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FAULT TOLERANT CONTROL FOR SENSOR FAULT OF A SINGLE-LINK FLEXIBLE MANIPULATOR SYSTEM

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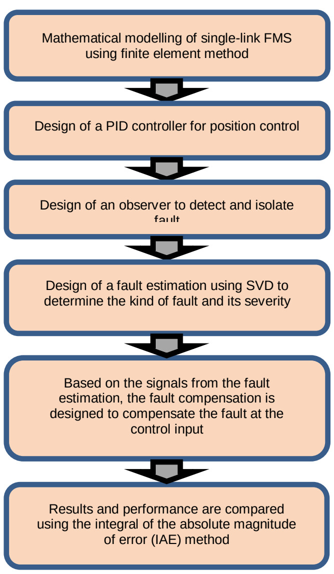
Graphical abstract



Abstract

This paper presents a new approach for sensor fault tolerant control (FTC) of a single-link flexible manipulator system (FMS) by using Finite Element Method (FEM). In this FTC scheme, a new control law is proposed where it is added to the nominal control. This research focuses on one element without any payload assumption in the modelling. The FTC method is designed in such way that aims to reduce fault while maintaining nominal FMS controller without any changes in both faulty and fault free cases. This proposed FTC approach is achieved by augmenting Luenberger observer that is capable of estimating faults in fault detection and isolation (FDI) analysis. From the information provided by the FDI, fault magnitude is assessed by using Singular Value Decomposition (SVD) where this information is used in the fault compensation strategy. For the nominal FMS controller, Proportional- integral- derivative (PID) controller is used to control the FMS where it follows the desired hub angle. This work proved that the FTC approach is capable of reducing fault with both incipient and abrupt signals and in two types of faulty conditions where the sensor is having loss of effectiveness and totally malfunction. All the performances are compared with FTC with Unknown Input Observer (FTC-UIO) method via the integral of the absolute magnitude of error (IAE) method.

Keywords: Fault tolerant control; sensor fault; flexible manipulator system; finite element method; singular value decomposition

1.0 INTRODUCTION

Due to high demands on reliability, safety and acceptable performance of automatic systems, such as vehicle control systems, manufacturing process and robotics [1-3], fault detection and isolation (FDI) and fault tolerant control (FTC) have become important studies in control field [4-7]. The studies involve actuator faults and sensor faults to which this paper is dedicated.

The application of an FTC scheme under variation of sensor faults of FMS is the main concern in this work. When a robotic manipulator is handling hazardous material or performing a dangerous task, a good FTC scheme is essential. There are a number of studies on FTC of FMS. Yu Izumikawa has started from an issue of the sensor fault where a disconnection of sensor can lead to wrong information to the system [8-9]. As a solution, an adaptive signal observer is presented to monitor the signal sensor by an adaptive law [10]. According to [11], presented a FTC approach for a manipulator which reconfigures the trajectory when the actuator is totally malfunctioning. The peak error of the end- effector velocity in the event of fault is minimized by a method presented in [12]. This was done by minimizing a performance index associated with the Jacobian of the faulty system. Lewis and Maciejewski [13] conducted a study of fault locked joint for a multi-link manipulator by determining the necessary constraints of each joint, in an event where the manipulator is still able to reach the target points while one of the joints are failing. In [14], the observer is developed according to inequality using the linear matrix inequality (LMI) under Bounded Real Lemma in order to minimize the effect of the non-linearities or uncertainties on the fault reconstruction. Whereas, in a real system, there are non-linearities and uncertainties impossible to be fully modelled. This may lead to inaccurate state estimation, which distort the reconstructed fault as well as the output of the virtual sensor [15].

This work is mainly concerned with the accuracy of the desired hub angle position of the FMS. The positon of the hub angle is measured using an encoder. When an encoder (sensor) is having a failure, it did not directly affect the process dynamics in the open loop system. However, in the closed-loop system, the fault may affect the process for the measurement in the control law. As a consequence, the FMS may have a performance degradation. One of the ways to cope with fault issues is by modifying the controller parameters according to an online identification. However, due to difficulties inherent to the online multivariable identification in closed-loop systems, such as noise or random unwanted signal, this paper therefore proposes a new FTC scheme based on the computation of a new control law to be added to the nominal control.

