# Robust detection and isolation of actuator and sensor faults in semi-actively controlled building structures using a set of unknown input observers

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***Abstract*— Building structures are subject to earthquakes and unwanted vibrations which can be effectively managed via controllers. Semi-actively controlled building structures are prone to sensor and actuator faults very similar to other dynamical systems. When a fault occurs in sensors or actuators of a controlled systems, the system faces a performances degradation or even failure. Consequently, it is vitally important to detect and isolate a fault at the right time in these systems. To do so, in this paper, a set of unknown input observers (UIO) are proposed for robust detection and isolation of actuator and sensor faults in buildings. For the proof of concept, a three-story structure with magnetorheological (MR) dampers is taken into account. Via designing these observers, each faulty actuator and/or sensor is detected and isolated. Here, the LQR controller is also used to facilitate an optimal control strategy over the system. The obtained simulation results demonstrate the acceptable accuracy of the proposed method in the detection of fault (time and location) and the robustness of the fault detection method against external disturbances.**

***Index Terms*-- Building structure, earthquake, robust fault detection and isolation, unknown input observers**

## I. INTRODUCTION

One of the recent attractive fields in the control engineering is the performance improvement of building structures subject to earthquakes. With the development of science and technology, the attention of many researchers has been directed towards providing control systems that counteract forces exerted on buildings and structures. Control systems in this respect are categorized into three main groups, namely passive, active, and semi-active [1-3]. Among those, Semi-active control systems, as a conjunction between active and passive systems, exclude energy-consuming passive actuators on the one hand and include sensors and active controller on the other hand. Generally, a semi-active control system incurs lower costs and offers better performance compared to active and passive systems [1-3]. In this respect, [4] addressed different dampers used in semi-active control systems, [5] benefited from bang-bang, Lyapunov, and clipped-optimal (a combination of $H_2$ and LQG) controllers to provide semi-active control over MR dampers and [6] employed LQR and LQG methods to control MR dampers.

However, one of the critical challenges in the control of building structures, is how to detect faults of the whole system's sensors and actuators. With these faults, the performance of control system may degrade or even the entire system may fail. Consequently, these faults must be immediately detected and their locations need to be addressed. For this purpose, [7] proposed a framework to assess the performance of fault detection and isolation (FDI) systems in building structures. Also, [8] carried out a review of fault detection and feature extraction methods, including grey-box, white-box, and black-box models, used in these structures. It is worth noting that there are substantially limited studies on fault detection and isolation in building structures and MR dampers. For detection and isolation of sensor faults in building structures, [9] performed the principle component analysis and Bayesian statistical analysis. In this method, MR dampers were controlled using a fuzzy system and [10] presented fault detection using sliding-mode observer followed by robust fault control of MR dampers in the semi-active control of building structures.

Regarding the strengths and higher discretion due to more design parameters, observer-based methods for fault detection and isolation purposes have gained more interest than others. Various observers have been proposed in this respect, Luenberger observer, different types of Kalman filters such as extended and unscented, and unknown input observers are among those. An observer is designed for fault detection and isolation following 5 steps: 1. Specification of observer structure, 2. providing the estimation equations, 3. obtaining the dynamical equations of the estimation error system, 4. getting the system's residual signal, 5. determination of the observer parameters to ensure stability and guarantee a successful fault detection, followed by a complete fault isolation and false alarms reduction. Critical challenges of FDI for structural buildings include modeling uncertainty, external disturbance, and variability of the system parameters over time. All items cause an imperfect fault detection and increase the number of false alarms. Consequently, the fault detection algorithm for these systems must be robust against the abovementioned items.

