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FAULT TOLERANT FLIGHT CONTROL FOR THE UAV BASED ON SDRE CONTROL SCHEME

Burak Ergöçmen*
Army Aviation Branch-Turkish Land Forces
Ankara, Turkey

İlkay Yavrucuk†
Middle East Technical University
Ankara, Turkey

ABSTRACT

For aviation, improving the safety of the flight is the most essential purpose. A lot of areas are studied for this objective and one of them is controlling the aircraft during normal flight and emergency. In this paper, actuator degradation is studied for an emergency. In other words, the respond of the actuator is degraded and the normal signal generated by the flight control computer (FCC) becomes faulty due to a faulty actuator. This can be lead to loss of control in-flight (LOC-I). However, if the FCC is reconfigurable for degradation, LOC-I can be prevented. In the FCC, nonlinear algorithm, state-dependent Riccati equation (SDRE) is used. SDRE captures not only the nonlinearities of the system but also can be reconfigurable easily with the help of different weight matrices. This weight matrices are used for slowing or increasing the movement of the control surfaces. Comparative figures are given to illustrate the effectiveness of the controller algorithm.

INTRODUCTION

For the control of the aircraft; mechanical, hydro-mechanical or fly-by-wire systems are used. These systems are connected to the actuators. There are different types of actuators. Finally, control surfaces are manipulated with the help of these actuators. No matter which system used, there are problems with these systems. These problems can be degradation, stuck or damage to actuators. The outcome can be Loss of Control in-flight (LOC-I). The meaning of the LOC-I is unable to recover from the control problem of the aircraft [ICAO, 2018]. Due to LOC-I, fatal accidents for worldwide commercial jet fleet approximately doubled compared with the Controlled Flight into Terrain (CFIT) accidents and in connection with the LOC-I, 14 accidents 1129 onboard fatalities have occurred between 2008-2017 for Worldwide Commercial Jet Fleet [Boeing, 2017].

There are three main contributing factors for LOC-I: meteorological, human and system-induced. About system-induced LOC-I, faults or failures or damage of or to any or all of the aircraft control effectors is one of the sub-categories [Jacobson, 2007]. Actuator degradation can be lead to the system induced LOC-I. In this article, this type of LOC-I was tried to be prevented.

About fly-by-wire control systems, there are flight control computers (FCC). In these computers,

*The degree of Master of Science, Email: ergocmen.burak@metu.edu.tr
†Assoc. Prof. Dr. in a Aerospace Engineering Department, Email: ilkay.yavrucuk@ae.metu.edu.tr

different algorithms can be used. Besides, numerous algorithms are used as fault-tolerant control [Edwards et al., 2010]. For fault tolerant control, there are mainly two methods: active and passive. In this paper, State-Dependent Riccati Equation (SDRE) is used as an Active Fault Tolerant Flight Control algorithm in the FCC and the control system is assumed to be fly-by-wire. Besides, as a reference command, proportional-integral-derivative (PID) algorithm is used.

GENERAL ARCHITECTURE

There are different components to represent the simulation model shown in Figure 1. In the UAV block, aerodynamic behavior of the UAV is represented by derivatives, in addition to performance characteristics. The atmospheric environment block consists of atmospheric values such as temperature and pressure. Besides, wind, wind shear, and gust effects can be adjusted. In the Flight Control Computer (FCC), SDRE and PID algorithms are used to control the UAV. With the help of the mode selection (MS) block, pilot or operator can adjust reference values such as altitude, heading to control the UAV. Reconfiguration Block is used for reconfiguring FCC and MS for different emergencies. Besides, it consists of a supervisor and mechanisms. In this article, Fault Detection and Isolation/ Fault Diagnosis and Detection (FDI/FDD) is not modelled.

