FAULT TOLERANT RE-CONFIGURING SLIDING MODE CONTROLLER

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

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 gain vector of the sliding mode controller. As a result, a fault tolerant adaptive controller keeps the system performance within acceptable limits.

I. 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 gain vector 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 simple 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 gain vector is 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 the decision of chattering and robustness levels.

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.

II. 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 (See for example [17]). In this work, it is assumed that there is no disturbance for modelling uncertainty or at least modelling uncertainty can be handled with sliding-mode controller. On the other hand, a typical description for the system uncertainty caused by system faults can be represented with the following linear model of the system.

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

where $\mathbf{x}(t) \in \Re^n$ is the state vector, $\mathbf{u}(t) \in \Re^r$ is the control input vector and $\mathbf{y}(t) \in \Re^m$ is the measurement vector, $\mathbf{f}(t) \in \Re^g$ represents the fault vector which is considered as an unknown time function. **A**, **B** and **C** are system parameter matrices and the pair $\{\mathbf{C}, \mathbf{A}\}$ is assumed to be observable. Here **R** matrix is the distribution matrix of a system fault.

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

$$\begin{aligned} \dot{\hat{\mathbf{x}}}(t) &= (\mathbf{A} - \mathbf{L})\hat{\mathbf{x}}(t) + \mathbf{B}\mathbf{u}(t) + \mathbf{L}\mathbf{x}(t), \\ \mathbf{r}(t) &= \mathbf{x}(t) - \hat{\mathbf{x}}(t). \end{aligned}$$

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

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

error dynamics can be written as,

$$\begin{aligned} \dot{\mathbf{e}}(t) &= \dot{\mathbf{x}}(t) - \dot{\hat{\mathbf{x}}}(t), \\ \dot{\mathbf{e}}(t) &= (\mathbf{A} - \mathbf{L})\mathbf{e}(t) + \mathbf{R}\mathbf{f}(t) \end{aligned} \tag{2}$$

From (2), the disturbance distribution vector $\mathbf{R}\mathbf{f}(t)$ follows that,

$$\mathbf{R}\mathbf{f}(t) = \dot{\mathbf{e}}(t) - (\mathbf{A} - \mathbf{L})\mathbf{e}(t).$$

III. CONTROLLER DESIGN

The controller 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 the corrective gain vector with the disturbance distribution vector to achieve the acceptable performance criteria. 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 switching surface function is defined as follows [18],

$$\mathbf{s}(t) = \tilde{\mathbf{x}}(t) + \mathbf{\Lambda}\int \tilde{\mathbf{x}}(t)dt \tag{3}$$

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

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

where $\mathbf{x}$ is the actual state vector and $\mathbf{x_d}$ is the desired trajectory vector. A Lyapunov function is defined as,

$$\mathbf{V} = \frac{1}{2}\mathbf{s}^T\mathbf{s}$$

which is positive definite and it is required that the following condition must be satisfied for overall system response to be stable,

$$\dot{\mathbf{V}} < 0 \qquad \forall t > 0$$

The dynamics of the sliding surface can be written as

$$\dot{\mathbf{s}} = 0$$

First derivative of sliding surface function in (3) becomes [18]

$$\dot{\mathbf{s}}(t) = \dot{\tilde{\mathbf{x}}}(t) + \mathbf{\Lambda}\tilde{\mathbf{x}}(t) = 0 \quad (4)$$

By solving the above equation from (1) and (4), the control input can be obtained as,

$$\dot{\mathbf{s}}(t) = \mathbf{A}\mathbf{x}(t) + \mathbf{B}\mathbf{u}(t) + \mathbf{R}\mathbf{f}(t) - \dot{\mathbf{x}}_d(t) + \mathbf{\Lambda}\tilde{\mathbf{x}}(t)$$

Assuming $\mathbf{B}_n$ is invertible,

$$\mathbf{B}_n\mathbf{u}_{eq}(t) = \left[-\mathbf{A}_n\mathbf{x}_n(t) - \mathbf{R}_n\mathbf{d}(t) + \dot{\mathbf{x}}_d(t) - \mathbf{\Lambda}\tilde{\mathbf{x}}(t)\right],$$
$$\mathbf{u}_{eq}(t) = \mathbf{B}^{-1}\left[-\mathbf{A}\mathbf{x}(t) - \mathbf{R}\mathbf{f}(t) + \dot{\mathbf{x}}_d(t) - \mathbf{\Lambda}\tilde{\mathbf{x}}(t)\right]. \quad (5)$$

where $\mathbf{u}_{eq}$ is the equivalent control term of the overall controller which guarantees system states to track the desired trajectories.

