

Sensor and Actuator Fault-Tolerant Control Scheme applied to a Winding Machine

Hassan NOURA, Mustapha OULADSINE
Laboratoire des Sciences de l'Information et des Systèmes
LSIS, UMR CNRS 6168
Université Paul Cézanne, Aix-Marseille III,
Domaine Universitaire de Saint-Jérôme
Avenue Escadrille Normandie-Niemen
F-13397 Marseille Cedex 20, France,
Phone: (33) 4 91 05 60 59 - Fax: (33) 4 91 05 60 33
e-mail: hassan.noura@lsis.org

Keywords: Fault-tolerant control, Fault diagnosis, Sensor and actuator failure, Winding machine.

Abstract

A conventional feedback control design may result in unsatisfactory performances in the event of malfunctions in actuators, sensors or other components of the system. This paper deals with the analysis and the design of the fault-tolerant control (FTC) in case of actuators and sensors faults. A classification of the FTC methods is proposed and according to the severity of faults affecting the system. The discussion of FTC is shown by its application to a winding machine.

1 Introduction

Much effort has been done in the field of fault-tolerant control (FTC) systems in the presence of faults in the functioning of the systems where the security of people could be affected. The various studies dealing with this problem in these systems are based on hardware redundancy.

In other industrial processes, hardware redundancy is rare and even it does not exist, because of its expensive financial cost. Thus, in the presence of a major actuator failure, it is impossible to maintain the damaged system to some acceptable level of

performances. It becomes of prime importance to lead it to its optimal operating order, with respect to desirable performances and their degrees of priority. Therefore, the main feature is to minimize the loss in its productivity (to produce with a lower quality) or/and to operate safely without danger to human operators or to equipments. The system can continue its operation with decreased performances as long as it remains in acceptable limits.

The use of analytical redundancy makes the reduction of the cost and the maintenance of the instruments possible. Recently, a very interesting bibliographical review in fault tolerance has been done by [5].

The active fault tolerant operation can be achieved by a failure detection and isolation mechanism and the redesign of a new control law. In this article, a complete design of an active FTC system is proposed and analysed. The originality of this paper consists of the description of the effect of various kinds of faults or failures which may affect the system and the classification of FTC techniques according to the severity of these malfunctions. It is shown that the strategy to adopt and the level of performance to recover depends on the process itself, the degree of the available (hardware and/or analytical) redundancy in the system, the severity of the fault or the failure, and the level of desired performance.

This study takes into account minor faults and major failures. Minor faults could be biases or drifts on actuators or sensors, [4]. Major failures, which involve drastic and discontinuous variations in the plant dynamics, correspond for instance, to an actuator blocked or completely lost. In the presence of such faults, the nominal system performance cannot be reached anymore. Thus, according to the role that the faulty actuator plays in the system control design, a restructuration of control objectives with degraded performances must be set up or the system has to be stopped immediately and safely.

This paper is organized as follows: Section 2 is devoted to the classification of FTC techniques according to the severity of the fault. In Section 3, the identification and the nominal control of the winding machine used to illustrate the aim of the paper are given. Section 4 describes a reconfiguration strategy in the presence of minor faults and a restructuration strategy in the presence of more critical failure. The results of the application of these method to the winding machine are shown and commented. Finally concluding remarks are given.

The study led here is conducted through an application to a winding machine. the various steps of active methods are illustrated according to the severity of the faults and the ability to tolerate them or not.

2 Winding machine

2.1 Process description

The method proposed in this article is applied to a winding machine (Fig. 1) representing a subsystem of many industrial systems as sheet and film processes, steel industries, and so on. The system is composed of three reels driven by DC motors (M_1 , M_2 , and M_3), gears reduction coupled with the reels, and a plastic strip. Motor M_1 corresponds to the unwinding reel, M_3 is the rewinding reel, and M_2 is the traction reel. The angular velocity of motor M_2 (Ω_2) and the strip tensions between the reels (T_1 , T_3) are measured using a tachometer and tension-meters, respectively. Each motor is driven by a local controller. Torque control is achieved for motors M_1 and M_3 , while speed control is realized for motor M_2 . For a multivariable

control application, a dSPACE board associated with *MatlabTM/Simulink* software is used.

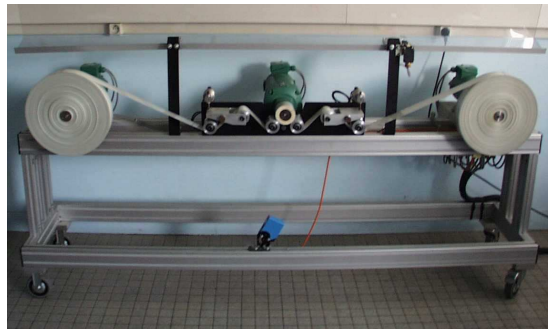


Figure 1: Winding machine.