The proposed FTC scheme consists of two parts: a) the development of FDI; and b) fault compensation. All the design is based on the FEM model. The controller must achieve the optimal performance of a nominal control behavior before implementing the FDI scheme. There are a number of control methods that have been proposed for positioning control of FMS [16-18]. However, PID controller is considered in this work. The FDI is a supervisory method that provides information about the location and time occurrence of the sensor fault. Luenberger observer (LO) is designed in such a way so as to enable fault detection and the residual values, which are then compared with the threshold values. The fault estimation is estimated using a pseudo-inverse in SVD approach. Based on the information obtained by the fault estimation, a new control law is designed to modify the nominal control law in order to compensate the effects of the fault. The performance of the proposed FTC-LO under variation of types of fault is compared with the FTC-UIO approach.

The rest of the paper is organized as follows. Section 2 describes the mathematical modelling of FMS using FEM. The description of PID control as the nominal control is explained in Section 3. In Section 4, the development of FDI is briefly explained in this chapter including the description on types of fault, fault detection, isolation and estimation. Next, a new control law is proposed in Section 5 for the design of fault compensation. The simulation results and performance assessment are presented in Section 6. Finally, the paper is concluded in Section 7.

2.0 MODEL DESCRIPTION

2.1 The Flexible Manipulator System

Figure 1 shows the single-link flexible manipulator system used in this work. It consists of a modular structure where the link is a long stiff steel beam that is clamped to the rigid hub of the beam. For the modelling of FMS, it is described in mechanical model which is illustrated in Figure 2.

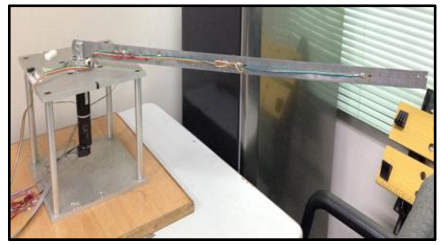


Figure 1 The flexible manipulator system

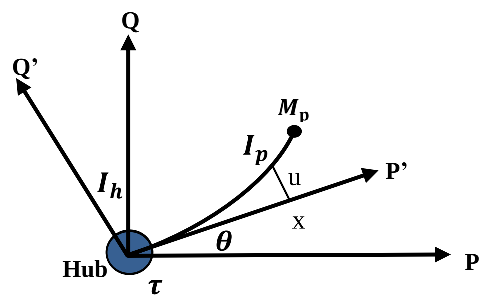


Figure 2 Mechanical model of the flexible manipulator

Based on Figure 2, $\boldsymbol{I_h}$ represents the hub inertia of the manipulator. A payload mass $\boldsymbol{M_p}$ with its associated inertia $\boldsymbol{I_p}$ is attached to the end- point. A control torque $\boldsymbol{\tau}(t)$ is applied at the hub of the manipulator, moving in the *POQ* plane, is denoted by $\boldsymbol{\theta}(t)$. The height of the link is assumed to be much greater than its width, thus, allowing the manipulator to vibrate (be flexible) dominantly in the horizontal direction. The shear force deformation and rotary inertia effects are ignored.

According to [19], there are a few steps to develop the FEM

STEP 1: Discretization of element where the number of element is selected. Based on the selected number, the beam is then divided into elements. In this work, one element is considered which is $n = 1$.

STEP 2: Select the approximating function in order to calculate the nodal displacement.

STEP 3: Derivation of the basic element equation is done in this step where the element stiffness matrix, K and mass matrix, M are calculated as well as the damping matrix, C and vector of applied nodal forces *F*. This yields

$$M^n = \frac{\rho Al}{420}\begin{bmatrix} m(1,1) & m(1,2) & m(1,3) & m(1,4) & m(1,5) \\ m(1,2) & 156 & 22l & 54 & -13l \\ m(1,3) & 22l & 4l^2 & 13l & -3l^2 \\ m(1,4) & 54 & 13l & 156 & -22l \\ m(1,5) & -13l & -3l^2 & -22l & 4l^2 \end{bmatrix}$$