UIO is one of the most effective frameworks to detect and identify faults in practical systems. This observer is popular as it can perform robustly against disturbance, changes in system's operating point, input signals, its states and noise [11- 12]. UIOs with structured residual generation are utilized in [13] for actuator and sensor FDI. They are also used in [14] to detect several faults occurring simultaneously in a system. UIOs are addressed for robust FDI under disturbances in high-order multi-agent systems [15], quadrotor systems [16], and interconnected smart power systems in the presence of PER and EVs [17]. The scheme in [18] utilizes the Takagi-Sugeno UIO for robust fault estimation in a DC motor with bounded uncertainties. UIOs are also designed for fault detection in sensors of induction machines [19] and biped robots [20]. To design a robust fault tolerant control, UIO with linear functional transformation is used in [21] and [22] introduces a reduced-order UIO for fault detection in multi-agent systems. Robust actuator FDI based on zonotopic UIO is given by [23] for time-varying descriptor systems where the system is subject to state disturbance and measurement noise, both in the form of unknown terms bounded by zonotopes. A comparison between robust fault detection by Luenberger-structure observer and set-theoretic UIO is given in [24]. Nonlinear UIO is also designed for sensor FDI purposes in the presence of disturbance for nonlinear continuous stirred tank reactor in [25]. The comparison of the results obtained from the UIO-based method with the results of extended Kalman filter and unscented Kalman filter shows the superiority of the UIO-based method for robust fault detection.

In this study, a bank of UIOs is proposed for detection and isolation of actuator and sensor faults in buildings with MR dampers, which has not been addressed for these structures so far. By this UIO bank, faults in actuators and sensors are detected first then isolated from the disturbance in the structure, i.e. earthquake. To prove the concept a three story building is selected and which has three set of sensors and actuators. In the proposed method, 8 observers are designed where 3 of them are dedicated to fault detection of actuators and 3 assigned to fault detection of sensors. These observers are sensitive to faults of a specific sensor/actuator and do not react to other faults. Nonetheless, given these 6 observers, one can only determine the number of faults and not able to determine if it is a sensor or actuator fault. Therefore, to isolate sensor fault from actuator fault, another observer is employed. Finally, to retrofit the fault detection procedure against disturbance (i.e. earthquake), one last observer is added which is sensitive to all faults and doesn't react to disturbance. Based on the adaptive threshold over the residuals generated by the observers, the necessary decisions are made about fault alarms and their types. These observers are used with a LQR optimization mechanism to control the building structure and track reference trajectory.

The rest of the paper is organized as follows. Section 2 explains the dynamic of building structure. In the thirds section, the design procedure of UIO bank is expressed. Section 4 analyzes and evaluates simulation results and section 5 provides conclusions.

## II. Dynamic of Building Structure

To prove the concept of the FDI design, a three-story shear-frame structure is considered here, which is an in-plane lumped-mass shear structure. To control of the structure, three MR dampers are employed. As shown in Fig. 1, each damper is located between every two adjacent floors. The dynamics of this structure is formulated in the form of state space equations as below [13].

$$\dot{x}_I(t) = A_I x_I(t) + B_I u(t) + M_I \ddot{x}_g(t) \tag{1}$$

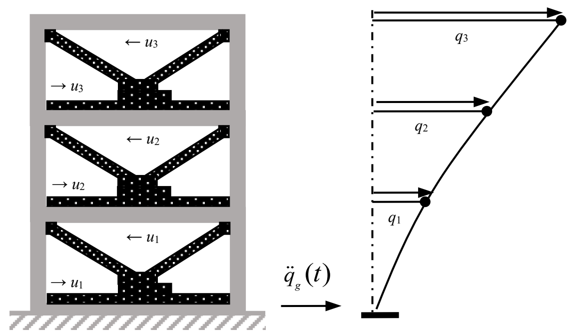


Figure 1. A three-story shear-frame structure

Where $x_I = [q, \dot{q}]^T$ ($q, \dot{q}$ are displacement vector and its derivative) and $u$ are the state and input vectors. $A_I \in R^{2n\times 2n}$, $B_I \in R^{2n\times m}$ and $M_I \in R^{2n\times r}$ are the system, input and excitation matrices, respectively, $n$, $m$ and $r$ are the number of states, inputs and excitations, respectively. The system matrices are defined as (2),

$$A_I = \begin{bmatrix} 0_{n\times n} & I_{n\times n} \\ -\bar{M}^{-1}\bar{K} & -\bar{M}^{-1}\bar{C} \end{bmatrix}, B_I = \begin{bmatrix} 0_{n\times m} \\ -\bar{M}^{-1}L_u \end{bmatrix}, M_I = \begin{bmatrix} 0_{n\times 1} \\ -1_{n\times 1} \end{bmatrix} \tag{2}$$