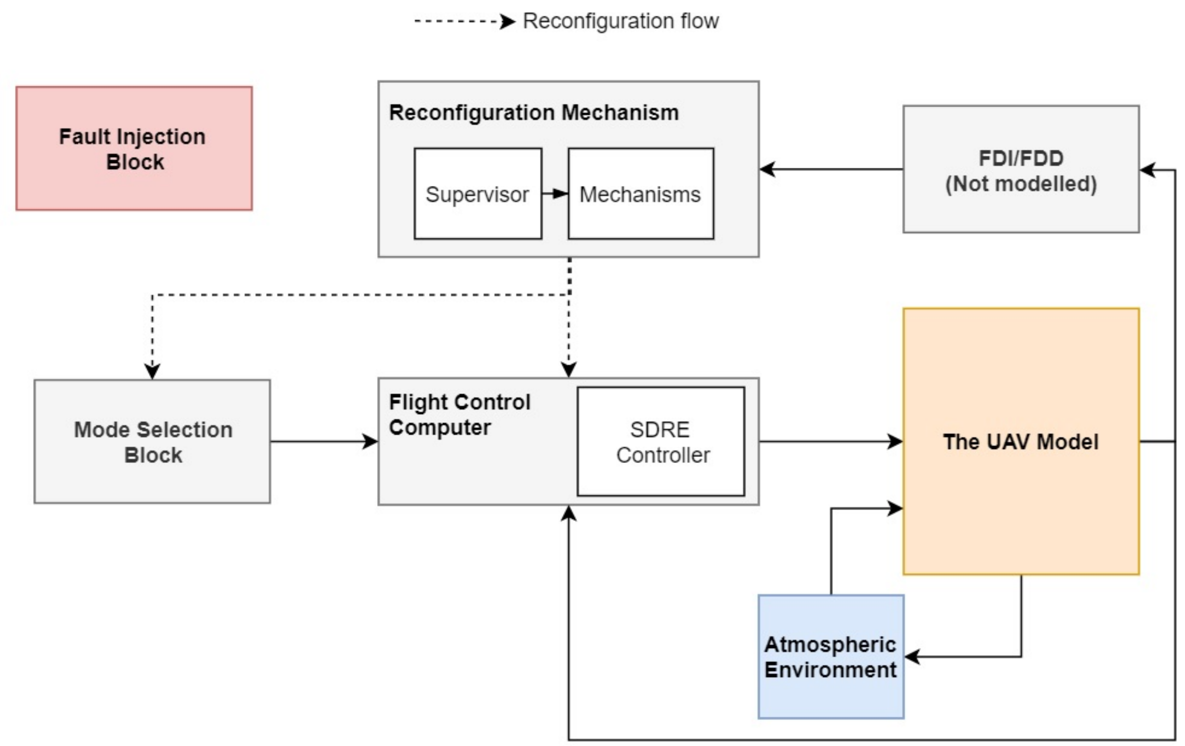

Figure 1: The general architecture of simulation.

Aerodynamics derivatives in the UAV model block are obtained from the XFLR5 open-source program. 169 kg. UAV is a single-engine type. The aerodynamic derivatives and other UAV parameters are given by [Ergöçmen, 2019].

METHOD

In the FCC, SDRE method is used. It is a nonlinear control algorithm. It represents the dynamics of the system accurately. Representation of the nonlinear system is given as:

$$\dot{x}(t) = f(x) + B(x)u \quad x(0) = x_0 \tag{1}$$
$$y(t) = Cx(t) \tag{2}$$

The nonlinear term, $\mathbf{f(x)}$ is transformed to $\mathbf{A(x)x}$. A(x) consists of states and updated by states. As a result $\mathbf{A(x)}$ is constantly changing and state-dependent coefficient $\mathbf{(SDC)}$ matrix is formed. The equation becomes:

$$\dot{x}(t) = A(x)x(t) + B(x)u(t) + f(t) \tag{3}$$
$$y(t) = Cx(t) \tag{4}$$

A(x) is not unique and theoretically, there are infinite A(x) matrices. Some assumptions are made: The system is affine in the input, nonlinear in the state, autonomous, state observable. Also, f(t) is a nonlinear term which can not be included in the A(x) matrix. At each instant, the matrix A is linear, so that the solution of the problem can be found by the linear-quadratic optimal problem [Çimen, 2008]. One of the best-known performance index, quadratic performance index function or cost function is given as respectively for regulator and tracking and one of the main objectives is minimizing these cost functions:

$$J_R = \frac{1}{2}\int_0^\infty [x^T(t)Qx(t) + u^T(t)Ru(t)]dt \tag{5}$$
$$J_T = \frac{1}{2}\int_0^\infty [e^T(t)Qe(t) + u^T(t)Ru(t)]dt \tag{6}$$

$\mathbf{x(t)}$ is the nth order state vector; $\mathbf{Q}$ is nxn order positive and symmetric semi-definite matrix (Q≥0); $\mathbf{R}$ is mxm order positive and symmetric definite matrix (R>0). Q and R are weight matrices and they can be expressed in the form of function of states which means it becomes state-dependent weight matrices and they represented by $\mathbf{Q(x)}$ and $\mathbf{R(x)}$.

Algebraic Riccati Equation (ARE) for SDRE is given as respectively for regulator and tracking:

$$PA(x) + A^T(x)P + Q - PBR^{-1}B^TP = 0 \tag{7}$$
$$PA(x) + A^T(x)P + C^TQC - PBR^{-1}B^TP = 0 \tag{8}$$

After finding P from the ARE, the control law is calculated. The tracking is represented as K_T and the regulator is represented as K_R. The control law is [Naidu, 2003] given as:

$$u(t) = -K_Rx(t) + K_Tz(t) \tag{9}$$
$$K_R = R^{-1}B^TP \tag{10}$$
$$K_T = R^{-1}B^T(PE - A^T)^{-1}W \tag{11}$$
$$E = BR^{-1}B^T \tag{12}$$
$$W = C^TQ \tag{13}$$

For SDRE, K is always vary due to P, A(x) and B(x) matrices, so that K can be a function of P, A and B. The mathematical representation of gains can be depicted as $K_T(P, A(x), B(x))$ and $K_R(P, B(x))$.