Where

$$\begin{aligned} m(1,1) &= 140(\rho Al)(3n^2 - 3n + 1) \\ m(1,2) &= m(2,1) = 21(\rho Al)(10n - 7) \\ m(1,3) &= m(3,1) = 7(\rho Al^2)(5n - 3) \\ m(1,4) &= m(4,1) = 21(\rho Al)(10n - 3) \\ m(1,5) &= m(5,1) = -7(\rho Al^2)(5n - 2) \end{aligned}$$

$$K^n = \frac{EI}{l^3}\begin{bmatrix} 0 & 0 & 0 & 0 & 0 \\ 0 & 12 & 6l & -12 & 6l \\ 0 & 6l & 4l^2 & -6l & 2l^2 \\ 0 & -12 & -6l & 12 & -6l \\ 0 & 6l & 2l^2 & -6l & 4l^2 \end{bmatrix}$$

where E, I, ρ, A, and l represent the Young modulus, area moment of inertia, mass density, cross-sectional area and length of the ith element respectively.

STEP 4: Apply the boundary conditions as without any boundary conditions, the matrices K and M will be singular and their inverse will not exist. In this step, the Lagrange equation is utilised in order to obtain the matrix differential equation. This can be obtained as:

$$M\ddot{Q}(t) + KQ(t) = F(t) \quad (1)$$

where $F(t)$ is the vector of applied forces and torques.

STEP 5: The matrix differential equation in (1) can be represented in a state-space form as

$$\begin{aligned} \dot{v} &= \boldsymbol{A}v + \boldsymbol{B}u \\ y &= \boldsymbol{C}v + \boldsymbol{D}u \end{aligned} \quad (2)$$

where

$$\boldsymbol{A} = \begin{bmatrix} 0_3 & I_3 \\ -M^{-1}K & 0_3 \end{bmatrix}, \qquad \boldsymbol{B} = \begin{bmatrix} 0_{3\times1} \\ M^{-1} \end{bmatrix},$$
$$\boldsymbol{C} = [0_3 \quad I_3], \qquad \boldsymbol{D} = [0_{2\times3\times1}]$$

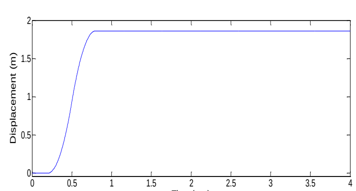
0_m is an $m \times m$ null matrix, I_m is an $m \times m$ identity matrix, $0_{m\times1}$ is an $m \times 1$ null vector,

$$u = [\tau],$$
$$v = [\theta \quad w_\alpha \quad \theta_\alpha \quad \dot{\theta} \quad \dot{w}_\alpha \quad \dot{\theta}_\alpha]$$

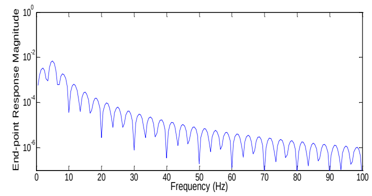
where u is the control input and v is the state vector that incorporates the angular, end- point flexural and rotational displacements and velocities.

STEP 6: Convert the state-space modelling to discrete modelling with a sampling time period $T_s = 0.0001s$.

STEP 7: The outputs for displacement are depicted in time domain and spectral density as shown in Figures 3(a) and 3(b) respectively.



a)



b)

Figure 3 FE response of the system at the end-point in: a) time domain; b) spectral density

3.0 NOMINAL FEEDBACK CONTROL

In this work, the proposed method must provide detailed information on the post fault system as accurately as possible, and the controller must achieve the optimal performance with the limited amount of information. Therefore, in this proposed method, it is divided into two which are the feedback control and the FDI for designing the fault compensator in the FTC scheme.

3.1 PID Controller

In this section, the design of feedback controller is explained. PID controller is one of the favorable controller for FMS [20]. The control scheme consists of two negative feedback control loops which are the PID controller and a gain constant $K_2 = 0.001$.

The design for the PID control method is described as follows:

$$u(k) = \left[\left(\left(K_P + K_I T_s\left(\frac{1}{z-1}\right) + K_D\left(\frac{1}{1 + N * T_s\frac{1}{z-1}}\right)\right)(R(k) - y1(k))\right] - K_2 y2(k) \quad (3)$$

where $K_P, K_I, K_D, R(k), y1(k), y2(k), N$ and T_s denote the proportional gain, integral gain, derivative gain, output for the first state of FMS which is displacement, output for the second state of FMS which is deflection, filter coefficient and sampling time respectively. All the PID discrete gains are tuned using the PID tuner block from the PID controller Simulink block.