where the mass, stiffness, damping and the control force location matrices are given as:

$$\bar{M} = 6\times 10^3 I_{3\times 3},\quad \bar{K} = \begin{bmatrix} 3.4 & -1.8 & 0 \\ -1.8 & 3.4 & -1.6 \\ 0 & -1.6 & 1.6 \end{bmatrix}\times 10^6$$

$$\bar{C} = \begin{bmatrix} 12.4 & -5.16 & 0 \\ -5.16 & 12.4 & -4.59 \\ 0 & -4.59 & 7.2 \end{bmatrix}\times 10^3,\quad L_u = \begin{bmatrix} -1 & 1 & 0 \\ 0 & -1 & 1 \\ 0 & 0 & -1 \end{bmatrix} \tag{3}$$

Here, inter-story relative velocities are considered as outputs, which are extracted from the measured acceleration of floors. The system dynamic states in (1) are linearly transformed to the inter-story drift and velocities given below,

$$x = Tx_I = \left[q_1, q_2 - q_1, q_3 - q_2, \dot{q}_1, \dot{q}_2 - \dot{q}_1, \dot{q}_3 - \dot{q}_2\right]^T \tag{4}$$

$$T = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ -1 & 1 & 0 & 0 & 0 & 0 \\ 0 & -1 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & -1 & 1 & 0 \\ 0 & 0 & 0 & 0 & -1 & 1 \end{bmatrix} \tag{5}$$

The transformed dynamic system is defined as (6) and (7).

$$\dot{x}(t) = A_c x(t) + B_c u(t) + M_c \ddot{x}_g(t) \tag{6}$$

$$A_c = TA_I T^{-1},\ B_c = TB_I,\ M_c = TM_I \tag{7}$$

The control forces and inter-story drifts are assumed as regulation objectives. Therefore, the regulated output, $y \in R^{n_y \times 1}$ is as follows:

$$y(t) = Cx(t) + Du(t) \tag{8}$$

$$C = \left[0_{3\times3}, I_{3\times3}\right],\ D = 0_{3\times3} \tag{9}$$

For simulation, the 1940 El Centro NS (Imperial Valley Irrigation District Station) ground motion record was assumed as an input excitation with peak acceleration scaled to 1 ms$^{-2}$ [10].

## III. DESIGN OF UNKNOWN INPUT OBSERVER

In fault detection and identification methods based on unknown input variable, disturbance is considered as an unknown input. The main objective in the design of these observers is to isolate disturbance from residual signal. Regarding the fact that the fault might happen due to the failure of the system equipment such (e.g. actuators and sensors, or some unknown disturbances), one can write the state space display of the system as follows:

$$\begin{aligned} x(k+1) &= Ax(k) + Bu(k) + Ef(k) + B_d d(k) \\ y(k) &= Cx(k) \end{aligned} \tag{10}$$

where $f$ and $E$ are the fault vector (containing disturbances) and the fault distribution matrix, respectively where $E$ is a known matrix. One may divide the fault vector into two parts as $f = \left[f_1, f_2\right]^T$ for fault isolation. $f_1$ and $f_2$ comprise the faults to which the observer is insensitive and sensitive, respectively. Similarly, matrix $E$ is reformed as $E = \left[E_1, E_2\right]$. Then a UIO structure is expressed as (11).

$$\begin{aligned} z(k+1) &= Fz(k) + TBu(k) + K_{12} y(k) \\ \hat{x}(k) &= z(k) + Hy(k) \end{aligned} \tag{11}$$

Here, $z$ stands for the UIO state vector obtained by linear transformation $z = Tx$ and $\hat{x}$ denotes the system estimated state vector. $F$, $T$, $H$ and $K_{12}$ are matrices designed to decouple the unknown input ($f_1$) from other inputs. For this purpose, specific design requirements are incorporated. The residual and state estimation error ($e = x - \hat{x}$) are as follows:

$$\begin{aligned} e(k+1) = {} & \left(A - HCA - K_1 C\right) e(k) \\ & + \left(A - HCA - K_1 C - F\right) z(k) \\ & + \left(I - HC - T\right) Bu(k) \\ & + \left(\left(A - HCA - K_1 C\right) H - K_2\right) y(k) \\ & + \left(I - HC\right) E_1 f_1(k) + \left(I - HC\right) E_2 f_2(k) \end{aligned} \tag{12}$$

