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# Fault Tolerant Control With Re-Configuring Sliding-Mode Schemes

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**Abstract**

*In this paper, a controller design method for linear MIMO systems is presented which a sliding mode controller is reconfigured in case of system faults. Faults are detected with the residual vector generated from a standard linear observer. Once a fault has been detected the fault distribution matrix can be obtained and used to update the corrective or equivalent control parts of the sliding mode controller. As a result, fault tolerant adaptive controllers keep the system performance within acceptable limits or at least avoids the system to wind-up.*

**Key Words:** *Fault detection, fault-tolerant systems, sliding-mode control, adaptive control, MIMO linear systems.*

## 1. Introduction

Progresses in control theory and computer technology stimulated a continuous improvement in control techniques in last decade. In the mean time the control systems became more and more sophisticated and complex. These complex systems require a high degree of reliability and maintainability and they must have fault accommodation in order to operate successfully over long periods of time [1]. Re-configurable control is a solution to achieve this goal and applied mainly in three situations: [2]

- to keep the system performance within acceptable boundaries during operation,
- to increase the performance of the process,
- to achieve the goal for fault accommodation.

Reconfigurable control is a critical technology [3, 4] with its objectives to detect the fault and recover the functionality of the faulty system as same as that of the nominal system [5]. Various methods are used for reconfigurable control to cover the requirements of different applications. The behaviour of the reconfigurable control depends upon whether the approach is passive or active. Such control ideas have been implemented on a variety of military and commercial applications in last two decades to accommodate faults, for example on flight control systems in [6, 7, 8, 9] on space technology in [10, 11] and on unmanned underwater vehicles in [12].

The idea to use variable structure system theory with sliding mode control [13] for reconfiguration purposes stems from the fact that this method alleviates the problems caused by uncertain or changing system dynamics or parameters. This is the case when a fault occurs in a system component. Variable structure systems with sliding mode control were first proposed in the 1950's [14]. Sliding-mode controllers nowadays enjoy a variety of applications such as in aerospace applications, in process control, in motion control applications and robotics [15, 16]. The main reason for this popularity is their attractive properties such as applicability to multi input multi output systems, good control performance for nonlinear systems and well established design criteria for discrete time systems. The most significant property of a sliding mode controller is its robustness when uncertainties are inserted into the system.

The reconfiguring control for fault accommodation purposes has usually been achieved by mainly adaptive controllers [2]. Up to the knowledge of authors, the novel idea proposed is the first application of variable structure system method as an active reconfiguring controller for fault accommodation. Here, the fault distribution matrix is used to switch the corrective or equivalent control part of the sliding-mode controller in an adaptive manner to compensate the uncertainty inserted into the system dynamics due to system fault. Applicability of the proposed algorithm is shown for the reconfiguration of a sliding-mode controller for a MIMO linear system. The objective of the controller is to control the MIMO system under nominal operation, as well as in case of an abrupt fault. The mentioned corrective or equivalent control parts are switched back to its nominal value when fault detection scheme detects that the related system component acts nominally.

The proposed method aims to avoid chattering for the nominal plant, nevertheless, to keep the process in operation by increasing the robustness of the controller with a larger gain for the faulty plant in accordance with the size of the fault distribution matrix. It is required to avoid an increase in the controller gain and, hence, in the chattering, for the nominal plant; but for the faulty plant the robustness is a delicate subject to be considered to keep the plant running with an acceptable performance. Here, a trade-off appears between chattering and robustness.

The proposed algorithm can be implemented for autonomous underwater and space vehicles when there is no way to stop the process and fix the faulty system component. Torpedo and missile guidance systems can also be considered as military applications.