4.0 DEVELOPMENT OF FDI

As for the second part of FTC scheme, this work involves the design to generate fault information. This information includes fault occurrence, fault isolation and fault magnitude. Therefore, this section describes the development of the FDI scheme in the proposed method.

4.1 Types of Fault

A fault can be defined as a disallowable characteristic which may be different from characteristic property of a variable that leads to a malfunction or failure in a system. In electrical system, it usually consists of a large number of components with various failure modes, like short cuts, loose or broken connection, parameter changes and contact problems. These failures may occur either in the actuator or sensor of a system. Moreover, faults can also be further classified into additive and multiplicative faults where additive faults appear as offsets of sensors whereas multiplicative faults are parameter changes within a process [21]. However, in this work, only system with additive fault is considered.

Fault can also be categorized in time behavior and this work, sensor fault is considered which can be written as

$$y_j^f(k) = \beta_j y_j(k) + y_{j0} \qquad (4)$$

where y_j and y_j^f denote the *j*th nominal and faulty sensor, respectively. y_{j0} represents a constant offset and $0 \leq \beta_j \leq 1$ corresponds to a gain degradation of the *j*th sensor.

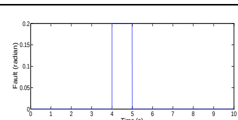
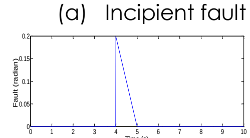
Based on Equation (4), the selection value for gain fault represents the behavior of the failure. Therefore, the behavior of sensor fault can be summarized in Table 1.

Table 1 Various types of failures

Type of sensor failures	β_j	y_{j0}
Faultless sensor	1	0
Loss of effectiveness only	< 1	$\neq 0$
Completely out of order	0	0

Another description for type of fault can be described in signal form such as incipient fault (drift like) and intermittent fault [22]. These signals fault are taken under consideration for this work. Table 2 shows the details of time dependency of faults including fault signatures.

Table 2 The fault parameter with time profile

$f_s(k) = \begin{cases} 0, & elsewhere \\ 0.2, & 4 < t < 5 \end{cases}$	 (a) Incipient fault
$f_s(k) = \begin{cases} 0, & elsewhere \\ -\frac{0.2}{t}, & 4 < t < 5 \end{cases}$	 (b) Intermittent fault

Using equation (4), the state- space representation can be written as

$$x(k+1) = \boldsymbol{A}x(k) + \boldsymbol{B}u(k)$$
$$y(k) = \boldsymbol{C}x(k) + \boldsymbol{D}u\,(k) + \boldsymbol{F}_s\boldsymbol{f}_s(k) \qquad (5)$$

where $\boldsymbol{x} \in \mathrm{R}^n$, $\boldsymbol{u} \in \mathrm{R}^p$ and $\boldsymbol{y} \in \mathrm{R}^m$ are the state vector, control input and output vector, respectively. $\boldsymbol{A} \in \mathrm{R}^{n \times n}$, $\boldsymbol{B} \in \mathrm{R}^{n \times p}$, $\boldsymbol{C} \in \mathrm{R}^{m \times n}$ and $\boldsymbol{D} \in \mathrm{R}^{n \times p}$ are the state, the control, the output matrices and feed-forward matrix, respectively. Matrices $\boldsymbol{F}_s$ is assumed to be known and $\boldsymbol{f}_s$ corresponds to the magnitude of the sensor fault. Figure 4 shows the representation of sensor fault in Matlab/Simulink block. Based on Equation (5), the sensor fault is injected into the output of the flexible manipulator system. The sensor fault signals that are injected into the system is as described in Table 2.