$$r(k) = y(k) - C\hat{x}(k) = \left(I - HC\right) y(k) - Cz(k) \tag{13}$$

If the following equations hold,

$$\begin{aligned} & T = I - HC,\ TE_1 = 0,\ F = TA - K_1 C \\ & K_2 = FH,\ K_{12} = K_1 + K_2 \end{aligned} \tag{14}$$

then equation (12) can be rewritten as:

$$e(k+1) = Fe(k) + TE_2 f_2(k) \tag{15}$$

Thus, the state estimation error asymptotically receives a zero value provided that the eigenvalues of $F$ are stable and $f_2 = 0$, irrespective of what $f_1$ is. This implies that the observer is not sensitive to the unknown input of $f_2$.

Considering the equations in (14), a certain solution to the UIO is obtained to ascertain $H$ as follows [12]:

$$H = E_1 \left(CE_1\right)^+ \tag{16}$$

where ($^+$) stands for the Moore-Penrose pseudo-inverse [12].

According to [12], the necessary and sufficient conditions for the design of a full-order UIO expressed by (10) include:

1) $\operatorname{rank}\left(CE_1\right) = \operatorname{rank}\left(E_1\right)$

2) $\left(C, TA\right)$ is a detectable pair.

An observer based fault detection system is established based on residual production. Benefiting from the discrepancy between the estimated and real outputs of the system, the residuals are produced. This discrepancy is typically computed utilizing the norm of the output estimation error vector. Applying the disturbance decoupling principle is inevitable in the UIO design for fault detection, wherein the residual is obtained considering the fact that the effect of faults is decoupled on various inputs. For fault isolation, it is required to decouple the impact of a fault from the impacts of other faults. A properly designed residual signal tends to zero in the fault-free cases:

$$\begin{aligned} & r(k) \approx 0 \qquad \text{Fault free case} \\ & r(k) \neq 0 \qquad \text{Faulty case} \end{aligned} \tag{17}$$

The residual is investigated as to the possibility of a fault, followed by a logical decision-making process aiming to determine whether the fault has occurred and to prevent incorrect decisions, namely false alarm and neglected fault [15]. Following a plain comparison between the residual evaluation function $J(r(k))$ and a threshold $Th(k)$ (adaptive or constant), the ultimate decision is made. Once the value of $J(r(k))$ surpasses the value of $Th(k)$, the fault alarm is on, otherwise it is off.

### A. Robust FDI based on UIOs in Building Structure

One must describe the system such that it is be appropriate for UIO design for FDI. After the system is discretized, the definition of faults in the system can be given:

$$\begin{aligned} x(k+1) &= Ax(k)+Bu(k)+E_{ad}fd_{ad}(k) \\ y(k) &= Cx(k)+E_s f_s(k) \end{aligned} \tag{19}$$

where $f_s$ stands for fault vector of sensors and $fd_{ad}=[f_a \quad d]^T$ denotes the augmentation of actuators fault ($f_a$) and disturbance ($d$). Moreover, the actuators/disturbance and sensors fault distribution matrices are denoted by $E_{ad}$ and $E_s$, respectively. $f_a$, $f_s$ and $d$ are unknown while $E_{ad}$ and $E_s$ are known. The former matrices are expressed in building structures as follows:

$$E_{ad}=[B \quad B_d],\ E_s=C \tag{20}$$

The definition is attributed to the nature of the disturbance as well as sensors and actuators faults, which have the same impacts on the system, measurements and inputs, respectively. The system needs to be appropriately represented, as described in (10), to design UIOs. It is not necessary to change the system representation for actuator faults and disturbances. Let be no more than one fault at a definite time, the system representation is as follows:

$$\begin{aligned} x(k+1) &= Ax(k)+Bu(k)+E_{ad}fd_{ad}(k) \\ y(k) &= Cx(k) \end{aligned} \tag{21}$$