The control inputs of the three motors are U_1 , U_2 , and U_3 . U_1 and U_3 correspond to the current set-points I_1 and I_3 of the local controller. U_2 is the input voltage of motor M_2 . In the winding processes, the main goal usually consists of controlling tensions T_1 and T_3 and the linear velocity of the strip which can be controlled by the angular velocity Ω_2 . A linearised model describing the dynamical behavior of the system in terms of input/output variations around an operating point has been obtained with the sampling interval is $T_s = 0.1$ s.

$$\begin{aligned} x(k+1) &= Ax(k) + Bu(k) \\ y(k) &= Cx(k) \end{aligned} \quad (1)$$

with:

$$y = x = \begin{pmatrix} T_1 \\ \Omega_2 \\ T_3 \end{pmatrix} \quad u = \begin{pmatrix} U_1 \\ U_2 \\ U_3 \end{pmatrix}$$

The system described by these matrices is completely observable and controllable.

2.2 Nominal control

The nominal control law is set up according to a tracking control design. The tracking control problem requires that the number of outputs that have to follow a reference input vector, y_r , must be less than or equal to the number of control inputs. This is the case for the winding machine: three control inputs are available, thus the three outputs T_1 , Ω_2 , and T_3 can be tracked. The feedback control law is based on the LQI technique to compute gain matrices K_1 and K_2 . z is the integrator vector of the tracking error. Figure (2) illustrates this nominal control law.

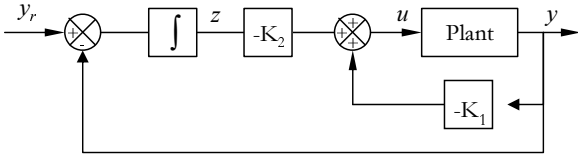


Figure 2: Nominal control law.

3 Fault-tolerant control

In this section, a complete active FTC scheme is developed according to the type and the severity of the faults affecting the system. This scheme is composed of the nominal control law associated with the fault diagnosis module which aims at giving information about the nature of the fault and its severity. According to this information, a reconfiguration or a restructuration strategy is activated. It is obvious that the success of the FTC system is tightly related to the reliability of this information issued from the fault diagnosis module. In the reconfiguration step, the fault magnitude is estimated. This estimation could be used as a redundant information to the one issued from the fault diagnosis module. The objective of this redundancy is to enhance the reliability of the diagnosis information. The complete FTC scheme discussed here is summarised by figure 3.

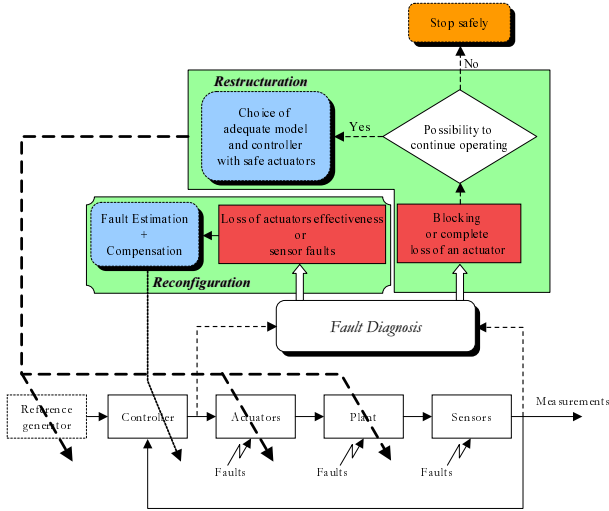


Figure 3: General Fault-tolerant control scheme.

In the sequel, the principle of a reconfiguration methodology in the presence of minor faults is presented and commented. For more detail, the reader can refer to [3]. Minor faults correspond to a loss in the effectiveness of

an actuator, a bias or a drift in a sensor. Then, more critical failures, such as a complete loss of an actuator, are analysed where a restructuration strategy has to be built.

3.1 Reconfiguration strategy

The aim of the reconfiguration method described in this article is to compensate for both actuators and sensors faults. An actuator fault, as for instance, a reduction in its effectiveness, acts on the system as a disturbance. In the nominal control law, the presence of an integrator in the controller may compensate only for the static error but not for a loss in the dynamical performance.