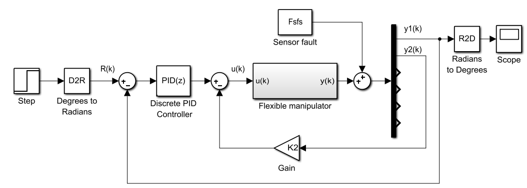
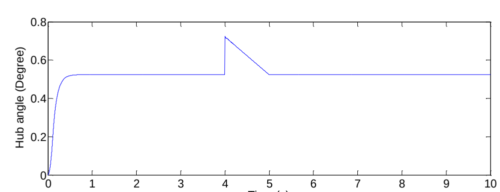


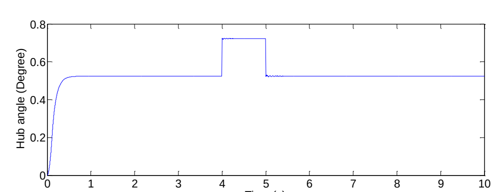
Figure 4 Simulink block for sensor fault

4.2 Sensor Fault Case

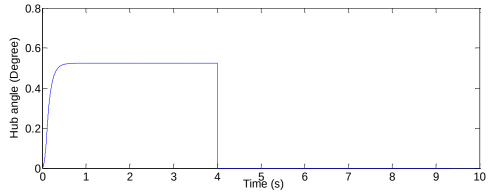
In Table 2, the fault parameters and time profile is shown. A constant offset on sensor fault has been created and added at instant 4s to 5s with $\beta = 1$ and $y_{10} = 0.2$ radian using incipient and intermittent signals. There are three types of faults considered in this paper which are the incipient fault, intermittent fault and fault malfunction condition. Figure 5 displays the output of the system with sensor fault in three scenarios of fault. Figure 5(c) shows a system when the sensor is totally malfunctioned or disconnected. It immediately drops to zero due to the disconnection signal from a sensor. While, Figure 6 displays the control input with incipient fault.



a)



b)



c)

Figure 5 The faulty output: a) incipient fault; b) intermittent fault; c) fault totally malfunction

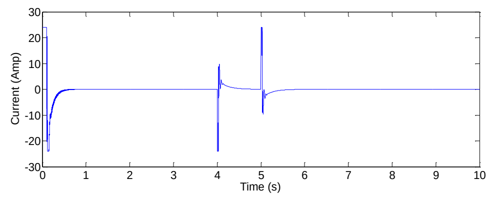


Figure 6 The faulty control input with feedback controller

These faults may cause degradation in performance and instability to the system. In order to maintain both of the control objectives, a model based fault detection and diagnosis is designed in such a way so as to detect, isolate and estimate the fault. A statistic of fault will be developed in order to observe the fault occurrence which will be helpful in providing information to the user.

4.3 Fault Detection: Luenberger Observer

Fault detection is a process of indication whether there is any occurrence of fault. This process determines the time at which the system is subjected to some fault. LO is one of the well-known state observer in control system [23]. The general equation for LO can be represented as

$$\hat{x}(k+1) = \boldsymbol{A}\hat{\boldsymbol{x}}(k) + \boldsymbol{L}\big(y(k) - \hat{y}(k)\big) + \boldsymbol{Bu}(k) \quad (6)$$
$$\hat{y}(k) = \boldsymbol{C}\hat{\boldsymbol{x}}(k) + \boldsymbol{Du}(k)$$

where $\hat{\boldsymbol{x}}(k)$, $\hat{y}(k)$, $\boldsymbol{A} \in \mathrm{R}^{n\times n}$, $\boldsymbol{B} \in \mathrm{R}^{n\times p}$, $\boldsymbol{C} \in \mathrm{R}^{m\times n}$ and $\boldsymbol{D} \in \mathrm{R}^{n\times p}$ are the estimated state vector, estimated output vector, the state, the control, the output matrices and the feed-forward matrix respectively. $(\boldsymbol{A}, \boldsymbol{C})$ must be observable and $\boldsymbol{L}$ is the observer gain matrix which is chosen to be at the left half plane. LO provides an estimation of the state vector used to generate a residual vector, $\boldsymbol{r}(k)$.

4.4 Fault Isolation

Fault isolation is a step where it finds which is the faulty component [24]. From Equations (5) and (6), both state space equations can be used to determine the fault by determining the difference which is called residual [25]. The residual vector can be defined as

$$\boldsymbol{r}(k) = \boldsymbol{y}(k) - \hat{\boldsymbol{y}}(k) \quad (7)$$

In faultless case, the residual is close to zero. In this paper, threshold has been set to 0.1 radian as comparison to the residual value for the fault detection. This fault indicator can be summarized in a statistic form [26]. If the threshold is greater than the threshold value, the fault indicator will equal to 1 as the faulty condition or else it will be equal to 0.