For any of the actuators, an UIO is designed. For the $i^{\text{th}}$ actuator the system is rewritten as follows:

$$\begin{aligned} x(k+1) &= Ax(k)+Bu(k)+E_{ad,i}fd_{ad,i}(k)+ \\ &\quad \bar{E}_{ad,i}\bar{fd}_{ad,i}(k) \\ y(k) &= Cx(k) \end{aligned} \tag{22}$$

where $fd_{ad,i}$ denotes the $i^{\text{th}}$ row of $f_{ad}$, indicating the $i^{\text{th}}$ actuator fault that is supposed to be the unknown input. $E_{ad,i}$ is the $i^{\text{th}}$ column of $E_{ad}$. Also $\bar{E}_{ad,i}$ and $\bar{fd}_{ad,i}$ are actuator fault distribution matrix actuator fault vector with their $i^{\text{th}}$ row and column being disregarded, respectively. Analogous to the case of actuator faults and assuming the occurrence of one fault at a definite time, one can rewrite the system for sensor faults as follows:

$$\begin{aligned} x(k+1) &= Ax(k)+Bu(k) \\ y(k) &= Cx(k)+E_{s,j}f_{s,j}(k)+\bar{E}_{s,j}\bar{f}_{s,j}(k) \end{aligned} \tag{23}$$

where $f_{s,i}$ denotes the $i^{\text{th}}$ row of $f_s$, showing the $i^{\text{th}}$ sensor fault, and $E_{s,i}$ stands for the $i^{\text{th}}$ column of $E_s$. Further, $\bar{E}_{s,i}$ and $\bar{f}_{s,i}$ are sensor fault distribution matrix and sensor fault vector with their $i^{\text{th}}$ row and column being removed, respectively. Obviously, this system representation is not identical to (10) and needs to be changed to provide the UIO design with an applicable representation of the system.

According to [13], a sensor fault-affected system can be viewed as an actuator fault-affected system. Let the dynamic of a sensor fault be defined as:

$$f_{s,j}(k+1)=f_{s,j}(k)+T_s\zeta(k) \tag{24}$$

where $T_s$ and $\zeta$ denote the sampling time (here equal to 1ms) and the sensor error input, respectively.

Based on (23) and (24), a new representation of the system consisting an auxiliary state can be obtained:

$$\begin{aligned} \begin{bmatrix} x(k+1) \\ f_{s,j}(k+1) \end{bmatrix} &= \begin{bmatrix} A & 0_{n\times1} \\ 0_{1\times n} & 1 \end{bmatrix} \begin{bmatrix} x(k) \\ f_{s,j}(k) \end{bmatrix} + \begin{bmatrix} B \\ 0 \end{bmatrix} u(k) \\ &\quad + \begin{bmatrix} 0_{n\times1} \\ T_s \end{bmatrix} \zeta(k) \\ y(k) &= \begin{bmatrix} C & E_{s,j} \end{bmatrix} \begin{bmatrix} x(k) \\ f_{s,j}(k) \end{bmatrix} \end{aligned} \tag{25}$$

This representation is now appropriate for UIO design.

## IV. Simulation Results

In this case, 8 observers generate residual signals using the input and output of the system. Observers 1, 2, and 3 corresponded to the faults of actuators 1, 2, and 3 respectively. Observer 4 is selected for disturbance and since this disturbance was added to the state equation, it would be identical to the actuator fault. Observers 5, 6, and 7 correspond to the faults of sensors 1, 2, and 3 respectively. Moreover, observer 8 is used to isolate sensor fault from actuator fault.

Observes are sensitive to all other faults leaving aside their own faults. The first observer is not sensitive to the fault of the first actuator. The second observer is not sensitive to the fault of the second actuator. The third observer is not sensitive to the fault of the third actuator. The fourth observer is not sensitive to the disturbance (earthquake). The fifth observer is not sensitive to the fault of the first sensor. The sixth observer is not sensitive to the fault of the second sensor. The seventh observer is not sensitive to the fault of the third sensor. The eighth observer is not sensitive to the faults of actuators. The eighth observer is used as the isolation of sensor fault from actuator fault can't be carried out by the last 7 observers which only detect the sensor or actuator faults with the same index as their name. For instance, it can be said that either actuator No. 1 or sensor No. 1 is faulty but it is not definite whether it is the fault of the sensor or the fault of actuator. This is attributed to the dissimilar design procedure of observers for fault detections of sensor and actuator. Therefore, an eighth observer is used which is not sensitive to both sensor and actuator and one can determine whether the fault pertains to sensor or actuator by using the residual of this observer.