The architecture of the FCC is shown in Figure 2. There are two loops for the controller. In the inner loop; rates (p, q, r) are controlled. In the outer loop, euler angles (ϕ and θ) are controlled. Reference command block consists of PID algorithms to create reference ϕ and θ commands. During actuator

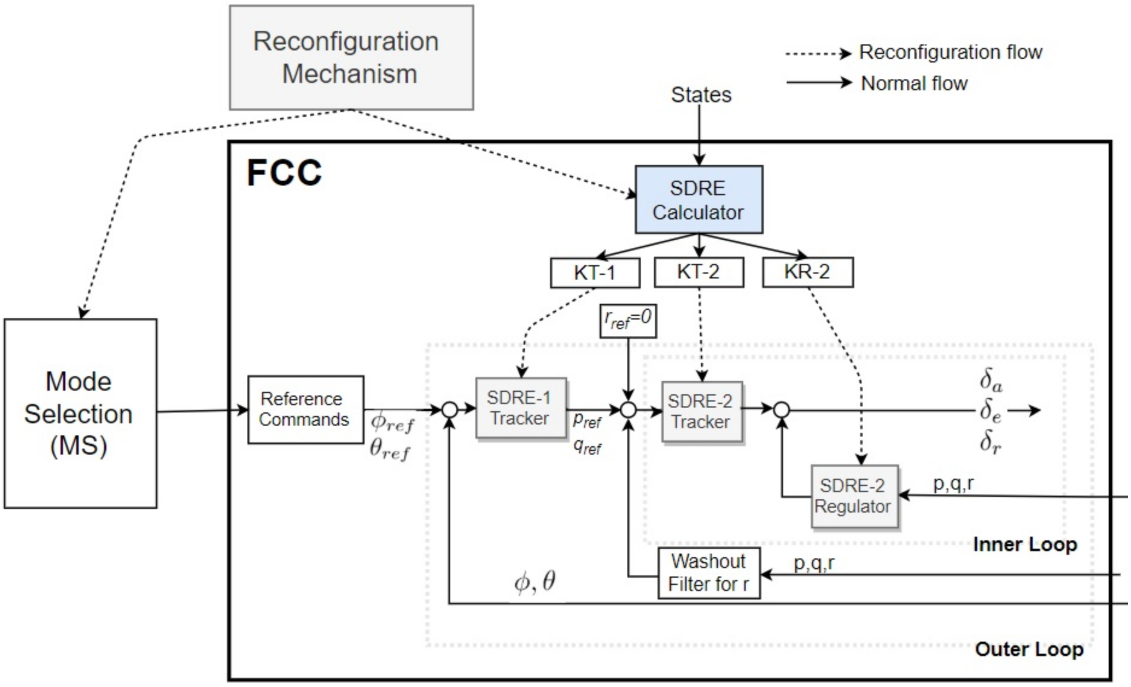

Figure 2: The general architecture of flight control computer.

degradation, reconfiguration mechanism sends signal to SDRE calculator for changing weight matrices shown in Figure 2. After that, controller generates control inputs (δ_a, δ_e, δ_r) for the UAV. Washout filter is used for only yaw rate r. Also, in the inner loop, there is a stability augmentation system (SAS) for controlling rates (p, q, r).

RECONFIGURATION MECHANISM

With regard to reconfiguration mechanism block, the supervisor is used for creating commands with regard to faults and solutions. Solutions are depicted in Figure 3.

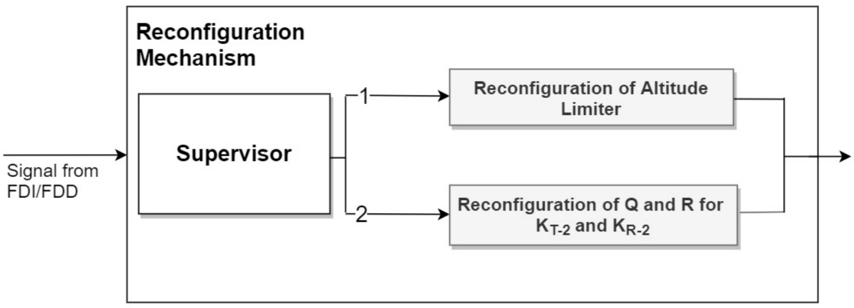

Figure 3: The Reconfigure Mechanism.

In the 1st solution, there is a reconfiguration for altitude rate limiters. Rate limiters are used for limiting the first derivative of the signal. In this work, this limiting value can be adjusted. A pilot can adjust the vertical speed from MS, like 0.5, 1, 1.5 and 2 vario. For example, 0.5 means 500 ft./second. However, with the help of the switch case block, if there is an emergency, this reconfiguration mechanism decreases vario to 0.5 during a climb, even though the pilot adjusts any vario. Especially, it is useful to prevent elevator actuator saturation.

In the 2nd solution, there are different weight matrices for K_{T-2} and K_{R-2} gains. Normally, the values of the $Q_2(a)$ and $R_2(a)$ are given as:

$$Q_2 = diag[5, 5, 2] \tag{14}$$

$$R_2 = diag[50, 10, 10] \tag{15}$$

During normal flight, these values are good for safety. However, if an emergency occurs, they are not only useless but also cause of the LOC-I. As a result, these values have to be changed by the reconfiguration mechanism. Therefore, interpolation tables are used for $Q_2(a)$ and $R_2(a)$. With regard to $R_2(a)$, these tables consist of 0.01 , 0.1, 50, 1250, 2050 for aileron (50 is the normal value); 0.1, 1, 10, 30, 110 for elevator (10 is the normal value); 0.0001, 0.001, 10, 130, 210 for rudder (10 is the normal value). In this paper, there is no need for a reconfiguration of $Q_2(a)$ matrix but it can be used for further studies. During an emergency, these values are sent to ARE calculator in the FCC depending on the problem and decided by the supervisor. Supervisor sent -2, -1, 0, 1 or 2 for slowing or increasing the controller response. For example, supervisor sent -2 (faster) to the 3rd solution block for aileron. The value for $R_2(a)$ changes to 0.01. This means with the help of this weight matrix value, the movement of the aileron is increased.