## 2. Fault Distribution Matrix

It is stated in many research results on FDI that a reasonable model for FDI purposes is the one which has a description about the system uncertainty, e.g. its distribution matrix or spectral bandwidth. Typical description for the system uncertainty caused by system faults can be represented with a linear state-space model of the system [17], namely,

$$\begin{aligned}\dot{\mathbf{x}}(t) &= \mathbf{A}\mathbf{x}(t) + \mathbf{B}\mathbf{u}(t) + \mathbf{R}\mathbf{f}(t),\\ \mathbf{y}(t) &= \mathbf{C}\mathbf{x}(t).\end{aligned} \tag{1}$$

where $x(t) \in \Re^n$ is the state vector, $u(t) \in \Re^r$ is the control input vector and $y(t) \in \Re^m$ is the measurement vector and $\mathbf{f}(t) \in \Re^g$ represents the fault vector which is considered as an unknown time function. Here,

$\Re^n$ denotes n-dimensional Euclidean space. On the other hand, **A**, **B** and **C** are system parameter matrices and the pair $\{C, A\}$ is assumed to be observable. Here, **R** matrix is the distribution matrix of a system or actuator fault. $\mathbf{Rf}(t)$ term in (1) denotes the uncertainty caused by system or actuator faults. For system faults uncertainty is inserted into system matrix **A,** system matrix turns out to be,

$$\mathbf{A}_{fault} = \mathbf{A} + \Delta\mathbf{A} \tag{2}$$

Uncertainty is inserted into control input matrix **B** for actuator faults, and

$$\mathbf{B}_{fault} = \mathbf{B} + \Delta\mathbf{B} \tag{3}$$

Hence, $\mathbf{Rf}(t)$ in (1) can be represented with respect to fault as follows,

$$\mathbf{Rf}(t) = \begin{cases} \Delta\mathbf{Ax}(t) \; system \; fault \\ \Delta\mathbf{Bx}(t) \; actuator \; fault \end{cases} \tag{4}$$

By means of an observer, the residual can be generated as,

$$\dot{\hat{\mathbf{x}}}(t) = (\mathbf{A} - \mathbf{LC})\hat{\mathbf{x}}(t) + \mathbf{Bu}(t) + \mathbf{Ly}(t), \tag{5}$$

and

$$\begin{aligned} \hat{\mathbf{y}}(t) &= \mathbf{C}\hat{\mathbf{x}}(t), \\ \mathbf{r}(t) &= \mathbf{y}(t) - \hat{\mathbf{y}}(t) = \mathbf{C}[\mathbf{x}(t) - \hat{\mathbf{x}}(t)]. \end{aligned} \tag{6}$$

where $r(t) \in \Re^p$ is the residual vector, $\hat{x}$ and $\hat{y}$ are state and output estimates. By defining the state estimation error as

$$\mathbf{e}(t) = \mathbf{x}(t) - \hat{\mathbf{x}}(t) \tag{7}$$

error dynamics can be written as,

$$\dot{\mathbf{e}}(t) = (\mathbf{A} - \mathbf{LC})\mathbf{e}(t) + \mathbf{Rf}(t), \tag{8}$$

Also note that,

$$\mathbf{r}(t) = \mathbf{Ce}(t). \tag{9}$$

It is required to reconfigure the sliding mode controller structure and adjust the controller gain according to the fault information, without referring to any prior information about the faults which might occur in the system. Therefore, the next step is to find an analytical relation between robustness of the sliding-mode controller and fault information. Therefore, fault distribution information need to be extracted by means of observers.

In this thesis, it is assumed that there is no modeling uncertainty or, at least, even if there is, it can be handled by the robustness property of a relatively low-gain sliding-mode controller. On the other hand, a typical description for the system uncertainty caused by system faults can be represented with the model of the system in (1). Also, remember that, by means of an observer, the residual can be generated as defined in (6) and (9),

Assuming $\mathbf{C}$ is a unity matrix and from (8), it follows that,

$$\begin{aligned} \dot{\mathbf{r}}(t) &= \dot{\mathbf{e}}(t), \\ &= (\mathbf{A}-\mathbf{L})\mathbf{e}(t) + \mathbf{Rf}(t), \end{aligned} \tag{10}$$

Rearranging (10),

$$\mathbf{Rf}(t) = \dot{\mathbf{r}}(t) - (\mathbf{A}-\mathbf{L})\mathbf{e}(t). \tag{11}$$

Extracted fault information can be embedded into sliding mode controllers in two possible approaches in order to obtain a reconfiguring controller, which is robust to any system faults.

Fault distribution information can be utilized in adjusting the corrective control part of sliding-mode controller.

Fault distribution information can be inserted into equivalent control part of sliding-mode controller output.