It is clear that all terms are known except fault distribution matrix in (5). 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 [18],

$$\mathbf{u}(t) = \mathbf{u}_{eq}(t) - \mathbf{B}^{-1}[\mathbf{k}sat(\frac{\mathbf{s}}{\mathbf{\Phi}})]. \quad (6)$$

where $\mathbf{k}$ is the corrective gain vector which is used to guarantee a sliding regime on the switching surface vector **s**(t) and a soft switching function is used to avoid chattering for the nominal plant,

$$sat(\frac{\mathbf{s}}{\mathbf{\Phi}}) = \begin{cases} +1 & if \quad \mathbf{s} > \mathbf{\Phi} \\ \mathbf{s} & if \quad -\mathbf{\Phi} \le \mathbf{s} \le \mathbf{\Phi} \\ -1 & if \quad \mathbf{s} < \mathbf{\Phi} \end{cases}$$

As the fault distribution vector $\mathbf{CRf}(t)$ term inserted into the controller scheme, the controller runs in a reconfiguring adaptive manner and makes it possible to accommodate with system faults. 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.

$$\|r_i(t)\| < \xi_i \qquad \text{for fault-free case,}$$
$$\|r_i(t)\| \ge \xi_i \qquad \text{for faulty case}$$

IV. DESIGN EXAMPLE AND SIMULATIONS

Consider state-space representation of a MIMO system as

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

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

$$\dot{\mathbf{x}}(t) = \begin{bmatrix} 6 & 10 \\ 20 & 5 \end{bmatrix}\mathbf{x}(t) + \begin{bmatrix} 5 & 0 \\ 0 & 1 \end{bmatrix}\mathbf{u}(t), \quad (7)$$
$$\mathbf{y}(t) = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}\mathbf{x}(t)$$

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

$$\mu_1 = -2.0397 \qquad \mu_2 = 3.0397$$

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

$$\alpha_1 = 19.6510 \qquad \alpha_2 = -8.6510$$

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,

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

Now, the fault information within fault distribution matrix will be obtained as follows,

$$\mathbf{CRf}(t) = \dot{\mathbf{r}}(t) - \mathbf{C}(\mathbf{A} - \mathbf{LC})\mathbf{e}(t),$$
$$= \dot{\mathbf{r}}(t) - \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}\left\{\begin{bmatrix} -2 & 0.1 \\ 2 & 3 \end{bmatrix} - \begin{bmatrix} 21 & -17.9 \\ 1692 & 21 \end{bmatrix}\begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}\right\}\begin{bmatrix} \tilde{x}_1 \\ \tilde{x}_2 \end{bmatrix},$$
$$= \begin{bmatrix} \dot{r}_1(t) + 23\tilde{x}_1 - 0.1\tilde{x}_2 \\ \dot{r}_2(t) - 2\tilde{x}_1 + 18\tilde{x}_2 \end{bmatrix}$$

Each fault distribution vector term has been inserted into the corrective gain vector of standard sliding-mode controller as an additive gain as can be seen in (5). 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 as given in (6) inserted at 1.25 sec. into the nominal system and this fault has been removed at 1.75 sec. of the simulation.

It is observed that the standard sliding mode controller can not cope with the structured (or parametric) uncertainties [18] inserted into the system as a result of the system fault. On the other hand proposed controller scheme performs fault tolerant control satisfactorily.

As can be seen from Fig. 1 the controller can not perform the desired trajectory task. It is also observed that the control inputs are out of realistic values during the faulty period as can be seen from Fig. 2.

Faults can be detected by means of residuals as can be seen from Fig. 5. Also, proposed reconfiguring sliding mode controller copes satisfactorily with the mentioned uncertainties by updating the correcting gain vector by means of inserting disturbance distribution vector as an additive term as can be seen from Fig. 3 and 4. In return, fault tolerant control is accomplished with reconfiguring sliding mode controller.