In addition, 1.2 can also be adjusted if required. Positive values represent the slower movement of the control surface, while the negative values are the opposite.

The supervisor depicted in Figure 3 is a decision maker for a different emergency situation. It is assumed that FDI/FDD finds the problem, problem location, level value. After that, it sends a signal to the supervisor in the reconfiguration mechanism. This signal is about fault type (problem) which consists degradation; fault location (problem location) which consists of aileron, elevator, rudder, FCC; the level of the degradation (severity). As a result, reconfiguration and reconfiguration degree are chosen by the supervisor which consists of two mechanisms as stated and shown in Table 1. With regard to level of degradation, there are different levels can be adjusted from the fault injection block. In this paper, 3rd and 4th level is used. The meaning of that is the FCC signal is multiplied by 0.025 for 4th and 0.1 for 3rd level to simulate degradation. For example 4th level aileron fault is selected and FCC creates 20 degree aileron command. However, due to degradation, 20 degree aileron command multiplied by 0.025.

Table 1: The supervisor logic.

Degradation level	Default	1st	2nd	3rd	4th	5th
Multiplied value	1	0.7	0.6	0.1	0.025	0

Location	**Problem**	**Problem Level**	**Reconfiguration Mechanism**	**Reconfiguration Degree**
Aileron	Degradation	3rd level	2nd	For Aileron 0.05 faster, For rudder 2.5 slower
		4th level	2nd	For Aileron 0.5 faster, For rudder 4 slower
Elevator	Degradation	3rd level	1st	Decrease vario to 0.5 (500 ft./sec.)
			2nd	For Elevator 2 slower
		4th level	1st	Decrease vario to 0.5 (500 ft./sec.)
			2nd	For Elevator 3 slower
Rudder	Degradation	3rd level	2nd	For Rudder 0.5 faster, For aileron 0.5 slower
		4th level	2nd	For Rudder 0.5 faster, For aileron 1 slower

For example, FDI/FDD is assumed to detect the 3rd level degradation at the elevator. After that, it is assumed to send this signal to the reconfiguration mechanism. Supervisor in the reconfiguration mechanism makes a decision by its logic which is shown in Table 1. In this logic table, reconfiguration for 3rd level elevator degradation is done by activating 1st and 2nd mechanism. In the 2nd mechanism, to decrease the movement of the elevator 2 (slower), R_2 matrix elevator value changes from 10 to 110 and sent to the SDRE calculator in the FCC. As a result, SDRE controller is reconfigured for the new condition.

RESULTS AND DISCUSSION

Aileron Degradation

The first case is the 3rd level (0.1) aileron degradation at the 25th second. At the beginning, pilot decided to decrease UAV air speed from 50 to 45 kt. After, he made a 40 degree heading change without any knowledge about degradation problem. First, there is not any safety problem with respect to altitude, airspeed. However, after heading change is completed, the UAV is not stabilized in the lateral. Without reconfiguration, this results in LOC-I shown in Figure 4. Besides, there is an oscillation for rudder deflection. There is an aileron degradation but rudder command can not work together with degraded aileron command to minimize β. As a result, the rudder movement has to be decelerated with weight matrices. Also, due to the degradation of the aileron command, aileron movement has to be accelerated. In the second case, the stated idea is followed during the same emergency with the help of reconfiguring FCC by weight matrices.