## 3. Reconfiguring Controller Design

The reconfigurable controller proposed here is a modified version of standard sliding-mode controller. Sliding-mode controller is robust to model uncertainties when the upper boundary of the uncertainty is given. Assume there is no information for the upper boundary of the uncertainty caused by model mismatch or a system fault. In that case, the proposed methodology replaces corrective gain vector with fault distribution information or inserts the fault distribution information into equivalent control part of sliding mode controller to achieve the acceptable performance criteria.

### 3.1. First approach: switching-gain sliding-mode control

Consider a general linear MIMO system of the form in (1). In order to achieve all states of the system in (1) to track the given desired trajectories at the same time, the sliding manifold is defined as follows [18],

$$\mathbf{s}(t) = \tilde{\mathbf{x}}(t) + \Lambda \int \tilde{\mathbf{x}}(t)dt \tag{12}$$

where $\mathbf{s}$ is the sliding surface vector, $\Lambda$ is a diagonal matrix which defines the slopes of the sliding surfaces, $\tilde{x}$ is the state error vector and defined as,

$$\tilde{\mathbf{x}} = \mathbf{x} - \mathbf{x}_d \tag{13}$$

In order to guarantee stability, a candidate Lyapunov function is given in terms of sliding manifold given in (12)

$$\mathbf{V}(\mathbf{s}) = \frac{\mathbf{s}^T\mathbf{s}}{2}, \tag{14}$$

If the control satisfies the negative definiteness of the time derivative of the Lyapunov function in (14) is guaranteed, then, the stability of the overall system is guaranteed. The system representation with fault distribution information can be presented in terms of system and actuator faults as defined in (4)

$$\dot{\mathbf{x}} = \mathbf{A}_{fault}\mathbf{x}(t) + \mathbf{B}_{fault}\mathbf{u}(t) \tag{15}$$

First derivative of sliding surface function becomes

$$\dot{\mathbf{s}}(t) = \dot{\tilde{\mathbf{x}}}(t) + \Lambda\tilde{\mathbf{x}}(t) = 0 \tag{16}$$

The system representation can be inserted into (16) under the assumption that there exists no uncertainty,

$$\dot{\mathbf{s}}(t) = \mathbf{A}\mathbf{x}(t) + \mathbf{B}\mathbf{u}(t) - \dot{\mathbf{x}}_{\mathbf{d}}(t) + \Lambda\tilde{\mathbf{x}}(t) \tag{17}$$

The best approximate of control law for the system with uncertainties turns out to be,

$$\hat{\mathbf{u}} = \mathbf{B}_{fault}^{-1}[-\mathbf{A}_{fault}\mathbf{x}(t) + \dot{\mathbf{x}}_{\mathbf{d}}(t) - \Lambda\tilde{\mathbf{x}}(t)] \tag{18}$$

The overall control scheme together with corrective control gain becomes,

$$\mathbf{u} = \hat{\mathbf{u}} - \mathbf{B}_{fault}^{-1}\mathbf{k}sgn(\mathbf{s}) \tag{19}$$

The condition for $\mathbf{k}$ can be obtained by inserting (18) and (19) into (17) as follows,

$$\begin{aligned}\dot{\mathbf{s}}(t) &= \mathbf{A}\mathbf{x}(t) + \mathbf{B}\mathbf{B}_{fault}^{-1}[-\mathbf{A}_{fault}\mathbf{x}(t) + \dot{\mathbf{x}}_{\mathbf{d}}(t) - \Lambda\tilde{\mathbf{x}}(t)] - \dot{\mathbf{x}}_{\mathbf{d}}(t) + \Lambda\tilde{\mathbf{x}}(t) - \mathbf{B}\mathbf{B}_{fault}^{-1}\mathbf{k}sgn(\mathbf{s}),\\ &= (\mathbf{A}\mathbf{x}(t) - \mathbf{B}\mathbf{B}_{fault}^{-1}\mathbf{A}_{fault}\mathbf{x}(t)) + (\mathbf{I} - \mathbf{B}\mathbf{B}_{fault}^{-1})(-\dot{\mathbf{x}}_{\mathbf{d}}(t) + \Lambda\tilde{\mathbf{x}}(t)) - \mathbf{B}\mathbf{B}_{fault}^{-1}\mathbf{k}sgn(\mathbf{s}).\end{aligned} \tag{20}$$