4.5 Fault Estimation using SVD

In fault estimation, it identifies the fault and estimates its magnitude. This step determines the kind of fault and its severity. According to Equation (5), it describes the augmented state-space representation in the presence of fault. The magnitude of the fault $\boldsymbol{f_s}$ can be estimated which is defined as a component of an augmented state vector $\overline{X_s}(k)$. Therefore, the system can be described as

$$\overline{E_s}\overline{X_s}(k+1) = \overline{A_s}\overline{X_s}(k) + \overline{B_s}\overline{U}(k) + \overline{G_s}y_r(k) \quad (8)$$

Where

$$\overline{E_s} = \begin{bmatrix} I_n & 0 & 0 \\ 0 & I_p & 0 \\ C & 0 & F_s \end{bmatrix}; \quad \overline{A_s} = \begin{bmatrix} A & 0 & 0 \\ -T_sC_1 & I_p & -T_sF_{s1} \\ 0 & 0 & 0 \end{bmatrix}; \quad \overline{B_s} = \begin{bmatrix} B \\ 0 \\ 0 \end{bmatrix};$$

$$\overline{G_s} = \begin{bmatrix} 0 \\ T_sI_p \\ 0 \end{bmatrix}; \qquad \overline{X_s}(k) = \begin{bmatrix} x(k) \\ z(k) \\ f_s(k) \end{bmatrix}; \qquad \overline{U}(k) = \begin{bmatrix} u(k) \\ y(k+1) \end{bmatrix}$$

The sensor fault magnitude $\widehat{f_s}$ can be estimated using the SVD of matrix $\overline{E_s}$ if this matrix is of full column rank [27].

Based on the LO in (6), the substitution of the state estimation can be described as

$$\boldsymbol{F_s f_s}(k) = \hat{\boldsymbol{x}}(k+1) - \boldsymbol{A}\hat{\boldsymbol{x}}(k) - \boldsymbol{Bu}(k) \quad (9)$$

Let $F_s = U\begin{bmatrix} R \\ 0 \end{bmatrix}V^T$ be the SVD of F_s. Thus, R is the diagonal and non-singular matrix and U and V are orthonormal matrix.

$$\bar{\hat{x}}(k+1) = \overline{A\hat{x}}(k) + \bar{B}u(k) + \begin{bmatrix} R \\ 0 \end{bmatrix}V^T f_s(k) \quad (10)$$

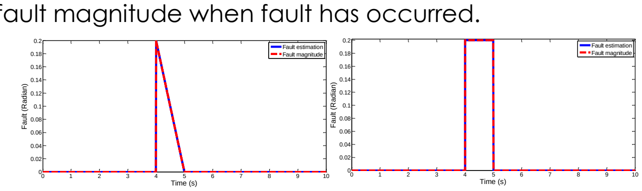
where

$$\hat{x}(k) = U\bar{\hat{x}}(k) = U[\overline{x_1}(k)] \quad (11)$$
$$\bar{A} = U^{-1}AU = \begin{bmatrix} \bar{A}_{11}(k) & \bar{A}_{12}(k) \\ \bar{A}_{21}(k) & \bar{A}_{22}(k) \end{bmatrix} \quad (12)$$
$$\bar{B} = U^{-1}B = [\bar{B}_1] \quad (13)$$

Based on Equation (10), the estimation of the sensor fault magnitude can be defined as

$$\hat{f}_d(k) = VR^{-1}(\bar{\hat{x}}_1(k+1) - \bar{A}_{11}\bar{\hat{x}}_1(k) - \bar{A}_{12}\bar{\hat{x}}_2(k) - \bar{B}_1u(k) \quad (14)$$

Sensor fault magnitude and its estimation are illustrated in Figure 7. The fault estimation is close to zero when it is in nominal condition, and is close to fault magnitude when fault has occurred.