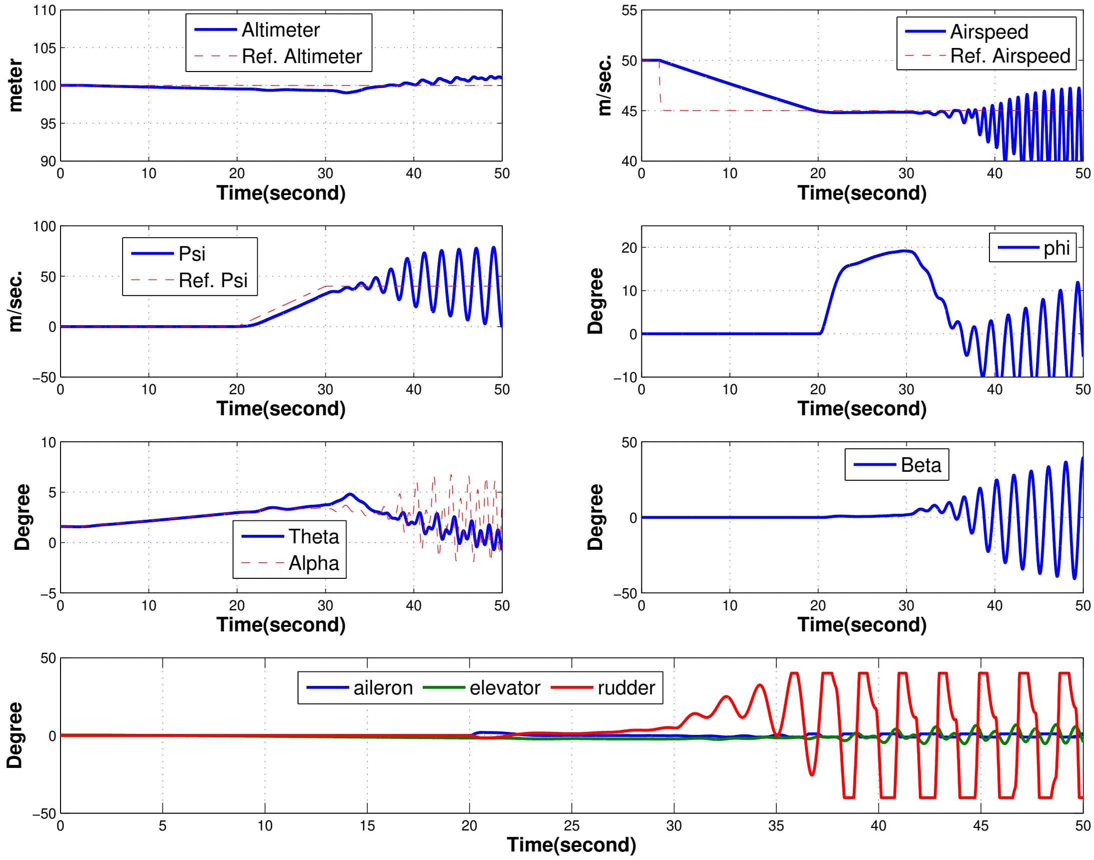

Figure 4: Aileron degradation with no reconfiguration.

In the second case, the UAV makes the same maneuver and encounter the same degradation but at this time, reconfiguration of the controller occurs. Reconfiguration mechanism-2 is activated by Supervisor to change R matrix to a different value to change control surface movement. With the help of this, the aileron movement gets faster (-0.05), rudder movement slower (2.5) which is shown in Table 1. As stated before, for the movement of the control surfaces, -2, -1, 0, 1, 2 values can be selected by the supervisor. Besides, all these values mean different weight matrices for control surfaces. For example, 0.05 or -1.2 can be selected. In this solution, 0.05 for aileron to make faster, 2.5 for the rudder to make slower movement are selected (with the help of the interpolation tables). As a result, there is no safety problem for altitude, airspeed, which are shown in Figure 5.

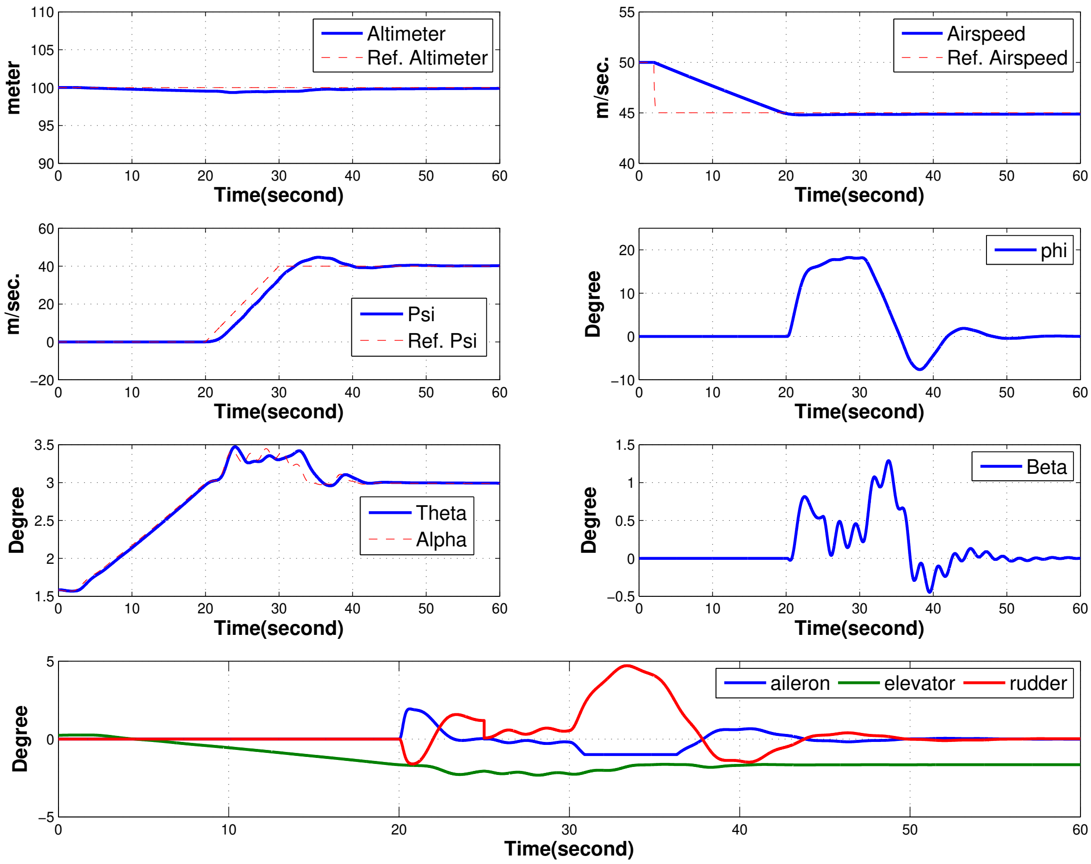

Figure 5: Aileron degradation with reconfiguration.