For design, first, equation (6) is discretized with the sampling time of $10^{-3}$. The coefficients of the LQR controller were set at $R = 10^{-3}I$ and $Q = 10^{3}I$. It is worth noting that since matrix $C$ was is cubature here (i.e. the number of outputs is not equal to the number of states), matrix $K1$ needs to be obtained through trial and error method whereby matrix $F$ is then calculated. In other words, all eigenvalues of this matrix is positioned in a unit circle so that the observer is stable. Three scenarios are considered to examine the results. In the first scenario, a fault occurred in the first sensor at t=13.33s with the amplitude of 4. The second scenario included a fault in the second actuator at t=13.33s with the amplitude of $0.510^{6}$ and an earthquake in a sinusoidal form with the amplitude of 10mm and frequency of 2Hz took place in the third scenario. Fig. 2 depicts residual when there was no fault or disturbance. It is evident that all residuals have substantially small values close to zero. Fig. 3 displays the residuals in the first scenario. Since no fault occurred in the first sensor in this state, the residual of the corresponding observer is not sensitive to the fault where all other observers, including the eighth observer, reacts to this fault and their residuals have non-zero values.

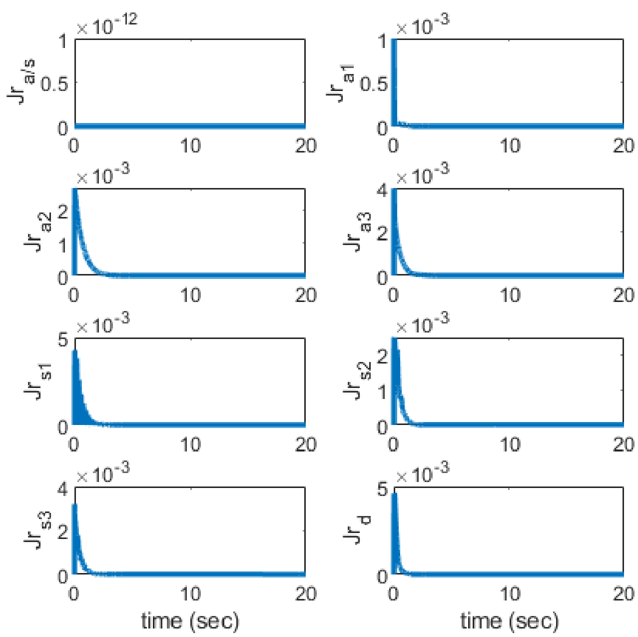


Figure 2. Residuals of fault and disturbance free case

The eights observer is designed to be insensitive to the sensor fault.

Fig. 4 is related to the second scenario where the fault occurs in the second actuator and, therefore; the observer of actuator 2 and the eighth observer do not react to this fault, while other observers are sensitive to the fault.

Fig. 5 shows the third scenario wherein there is disturbance, i.e. earthquake. As can be seen in the figure, the fourth and eights observers are not sensitive to earthquake but the residuals of other observers have non-zero values. Regarding the similarity of disturbance and actuator fault in terms of the fault location, the eights observer is not sensitive to disturbance. According to the obtained result, it can be seen that all faults along with their occurrence locations are fully detected.

Furthermore, due to the use of an additional observer, the occurrence of disturbance was detected and was not mistaken for a fault.