(a) (b)

Figure 7 Fault magnitude and its estimation for sensor fault for: a) incipient fault and b) intermittent fault

5.0 FAULT COMPENSATION

When a system is affected by a fault, it affects the closed-loop system where the error between the tracking error and the reference input no longer converges to zero. Therefore, the state- feedback controller tries to bring back the error back to zero by compensating the fault at the control input. In order to compensate the fault effect, a new control law $u_{add}(k)$ is assessed and added to the feedback controller [28]. The total control law can be described as

$$u(k) = U(k) + u_{add}(k) \qquad (15)$$

Using the estimation of the fault magnitude described in the previous section, the new control law u_{add} can be obtained if matrix B is full of rank:

$$u_{add}(k) = -B^{-1}\hat{f}_d(k)\left(\frac{5}{z-1}\right) \qquad (16)$$

6.0 RESULTS AND DISCUSSION

This section presents the results of the manipulator. In the proposed FTC design, the feedback control of FMS must be designed first. Therefore, in this work, a discrete PID controller is presented where the link of the manipulator is required to follow the desired angle of 30°. Figure 8 shows the response and performance of the hub angle.

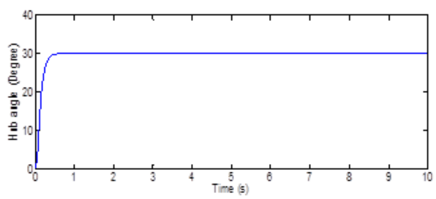
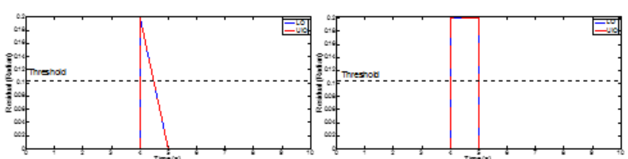


Figure 8 Response of the manipulator with discrete PID controller

Fault detection is indicated based on the residual values with respect to the threshold value which is 0.1 radian. The information from the plant and observer are used to assess the residual which is described in Equation (7). Figures 9(a) and 9(b) show a comparison of results between (LO) and (UIO) for fault detection analysis. From the results, both methods are able to detect the fault after being compared with the threshold value.



(a) (b)

Figure 9 Fault indicator: a) incipient fault; b) intermittent fault

Referring to Equation (14), this algorithm will be used in designing fault compensator in Equation (16). The fault magnitude must be designed as accurate as possible in order to get a good fault compensator for FTC scheme.

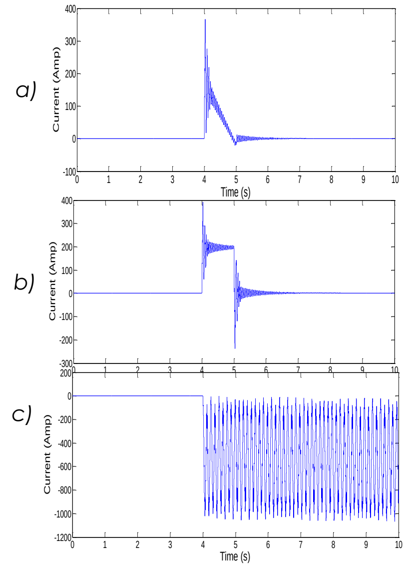


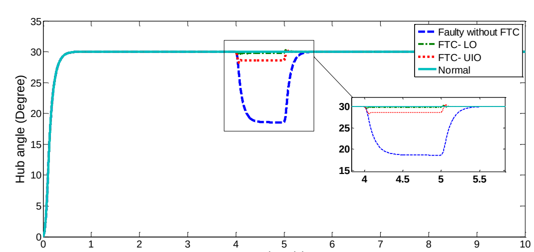
Figure 10 Reconstructed fault signals for: a) incipient, (b) intermittent and (c) out of order type of fault

Figures 10(a), 10(b) and 10(c), show the reconstructed fault. By reconstructing the faults, this new control law which is described in Equation (15) can be applied in order to compensate the faults. The whole result for the fault compensated is shown in Figure 11. From the reconstructed fault, it can also be shown that the fault is isolated by comparing with the inject signals fault which are the incipient and intermittent faults.