V. CONCLUSION

A reconfiguring sliding mode controller proposed for linear MIMO systems. Reconfiguring controller alleviates the disturbances inserted into the system dynamics in case of a fault by reconfiguring the corrective gain vector term of the sliding mode controller in an adaptive manner. It is observed that the standard sliding mode controller can not cope with uncertainties due to system fault. On the other hand, proposed control scheme satisfactorily cope with mentioned uncertainties. 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 fault tolerant techniques. The proposed controller scheme can be called as an active reconfiguring scheme.

This method can be implemented for the control of autonomous underwater and aerospace vehicles especially when there is no way to terminate the process and fix the faulty system component. Military applications are the candidates for this method such as torpedo and missile control systems.

Further steps to be taken include the extension of this method is to achieve the fault tolerant control goal for general nonlinear MIMO systems together with nonlinear observers.

REFERENCES

1. H. E. Rauch, Intelligent Fault Diagnosis and Control Reconfiguration, IEEE Control Syst. Mag., June 1994.
2. M. Huzmezan, Reconfigurable Flight Control Methods and Related Issues, A Survey, DERA Report No: ASF/3455, Sep. 1997.
3. M. Huzmezan and J.M. Maciejowski, Automatic Tuning for Model Based Predictive Control During Reconfiguration, in Proceedings of 14th IFAC Symposium on Automatic Control in Aerospace, Korea, August 1998.
4. H.E. Rauch, Autonomous Control Reconfiguration, IEEE Control Syst. Mag., Dec. 1995.
5. Z. Yang and M. Blanke, The Robust Control Mixer Module Method for Control Reconfiguration, in Proceedings of American Control Conference, June 2000.
6. D.D. Moerder, N.Halyo, J.R. Broussard, and A.K. Cağlayan, Applications Of Pre-Computed Control Laws In A Reconfigurable Aircraft Flight Control System, Journal of Guidance, Control and Dynamics, 13(6), 1990.
7. P.S. Maybeck and R.D. Stevens, Reconfigurable Flight Control via Multiple Adaptive Control Methods, IEEE Transactions on Aerospace and Electronic Systems, 27(3), 1991.
8. Y. Ochi and K. Kanai, Design of Reconstructable Flight Control Systems Using Feedback Linearisation, Journal of Guidance, Control and Dynamics, 14(5), Sep.-Oct. 1991.
9. W.D. Morse and K.A. Ossman, Model Following Reconfigurable Flight Control System for the AFTI/F-16, Journal of Guidance, Control and Dynamics, 13(6), 1990.
10. J.J. Burke, P. Lu and Z. Wu, Reconfigurable Flight Control Designs with Application to the X-33 Vehicle, NASA Report No: TM-1999-206582, Aug. 1999.
11. A.P.Buckley, Hubble Space Telescope Pointing Control System Design Improvement Study Results, Journal of Guidance, Control and Dynamics, Mar.-Apr. 1995.
12. J.W. Sullivan, P. McCarty, G. Yoshimoto, R. Gargan and R. Pelavin, Intelligent System for Autonomous UUV Monitoring, Diagnosis and Control, Proceedings of 1992 AIAA Guidance, Navigation and Control Conf., Aug 1992.
13. J.Y. Hung, G. Weibing and J.C. Hung., Variable Structure Control: A Survey, IEEE Transactions on Industrial Electronics, Vol. 40, No.1, 1993.
14. V.I. Utkin, Variable Structure Systems with Sliding Modes, IEEE Transactions on Automatic Control, ACC-22-2, 1977.
15. K.D. Young (Ed.), Variable Structure Control For Robotics And Aerospace Applications, New York: Elsevier-Science Publishers, 1993.
16. S.W. Wijesoma, Robust Trajectory Following of Robots Using Computed Torque Structure with VSS, International Journal of Control, Vol.52, No.4, 1990.
17. J. Chen and R.J. Patton (1999), Robust Model-Based Fault Diagnosis for Dynamic Systems, Kluver Academic Publishers, 1999.
18. J.E. Slotine and W.P. Li (1991), Applied Nonlinear Control, Prentice-Hall, 1991.