Elevator Degradation

In the first case, the results for elevator degradation with no reconfiguration is shown in Figure 6. Due to degradation, elevator saturates at approximately 1.2 degree. Normally, the saturation limit for the elevator is 40 degrees. However, due to 3rd level degradation, 0.025 value is multiplied by 40 degrees (during maximum value). Besides, there is an initial value for elevator deflection which approximately equals to 0.2. As a result, the maximum deflection value is 1.2 for the elevator.

For the altitude command, there is an overshoot. This problem can be solved with decreasing elevator movement command with the help of weight matrices. Also, decreasing vario (climbing performance) can be helpful with this solution.

Reconfiguration of the controller is not mandatory but for the better performance, it is required.

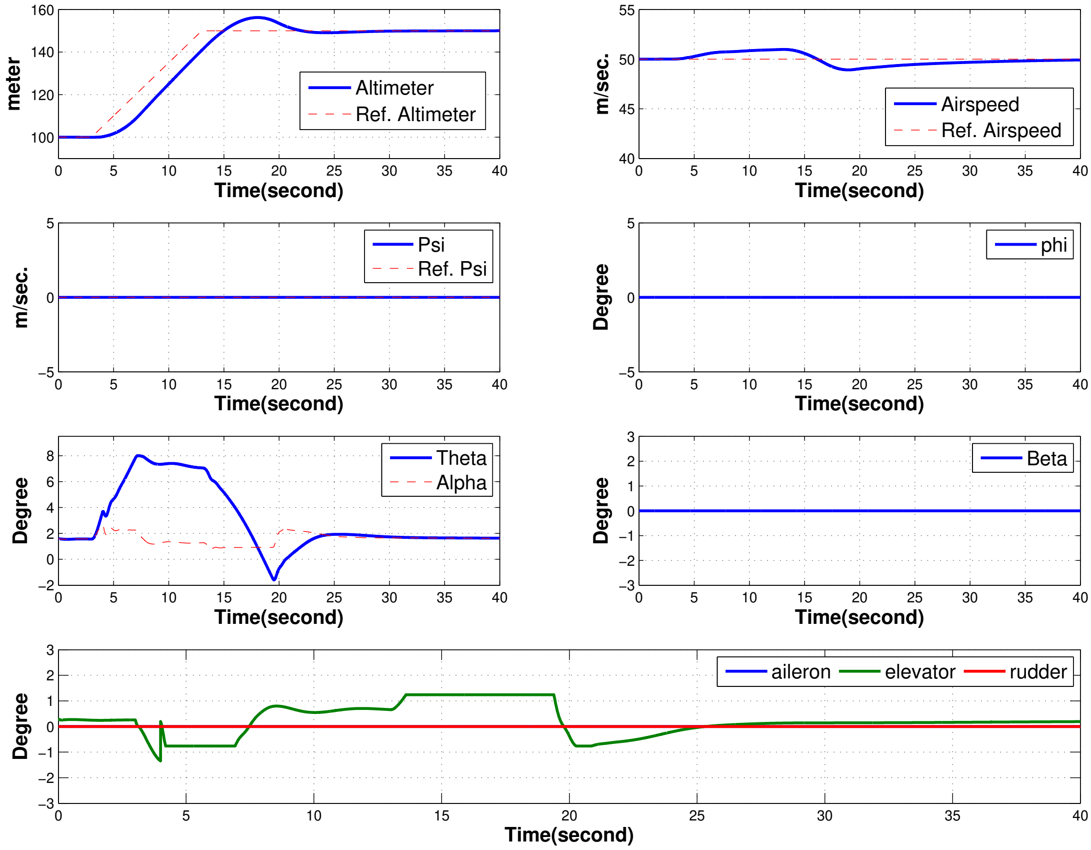

Figure 6: Elevator degradation with no reconfiguration.

Table 2: The supervisor logic for the elevator.

Location	Problem	Problem Level	Reconfiguration Mechanism	Reconfiguration Degree
Elevator	Degradation	3rd level	1st	Decrease vario to 0.5 (500 ft./sec.)
			2nd	For Elevator 2 slower
		4th level	1st	Decrease vario to 0.5 (500 ft./sec.)
			2nd	For Elevator 3 slower

In the second case shown in Figure 7, with the reconfiguration of the controller, the smooth climb is achieved. Besides, the elevator movement is decreased with the help of the weight matrix (3 faster value is used for the elevator movement). There is not any altitude command overshoot.