So that $\mathbf{k}$ must verify,

$$\mathbf{k} \geq \left\|\mathbf{B}^{-1}\mathbf{B}_{fault}\mathbf{A}\mathbf{x}(t) - \mathbf{A}_{fault}\mathbf{x}(t) + (\mathbf{B}^{-1}\mathbf{B}_{fault} - \mathbf{I})(-\dot{\mathbf{x}}_{\mathbf{d}}(t) + \Lambda\tilde{\mathbf{x}}(t))\right\| + \eta\mathbf{B}^{-1}\mathbf{B}_{fault}, \tag{21}$$

If there exists uncertainty in system matrix but not in input matrix, in other words, if $\mathbf{B} = \mathbf{B}_{fault}$, then,

$$\mathbf{k} \geq \|\mathbf{A}\mathbf{x}(t) - \mathbf{A}_{fault}\mathbf{x}(t) + (\mathbf{I} - \mathbf{I})(-\dot{\mathbf{x}}_{\mathbf{d}}(t) + \Lambda\tilde{\mathbf{x}}(t))\| + \eta\mathbf{I}, \tag{22}$$

Hence,

$$\mathbf{k}_{fault} \geq \mathbf{R}\mathbf{f}(t) + \eta, \tag{23}$$

The corrective gain vector $\mathbf{k}$ in (19) is replaced with fault distribution information for faulty case and a nominal gain vector is used for nominal case. In case a fault is detected by means of FD scheme, then the corrective controller gain vector is switched to fault distribution vector as shown below.

$$\mathbf{k} = \begin{cases} \mathbf{k}_{nom} = \eta \text{ for nominal plant} \\ \mathbf{k}_{fault} = \mathbf{Rf} + \eta \text{ for faulty plant} \end{cases} \tag{24}$$

In other words the fault distribution vector is taken as the corrective control gain vector of standard sliding-mode controller. The desired trajectories given in Figure 1 are required to be achieved by the controller.

The trajectory task performance has been achieved for both outputs of MIMO system with the proposed reconfiguring controller scheme, which uses sliding-mode controller as the baseline controller [19]. Here, the fault or uncertainty information is extracted from the system dynamics by means of an observer and embedded into corrective control part of reconfiguring sliding mode controller scheme. A soft nonlinear switching function is used to avoid chattering for the nominal plant.

The system fault is detected by comparing any component of residual vector with any corresponding scalar threshold component which is found by trial and error.

### 3.2. Second approach: fault information inserted into equivalent control part

Our second approach is based on the idea of updating the equivalent control part of the sliding-mode control action using the fault distribution information whenever a fault is detected.

It follows from (1) and (16), that the system representation with the fault distribution vector is inserted into (16)

$$\dot{\mathbf{s}}(t) = \mathbf{Ax}(t) + \mathbf{Bu}(t) + \mathbf{Rf}(t) - \dot{\mathbf{x}}_d(t) + \Lambda\tilde{\mathbf{x}}(t) \tag{25}$$

hence, the equivalent control term is obtained as

$$\mathbf{u}_{eq}(t) = \mathbf{B}^{-1}[-\mathbf{Ax}(t) - \mathbf{Rf}(t) + \dot{\mathbf{x}}_d(t) - \Lambda\tilde{\mathbf{x}}(t)]. \tag{26}$$

It is clear that all terms are known except fault distribution matrix in (26). To satisfy the sliding condition a corrective control term is used for sliding mode controllers. The overall controller with the corrective control term will be derived as,

$$\mathbf{u}(t) = \mathbf{u}_{eq}(t) - \mathbf{B}^{-1}[\mathbf{k}_{nom} sat(\frac{\mathbf{s}}{\Phi})]. \tag{27}$$

where $\mathbf{k}_{nom}$ is the corrective gain vector which is also used for nominal case to guarantee a sliding regime on the switching surface vector $\mathbf{s}$. As the fault distribution vector $\mathbf{Rf}(t)$ term inserted into the equivalent control part of controller scheme, the controller runs in a reconfiguring adaptive manner and makes it possible to accommodate with system faults.

