uot.ijccce.22.3.4

[6] S. Cao, L. Guo, and X. Wen, "Fault tolerant control with disturbance rejection and attenuation performance for systems with multiple disturbances," *Asian J. Control*, vol. 13, no. 6, pp. 1056–1064, 2011.

[7] J. Lan and R. J. Patton, "A new strategy for integration of fault estimation within fault-tolerant control," *Automatica*, vol. 69, no. February 2016, pp. 48–59, 2016.

[8] C. Martínez-García, V. Puig, C. M. Astorga-Zaragoza, G. Madrigal-Espinosa, and J. Reyes-Reyes, "Estimation of actuator and system faults via an unknown input interval observer for Takagi-Sugeno systems," *Processes*, vol. 8, no. 1, 2020.

[9] J. Lan and R. J. Patton, "Integrated fault estimation and fault-tolerant control design for large-scale interconnected systems," *Conf. Control Fault-Tolerant Syst. SysTol*, vol. 2016-Novem, no. 1, pp. 263–268, 2016.

[10] X. Li, D. Lu, G. Zeng, J. Liu, and W. Zhang, "Integrated fault estimation and non-fragile fault-tolerant control design for uncertain Takagi-Sugeno fuzzy systems with actuator fault and sensor fault," *IET Control Theory Appl.*, vol. 11, no. 10, pp. 1542–1553, 2017.

[11] J. Lan, R. J. Patton, and X. Zhu, "Integrated fault-tolerant control for a 3-DOF helicopter with actuator faults and saturation," *IET Control Theory Appl.*, vol. 11, no. 14, pp. 2232–2241, 2017.

[12] J. Lan, "Asymptotic estimation of state and faults for linear systems with unknown perturbations," *Automatica*, vol. 118, no. April, 2020.

[13] C. Edwards, "A comparison of sliding mode and unknown input observers for fault reconstruction," *Proc. IEEE Conf. Decis. Control*, vol. 5, no. 6, pp. 5279–5284, 2004.

[14] C. Liu, B. Jiang, R. J. Patton, and K. Zhang, "Hierarchical-Structure-Based Fault Estimation and Fault-Tolerant Control for Multiagent Systems," *IEEE Trans. Control Netw. Syst.*, vol. 6, no. 2, pp. 586–597, 2019.

[15] J. Lan and R. J. Patton, "A decoupling approach to integrated fault-tolerant control for linear systems with unmatched non-differentiable faults," *Automatica*, vol. 89, pp. 290–299, 2018.

[16] A. S. Hadi, M. S. Shaker, and Q. A. Jawad, "Estimation/decoupling approach for robust Takagi–Sugeno UIO-based fault reconstruction in nonlinear systems affected by a simultaneous time-varying actuator and sensor faults," *Int. J. Syst. Sci.*, vol. 50, no. 13, pp. 2473–2485, 2019.

[17] M. S. Shaker, "Hybrid approach to design Takagi-Sugeno observer-based FTC for non-linear systems affected by simultaneous time varying actuator and sensor faults," *IET Control Theory Appl.*, vol. 13, no. 5, pp. 1–10, 2019.

[18] A. S. Hadi, "Model-Based Fault Tolerant Control for Nonlinear Systems with Application to Wind Turbine," 2018.

[19] R. J. Patton, D. Putra, and S. Klinkhieo, "Friction compensation as a fault-tolerant control problem," *Int. J. Syst. Sci.*, vol. 41, no. 8, pp. 987–1001, 2010.

[20] Z. Gao, X. Liu, and M. Z. Q. Chen, "Unknown input observer-based robust fault estimation for systems corrupted by partially decoupled disturbances," *IEEE Trans. Ind. Electron.*, vol. 63, no. 4, pp. 2537–2547, 2016.

[21] K. Zhang, B. Jiang, and V. Cocquempot, "Adaptive observer-based fast fault estimation," *Int. J. Control. Autom. Syst.*, vol. 6, no. 3, pp. 320–326, 2008.

[22] C. Edwards, S. K. Spurgeon, and R. J. Patton, "Sliding mode observers for fault detection and isolation ଝ," vol. 36, 2000.

Received 17/September/2021; Accepted 26/November/2021
 ISSN (Print) 1811-9212 ISSN (Online) 2617-3352