In the fault-free case, the measurements issued from sensors are equal to the real outputs. When a sensor fault occurs, the integral control law makes the tracking error (the error between the measurements and the reference values) goes to zero. Hence, the real output is far from the desired value. The principle of the method developed here is based on the estimation of the fault magnitude, and then this estimation is used to compensate for the fault effect in case of an actuator fault, and to prevent the control input from reacting face to the sensor fault. The theoretical aspects of the method used here are developed and discussed in previous work. For more details, the reader can refer to [3] and [2].

3.1.1 Actuator and sensor fault description:

Actuator and sensor faults can be illustrated by means of an unknown input vector f_i , ($i = a$ (for actuator), s (for sensor)) acting on the system's dynamics or measurements.

An actuator fault corresponds to the modification of the global control input applied to the system as following:

$$U_f = \Gamma U + U_{f0} \quad (2)$$

- U is the global control input applied to the system,
- U_f is the faulty global control input,
- u is the variation of the control input around the nominal operating point U_0 , ($u = U - U_0$, $u_f = U_f - U_0$),
- U_{f0} corresponds to an additive fault affecting the actuator,

→ ΓU represents the effect of a multiplicative actuator fault

with $\Gamma = \text{diag}(k_1 \dots k_i \dots k_m)$. The i^{th} actuator is faulty if $k_i \neq 1$.

Using this actuator fault description leads the representation of the faulty system to become:

$$\begin{aligned} x(k+1) &= Ax(k) + Bu(k) + F_a f_a(k) \\ y(k) &= Cx(k) \end{aligned} \quad (3)$$

where $F_a = B$ and $f_a = (\Gamma - I)U + U_{f0}$.

In a similar way, and defining f_s as an unknown input illustrating the presence of a sensor fault, the faulty system can then be represented by:

$$\begin{aligned} x(k+1) &= Ax(k) + Bu(k) \\ y(k) &= Cx(k) + F_s f_s(k) \end{aligned} \quad (4)$$

3.1.2 Actuator fault estimation: When an actuator fault occurs on the system, the actuator fault magnitude f_a can be estimated as a component of an augmented state vector $\bar{X}_a(k)$ according to the following rearrangement of the system:

$$\bar{E}_a \bar{X}_a(k+1) = \bar{A}_a \bar{X}_a(k) + \bar{B}_a \bar{U}(k) + \bar{G}_a y_r(k) \quad (5)$$

where:

$$\bar{E}_a = \begin{pmatrix} I_3 & 0 & -F_a \\ 0 & I_3 & 0 \\ C & 0 & 0 \end{pmatrix}, \bar{A}_a = \begin{pmatrix} A & 0 & 0 \\ -T_s C & I_3 & 0 \\ 0 & 0 & 0 \end{pmatrix},$$

$$\bar{B}_a = \begin{pmatrix} B & 0 \\ 0 & 0 \\ 0 & I_3 \end{pmatrix}, \bar{G}_a = \begin{pmatrix} 0 \\ T_s I_3 \\ 0 \end{pmatrix},$$

$$\bar{X}_a(k) = \begin{pmatrix} x(k) \\ z(k) \\ f_a(k-1) \end{pmatrix}, \bar{U}(k) = \begin{pmatrix} u(k) \\ y(k+1) \end{pmatrix}$$

The magnitude of the actuator fault f_a which is the last component of the new state vector can be estimated by solving the equations obtained after the singular value decomposition (SVD) of \bar{E}_a . This must be of full column rank [1].

3.1.3 Actuator fault compensation: The fault estimation obtained by the previous calculation is then used to compute a new control law u_{ad} added to the nominal one in order to compensate for the fault effect on the system according to the scheme described by figure (4).

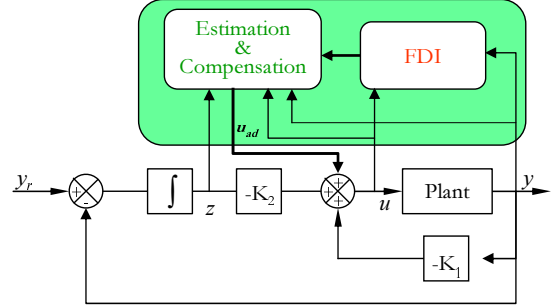


Figure 4: Fault-tolerance by additive control law.