## 4. Design Examle and Simulations

Consider state-space representation of a MIMO system as

$$\begin{aligned} \dot{x}(t) &= \begin{bmatrix} -2 & 0.1 \\ 2 & 3 \end{bmatrix} x(t) + \begin{bmatrix} 5 & 0 \\ 0 & 1 \end{bmatrix} u(t), \\ y(t) &= \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} x(t) \end{aligned} \tag{28}$$

A system fault is inserted into the system matrix **A** consequently, the state space representation of the faulty system becomes,

$$\begin{aligned} \dot{x}(t) &= \begin{bmatrix} 6 & 10 \\ 20 & 5 \end{bmatrix} x(t) + \begin{bmatrix} 5 & 0 \\ 0 & 1 \end{bmatrix} u(t), \\ y(t) &= \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} x(t) \end{aligned} \tag{29}$$

The MIMO linear system given as an example has two eigenvalues, one of them is unstable and the other one is stable as follows,

$$\mu_1 = -2.0397 \qquad \mu_2 = 3.0397 \tag{30}$$

During faulty situation unstable eigenvalue becomes stable and unstable one becomes stable. Eigenvalues for the faulty case are:

$$\alpha_1 = 19.6510 \qquad \alpha_2 = -8.6510 \tag{31}$$

It can easily be checked that the state vector is observable from both outputs.

A linear observer is designed to observe the system outputs with the following gain matrix,

$$\mathbf{L} = \begin{bmatrix} 21 & 32.1 \\ 1692 & 21 \end{bmatrix} \tag{32}$$

## 4.1. Simulations for first approach

The fault information within fault distribution matrix will be obtained as follows [20],

$$\begin{aligned} \mathbf{Rf}(t) &= \dot{\mathbf{r}}(t) - (\mathbf{A} - \mathbf{L})\mathbf{e}(t), \\ &= \dot{\mathbf{r}}(t) - \left\{ \begin{bmatrix} -2 & 0.1 \\ 2 & 3 \end{bmatrix} - \begin{bmatrix} 21 & -17.9 \\ 1692 & 21 \end{bmatrix} \right\} \begin{bmatrix} \tilde{x}_1 \\ \tilde{x}_2 \end{bmatrix}, \\ &= \begin{bmatrix} \dot{r}_1 + 23\tilde{x}_1 - 0.1\tilde{x}_2 \\ \dot{r}_2 + 2\tilde{x}_1 + 18\tilde{x}_2 \end{bmatrix} \end{aligned} \tag{33}$$

Each fault distribution vector term has been used as the corrective control gain vector of standard sliding-mode controller as defined in (22) and (23). In other words, the controller transformed to run in an adaptive manner in case a fault detected in the system dynamics. Matlab-SIMULINK software has been used for simulations. A bias system fault has been inserted at 1.25 sec. into the nominal system and this fault has been removed at 1.75 sec. of the simulation. Following desired trajectories given in Figure 1 are required to be achieved by the controller.