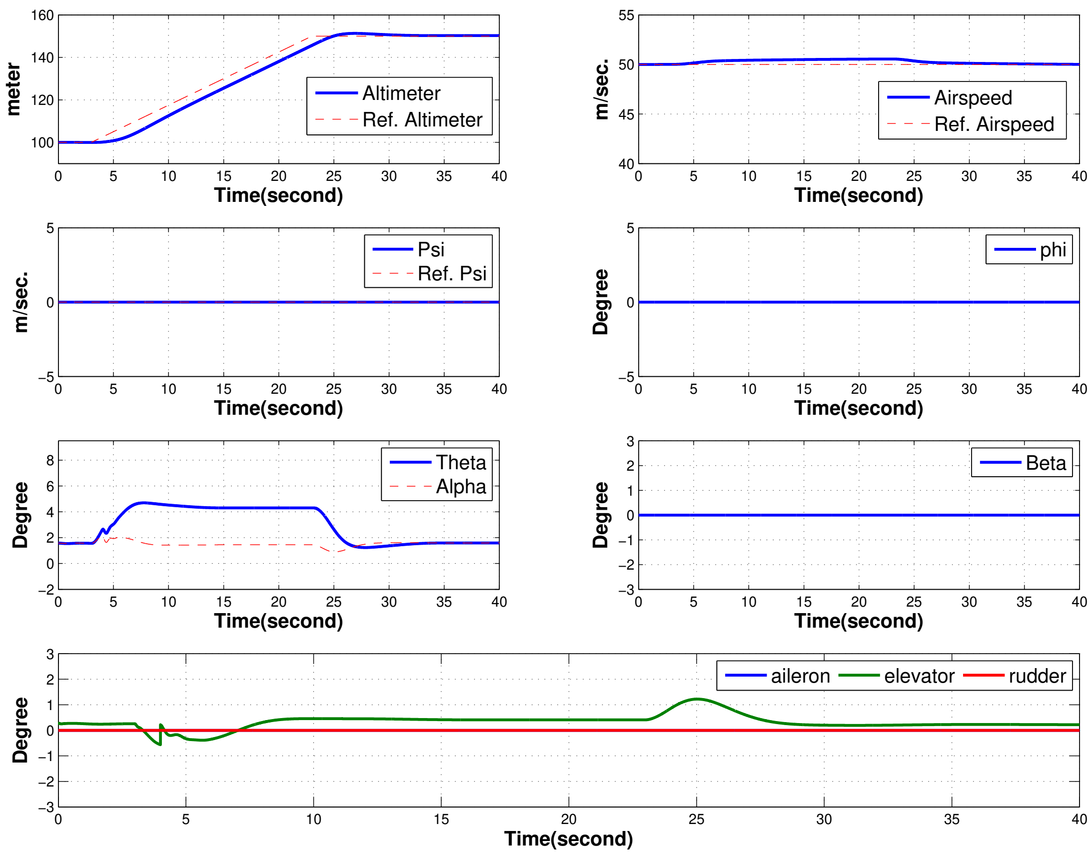

Figure 7: Elevator degradation with reconfiguration.

Rudder Degradation

In the first case, for rudder degradation with no reconfiguration is shown in Figure 8. The pilot decided to adjust 40 degree heading change without any knowledge about degradation. Oscillations start during heading change and continue after the maneuver. It shows that LOC-I is going to happen. There is rudder degradation but aileron command makes the UAV destabilized. In other words, aileron can not work properly with the degraded rudder. As a result, the aileron movement has to be decelerated while the rudder movement has to be accelerated. They can be work together after reconfiguration of the FCC.
To prevent LOC-I, reconfiguration of the FCC is mandatory. As a result, the path for supervisor logic is followed.