The additive control law u_{ad} must be computed such that the system behavior is as close as possible to the nominal one:

$$Bu_{ad}(k) + F_a f_a(k) = 0 \quad (6)$$

3.1.4 Application and results: An abrupt and a progressive decrease in the effectiveness of the third actuator have been tested on the winding machine. The abrupt fault corresponding to a reduction of 70 % in the 3rd actuator effectiveness is achieved by multiplying the global control input U_3 by a constant coefficient $k_3 = 0.3$. This fault occurs at instant 32 s. Since the actuator fault acts on the system as a disturbance, the steady state error is cancelled due to the presence of the integrator in the nominal control law. However, a loss in the dynamical performance of the system can be noticed after a change in the reference signal (increase of the time response). The FTC approach makes the compensation for this loss in the dynamical performance possible (see figures 5). It can be seen that the estimation of the faults components associated with each actuator. Notice also that the 3rd component associated with the faulty actuator is only different from zero after the fault occurrence.

Then, a progressive fault is assumed to occur on the 3rd actuator. Using the nominal control law, this fault leads to a nonzero steady-state error on strip tension

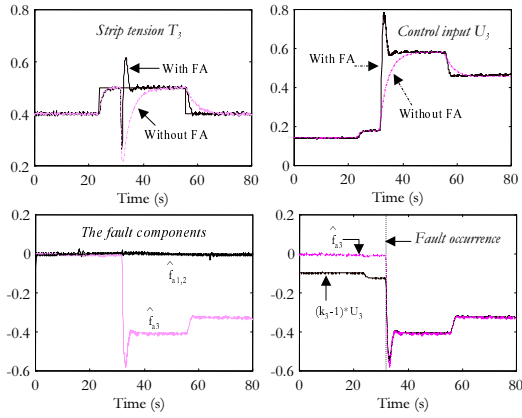


Figure 5: FTC for abrupt actuator fault.

T_3 , while the FTC allows the strip tension to reach its reference value as soon as the fault is detected (see figure 6). However, it is obvious that the compensation for a ramp fault is still possible while the control input does not reach its physical limits which are -1 and $+1$, corresponding respectively to $-10V$ and $+10V$. In this case, the objective of the FTC system is to avoid to stop the system immediately after the fault detection.

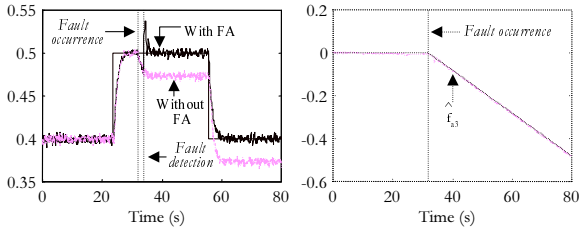


Figure 6: FTC for progressive actuator fault.

3.1.5 Sensor fault estimation: In the presence of sensor faults, the integral error vector z is also affected by the fault. The sensor fault magnitude can be estimated in a way similar to the actuator fault, by rearranging the augmented form of the system. The estimation of the fault magnitude \hat{f}_s is then obtained using the SVD of matrix \bar{E}_s .

The fault compensation is achieved by preventing the control law from reacting in the presence of the sensor fault. This is done by analysing the fault effect on the control law and by adding a new control law to the

nominal one:

$$u(k) = -K_1 x_0(k) - K_1 F_s f_s(k) - K_2 z_0(k) - K_2 \tilde{f}(k) + u_{ad}(k) \quad (7)$$

where x_0 and z_0 correspond to the safe values of x and z , and \tilde{f} is the integral of $-F_s f_s$. The sensor fault effect on the control law, and consequently on the system can be annihilated by using the fault estimation and by computing the additive control law such as:

$$u_{ad}(k) = K_1 F_s \hat{f}_s(k) + K_2 \tilde{f}(k) \quad (8)$$

Experimentations have been considered with a negative bias on the sensor measuring strip tension T_3 . The obtained results with or without FTC are shown by figures 7.

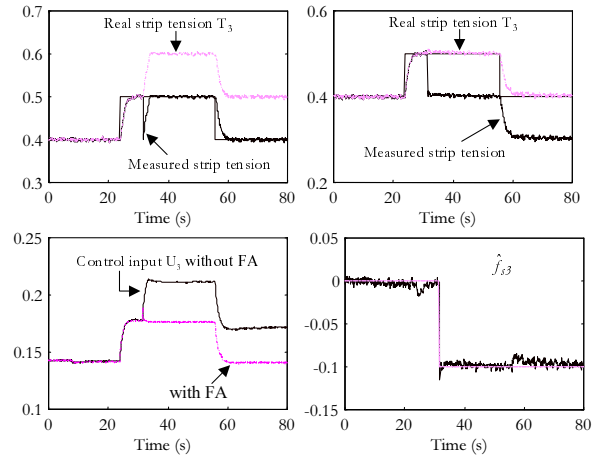


Figure 7: FTC for sensor fault.