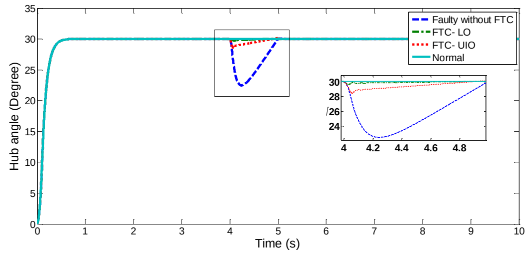
Table 3 shows the comparison between the fault in the plant and the estimated fault for both types of observers. The results show that both of the observers provide a good estimate of the observed states when all the faults occur at the exact same time.

Table 3 The fault detection and isolation analysis

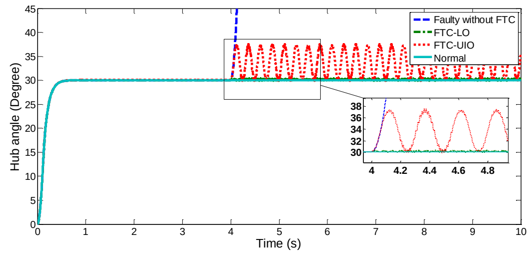
	Fault occurrence	**Fault isolation**	
		LO	UIO
Incipient fault	4s	4s	4s
Intermittent fault	4s	4s	4s



a) Incipient fault



b) Intermittent fault



c) Fault malfunction

Figure 11 The system response for nominal condition and faulty with and without FTC for type of fault: a) incipient fault; b) intermittent fault; c) fault malfunction

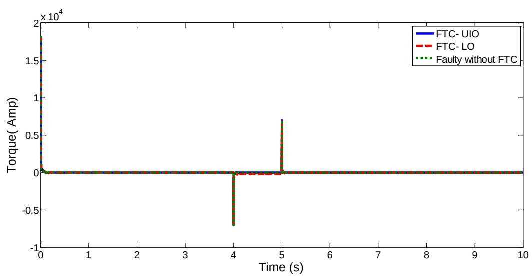


Figure 12 The control input with compensator

The response of hub angle for FTC- UIO and the proposed method, FTC- LO under incipient fault, intermittent fault and totally malfunction fault are shown in Figures 11(a), 11(b) and 11(c) respectively. It can be observed that the proposed method, FTC- LO exhibit better performance compared to FTC- UIO and system without FTC in terms of hub angle error. Figures 11(a) and 11(b) show the system without FTC and FTC- UIO systems, where it demonstrated a significant deviation for the desired hub angle. In contrasts to FTC- LO, this FTC scheme has returned the hub angle to the desired value with small magnitude of oscillation under incipient and intermittent faults which is shown in Figure 11(c). While the system without FTC and FTC- UIO has become unstable under this fault condition. Figure 12 shows the compensated control input based on Equation (15).

The performance of the FTC system is also assessed and compared using the integral of the absolute magnitude of error (IAE) performance index:

$$IAE = \int_{t_{i-1}}^{t_i} |e(t)|dt \tag{17}$$

Table 4 The performance index (IAE)

Type of fault	IAE of hub angle Without compensator	FTC- LO	FTC- UIO
Incipient	11.47	0.1024	1.528
Intermittent	4.454	0.0562	0.8076
Out of order	6.825×10^4	0.8376	22.61

Table 5 The improvement of the performance

Type of fault	Improvement (%) FTC- LO	FTC- UIO
Incipient	99.1072	86.6782
Intermittent	98.7382	81.8679
Out of order	99.9987	99.9666

The whole performance was measured using *IAE* method as summarized in Tables 4 and 5. The improvement measured in Table 5 is the improvement comparison between the FTC-UIO and the proposed method FTC-LO with the system without compensator.

7.0 CONCLUSION

In this work, the proposed FTC-LO is designed using FEM model and is presented under three fault conditions namely incipient, intermittent and totally malfunctioned faults. The performance of the proposed method is compared with the FTC-UIO scheme. Both types of observers, LO and UIO have achieved with satisfactory results the time performances in fault detection. In addition, LO and UIO have also successfully isolated the failing sensor and provided a correct estimate state. However, in the comparison with fault compensator, it is proven that FTC-LO method has better performance compared to FTC-UIO method by comparing the *IAE* values. Moreover, it is proven that this new control law in fault compensation is effective for sensor fault of a single-link flexible manipulator system with an improvement of up to 99% which is almost equal to the nominal system even with a system with a totally malfunctioned condition.

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