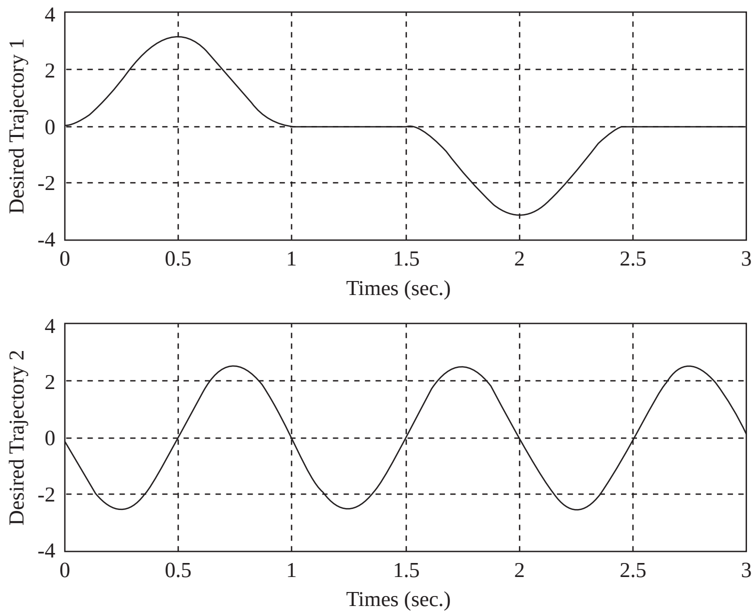


**Figure 1.** Desired trajectories [20].

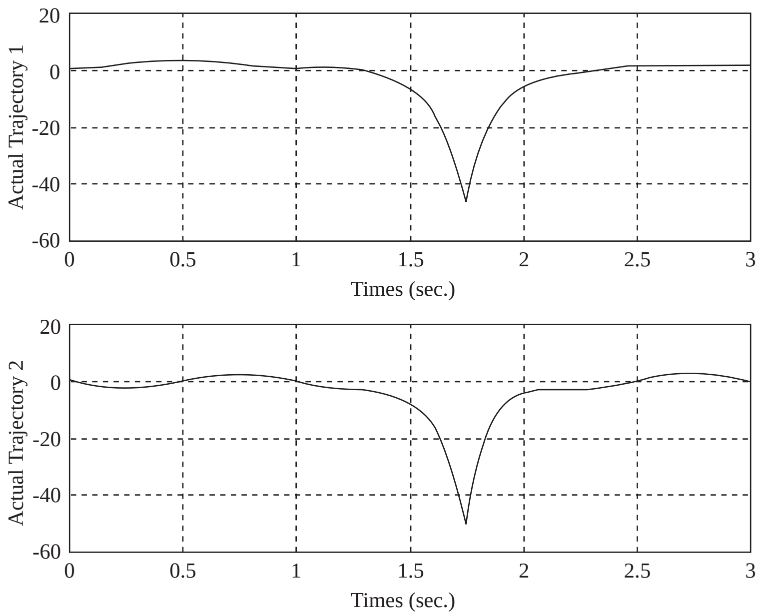


**Figure 2.** Actual trajectories with standard sliding-mode scheme [20].

It is observed that the standard sliding mode controller cannot cope with the structured (or parametric) uncertainties [18] inserted into the system as a result of the system fault. It is seen from Figure 2 that the magnitude of the fault would grow unboundedly if the system has not been simulated to act nominally. On the other hand proposed controller scheme copes with the fault and stops system dynamics to wind-up.

It is also observed from Figure 3 that the control inputs are out of realistic values during the faulty period. This illustrates the fact that the fault had adverse effect on the system dynamics and therefore the reconfiguration of the controller is essential.

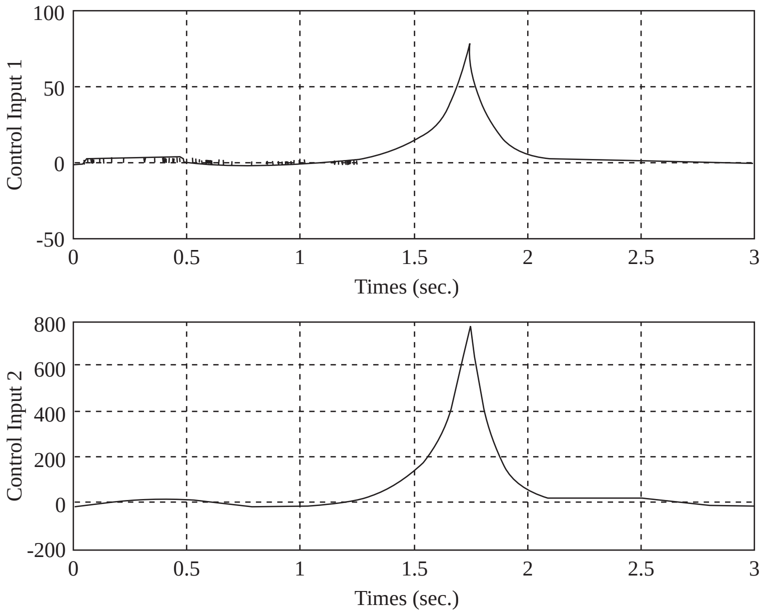


**Figure 3.** Control inputs with standard sliding-mode scheme [20].

First approach of proposed scheme which inserts fault distribution information into corrective control part of reconfiguring sliding mode controller shows better performance when compared with standard sliding mode controller as can be seen in Figure 4. The trajectory following is not perfect but the system is still in operation.