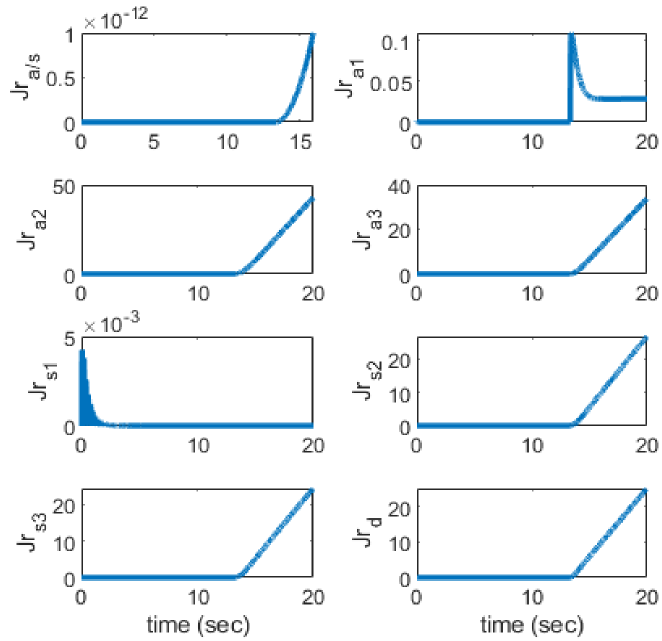


Figure 3. Residuals of scenario 1

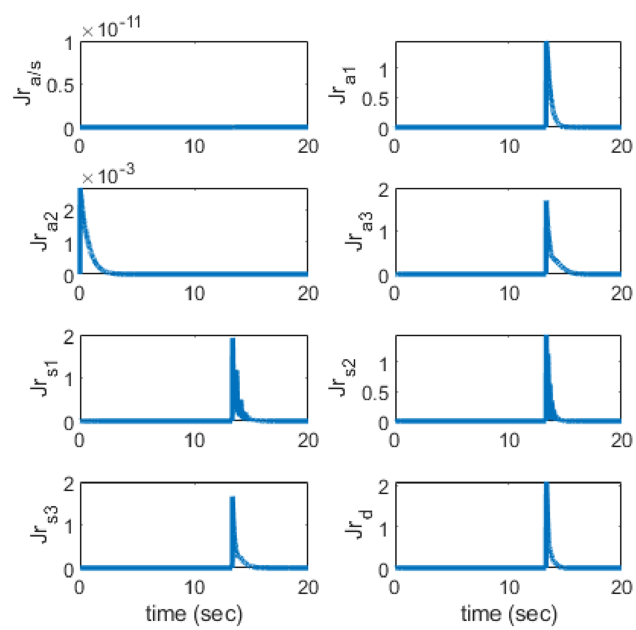


Figure 4. Residuals of scenario 2

## V. Conclusions

In this study, a bank of UIOs are designed for FDI of actuator/sensor in a building with three-story structure and MR dampers which is optimally controlled by the LQR controller. Regarding the dynamic equations of building structure used in this paper, seven UIOs are designed to detect three sensor faults, three actuator faults, and one disturbance. The eighth observer is proposed to isolate the actuator fault from sensor fault. In addition to the detection of fault and its type (actuator or sensor), the proposed observers are robust against disturbance (earthquake). In other words, once an earthquake occurs, no false alarm would be activated. The simulation results have indicated the suitable accuracy of the proposed method in FDI.

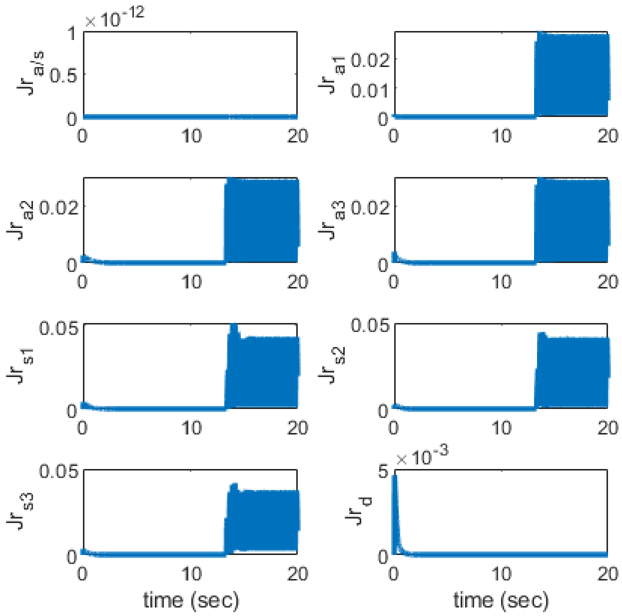


Figure 5. Residuals of scenario 3

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