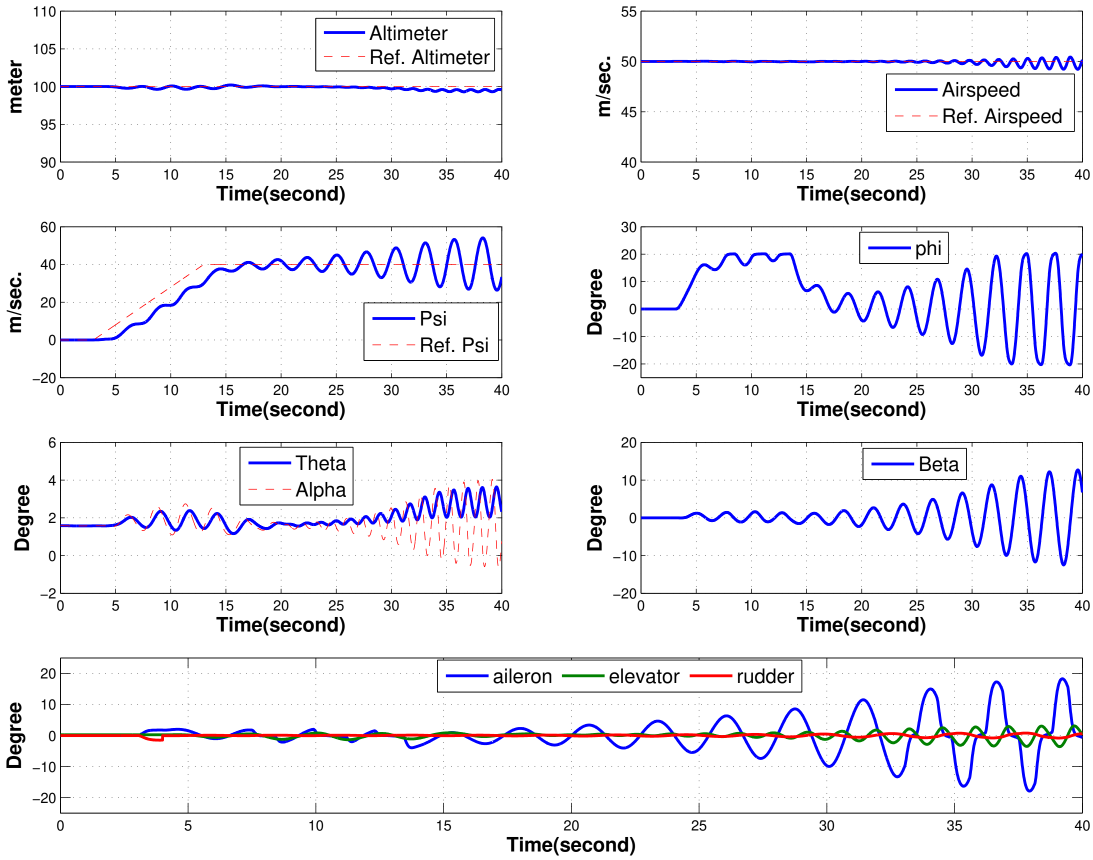

Figure 8: Rudder degradation with no reconfiguration.

In the second case, with the reconfiguration of the controller with the help of the supervisor logic, results show that oscillations go off shown in Figure 9. As a result, LOC-I is prevented.
Aileron and rudder can work together properly to achieve heading change. Bank angle is 20 degrees and there is not any oscillation for β. Also, aileron and rudder deflections are very well.

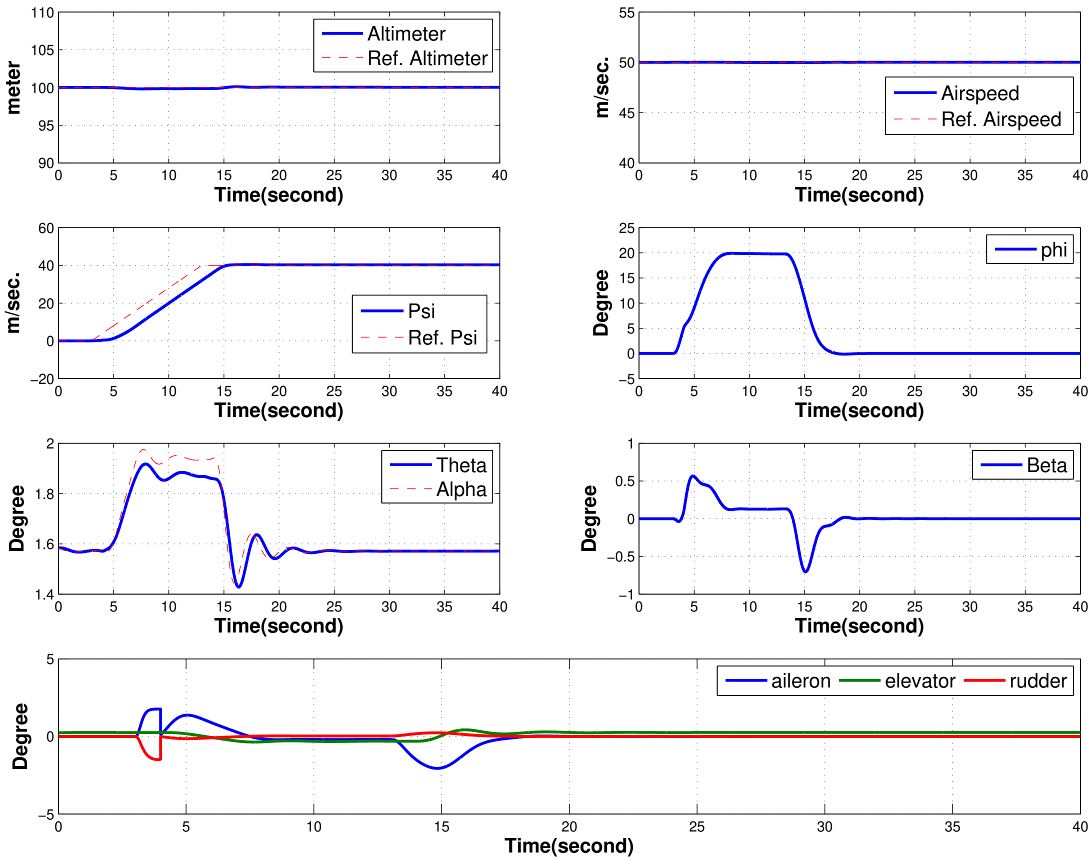

Figure 9: Rudder degradation with reconfiguration.

CONCLUSIONS

SDRE algorithm is used as a fault-tolerant flight control (FTFC). Design flexibility can be achieved with the reconfiguration of R matrix of the SDRE algorithm in the FCC. During aileron, elevator and rudder degradation, SDRE algorithm works well to prevent loss of control in-flight (LOC-I).

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