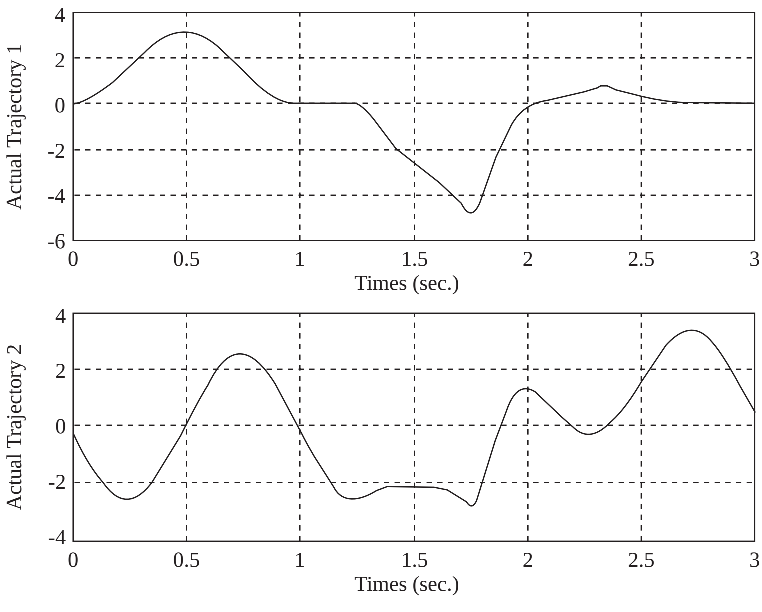


**Figure 4.** Actual trajectories with first approach of reconfiguring controller scheme.

The activity of the reconfigured controller under the faulty condition can be seen in Figure 5 clearly. Note, the control activity is considerably higher during the faulty situation, whereas it is reduced under nominal condition.

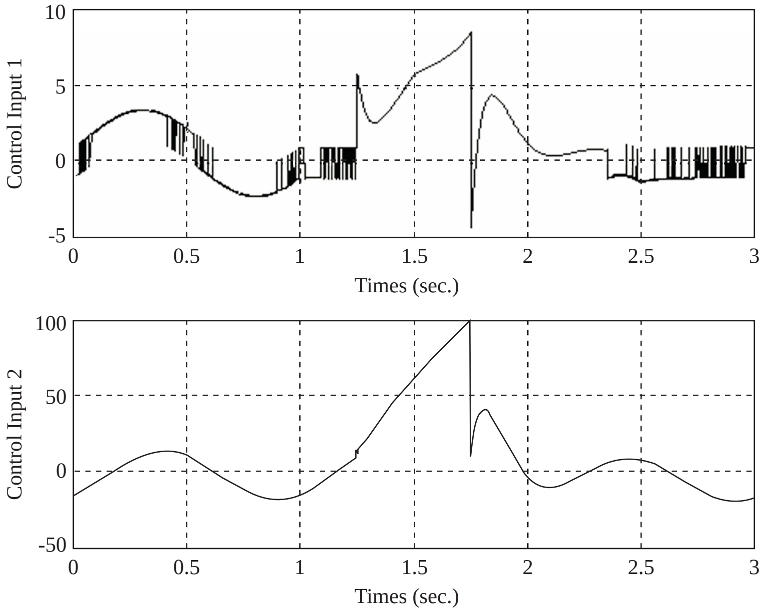


**Figure 5.** Controller inputs with first approach of reconfiguring controller scheme.

## 4.2. Simulations for Second Approach

Proposed second approach of reconfiguring sliding mode controller copes satisfactorily with the mentioned uncertainties by updating the equivalent control part of reconfiguring sliding mode controller as can be seen from Figure 6 and 7. Note that the control activity increases under faulty situation. In return, fault tolerant control is accomplished with reconfiguring sliding mode controller.