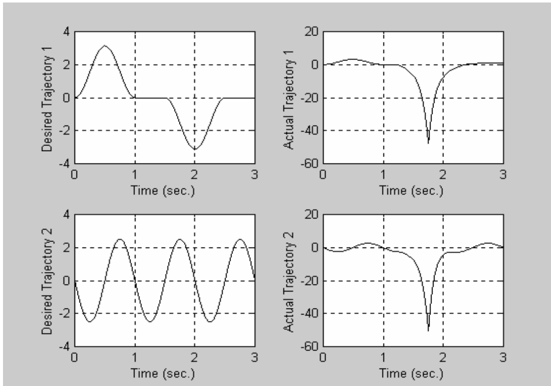

Fig. 1 Actual and desired trajectories with standard sliding mode controller.

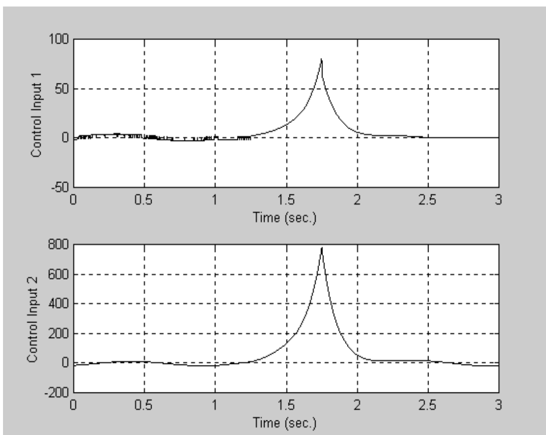

Fig. 2 Control Inputs with standard sliding mode controller.

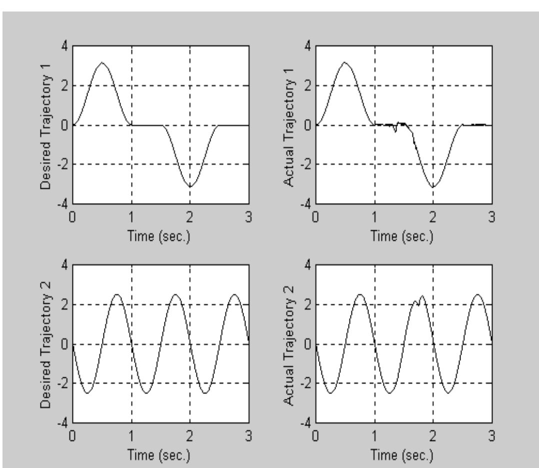

Fig. 3 Actual and desired trajectories with proposed reconfiguring sliding mode controller.

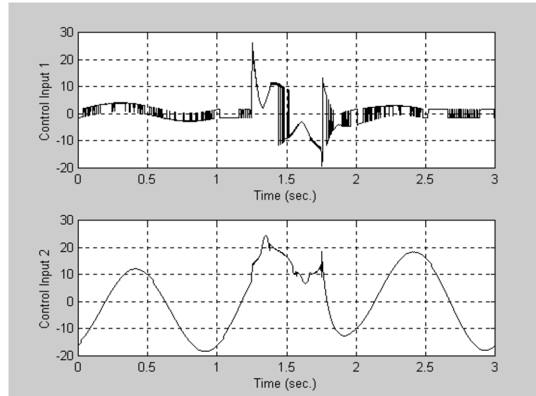

Fig. 4. Control Inputs with proposed reconfiguring sliding mode controller.

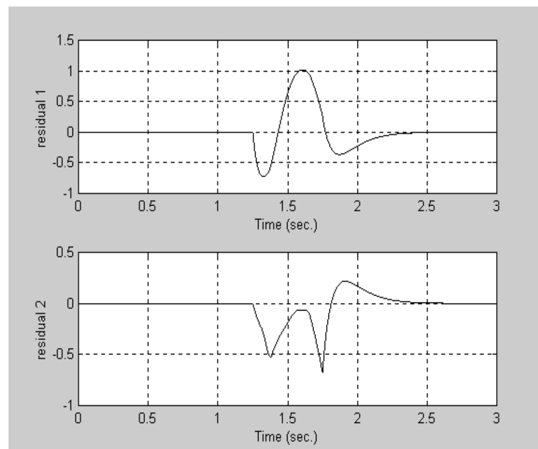

Fig. 5. Components of residual vector .