3.2 Restructuration strategy

The limits of this method are reached in case of an actuator has got stuck or completely lost. In this paper, the possibility to continue operating with degraded performance is analyzed in the presence of a critical failure such as the complete loss of an actuator.

The failure considered here is that motor M_1 is out of order at time instant $t_f = 49.5$ s; i.e. motor M_1 runs as if its control input $U_1 = 0$. This failure leads to a large decrease in the strip tension T_1 which cannot be controlled anymore. This failure is a severe failure because it leads to a large loss in the closed-loop system performance. As one of the system control inputs is out of order, it becomes impossible to track

the three system outputs. Hence, according to the system operation requirements, these outputs have to be divided into priority outputs to be maintained to their reference inputs with the detriment of other secondary outputs.

In equivalent industrial application, the objective is to roll up the strip in a correct way. This can be achieved, if tension T_3 and the angular velocity Ω_2 are mainly maintained to their reference inputs. These outputs are considered as priority outputs to be maintained with the detriment of strip tension T_1 considered as a secondary output.

Faulty system Model and Results: A new control law is achieved to track two system outputs Ω_2 and T_3 considering T_1 as a perturbation. This control law is computed using the new model of the system (obtained off line) having U_2 and U_3 as control inputs. Once the failure is detected and isolated, the fault-tolerant control module switches from the nominal control law to the new one. This control law guarantees the fact that the strip continues to be rolled up in a correct way and avoids stopping the machine due to a bad quality of the final product.

Figure (8) shows the results obtained when switching from the original model to the new one after the failure has been detected and isolated. The fault diagnosis module is not achieved here, but a delay of 10 sampling periods is considered before switching to the new control law. This delay corresponds to the detection and isolation task. It can be seen that strip tension T_1 is still far from its reference value because it is not tracked, while strip tension T_3 and the angular velocity Ω_2 follow their respective reference inputs after the switching process and the strip is rolled up in a correct way.

4 Conclusion

In this paper, a fault-tolerant control architecture in case of minor and more critical faults has been proposed and analyzed. This analysis has been conducted and validated through its application to a real pilot plant. This plant represents a subsystem of real

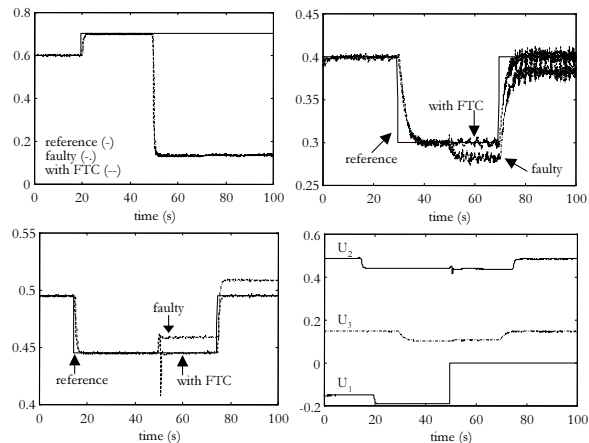


Figure 8: I/O for a complete loss of an actuator.

industrial systems. It has been shown that the design of a fault-tolerant control system depends on the plant itself and the degrees of freedom in terms of hardware redundancy. A classification of FTC techniques has been given according to the severity of the failure and the level of performance to reach.

References

- [1] A. Bassong-Onana, M. Darouach, and G. Krzakala. Optimal estimation of state and inputs for stochastic dynamical systems with unknown inputs. In *Proc. of Int. Conf. on Fault Diagnosis, Tooldiag'93*, pages 267–275, Toulouse, France, 1993.
- [2] H. Noura. Méthode d'accommodation aux défauts : Théorie et application. *Habilitation à Diriger des Recherches, Université Henri Poincaré, Nancy 1, France*, Mars 2002.
- [3] H. Noura, D. Sauter, F. Hamelin, and D. Theilliol. Fault-tolerant control in dynamic systems: Application to a winding machine. *IEEE Control Systems Magazine*, 20(1):33–49, 2000.
- [4] H. Noura, D. Theilliol, and D. Sauter. Actuator fault-tolerant control design: demonstration on a three-tank-system. *International Journal of Systems Science*, 31(9):1143–1155, 2000.
- [5] Y. Zhang and J. Jiang. Bibliographical review on reconfigurable fault-tolerant control systems. In *Proc. of the IFAC Symposium on Fault Detection, Supervision and Safety for Technical Processes-Safe process'2003*, Washington, USA, June 2003.