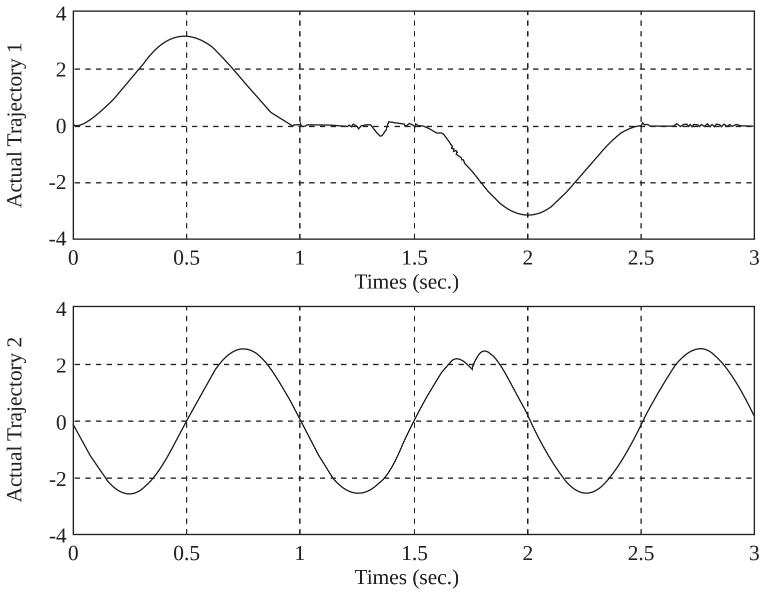


**Figure 6.** Actual trajectories with second approach of reconfiguring controller scheme [20].

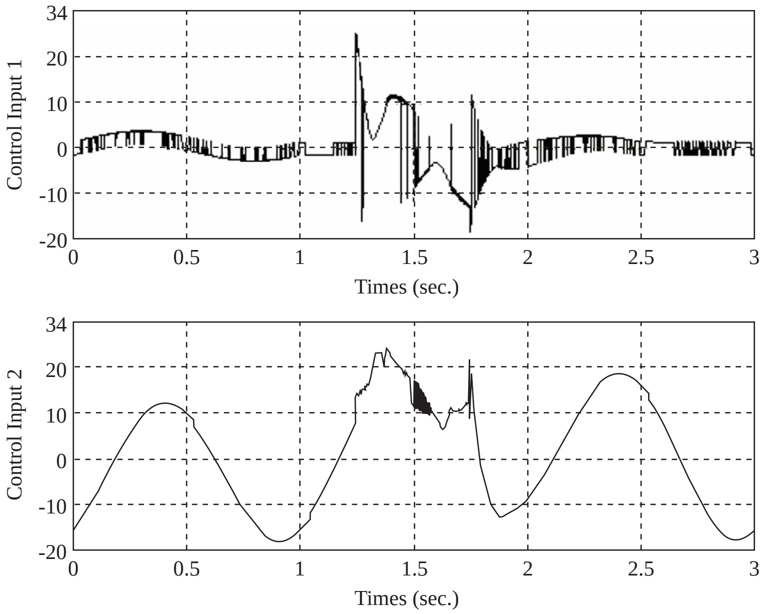


**Figure 7.** Controller inputs with second approach of reconfiguring controller scheme [20].

# 5. Conclusion

A reconfiguring sliding mode controller is proposed for linear MIMO systems. Reconfiguring controller alleviates the disturbances inserted into the system dynamics in case of a fault by reconfiguring the equivalent control term or corrective gain vector term of the sliding mode controller in an adaptive manner. It is observed that the standard sliding mode controller cannot cope with uncertainties due to system fault. On the other hand, the switching gain reconfiguration can cope with faulty condition much better than the standard sliding-mode controller and stops system dynamics to wind-up at the faulty situation. Second approach can also cope with mentioned uncertainties by updating the equivalent control part of a sliding-mode controller with respect to fault distribution information. In fact, by comparing Figure 5 and 7, it is seen that updating the equivalent control term yields better performance as compared to a switched gain controller.

The algorithm based on the extraction of fault distribution information from system dynamics by means of a linear observer. This method is an example for the integration of fault detection methods with robust control techniques to obtain fault tolerant control. The proposed controller schemes can be seen as active reconfiguration methods. This method can be implemented for the control of underwater and aerospace vehicles especially when there is no way to terminate the process and fix the faulty system component.

The proposed scheme based on corrective gain vector re-configuration shows better performance than standard sliding-mode controller for the given case and stops system dynamics to wind-up, whereas the standard sliding-mode controller cannot cope with the faulty situation and causes system dynamics to wind-up.

The second approach for reconfiguring sliding-mode controller uses the extracted fault or disturbance information for the equivalent control part of the sliding-mode controller. This approach is implemented for the same MIMO system under the same faulty situation. It has been observed that the second approach gives better performance than the first one.

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