A Novel Reconfigurable Control Method for an Aircraft with Potential Actuator Failures

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Abstract: This paper presents a novel reconfigurable control method for an aircraft with potential actuator failures. A Variable Structure Model Reference Adaptive Control (VS-MRAC) scheme is deployed to counteract the adverse effects when the actuator failure occurs. Combined with exponential reaching law, the convergence rate is improved and the chattering is reduced. This approach ensures that the reference input value can be tracked rapidly and accurately. The safety and stability of the aircraft is much improved during the event of actuator failures. Finally, the simulation results are given to show the effectiveness and performance of the developed method.

Keywords: VS-MRAC; Exponential reaching law; Convergence rate; Reconfigurable control; Actuator failure


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1 Introduction

Over the past decades, fault-tolerant control (FTC) has been widely developed and used in the flight control system due to the increasing demands for survivability and reliability in modern aircrafts (Wang et al. 2015, Adrien et al. 2015). A direct allocation (DA) and iterative algorithm was developed in (Asim et al., 2015). Off-line lookup tables were used under normal condition, and DA algorithm was applied when actuators were faulty.

In (Qin et al., 2016), an active fault-tolerant control scheme was used for a quadrotor unmanned helicopter with velocity sensor failure. The two-loop control law was designed to guarantee the trajectory, with PD (Proportion Differentiation) control in the external loop and PID (Proportion Integration Differentiation) control in the internal loop. Sensor failures were detected and estimated by both an observer and an augment one.

A novel integral sliding mode control (ISMC) scheme was proposed for actuator outage in (Li et al., 2016). For an uncertain non-linear system, this scheme consisted of the adaptive control method and matrix full-rank factorization technique, and was synthesized with fuzzy logic systems to guarantee system robustness against actuator failures. In (Hartley and Maciejowski, 2015), a robust algorithm based on MPC and H2 control theory was developed. In this work, the flight control law could follow independent parameters such as airspeed, sideslip angle, angle of attack, etc.

A new model reference adaptive control (MRAC) scheme was proposed for structural damage of aircraft, which used a discrete-time method to linearize the flight control system (Guo and Tao, 2015). Several issues were addressed on the damaged aircraft, and the stability was also studied as well as asymptotic output tracking. In (Zhang and Hu et al. 2017), an adaptive neural network based control scheme is introduced for the trajectory tracking of a micro aerial vehicle (MAV). This work used a novel combination of outer and inner loop control to directly handle the plant. Lyapunov function and estimation approach were deployed to guarantee the stability and real-time performance.

A robust control method was proposed for a multi-variable aircraft, which consists of H∞ and μ-synthesis control to optimize between the robustness and performance requirements (Almutairi and Aouf, 2015). In (Liu et al., 2016), a linear parameter varying (LPV) methodology was used to deal with actuator failures of an unmanned quadrotor helicopter, which was an active fault-tolerant control. The fault was obtained by a fault detection and diagnosis (FDD) to use for fault-tolerant control (FTC).

Moreover, a FTC scheme was proposed in (Alwi et al., 2015) to guarantee the system performance, which was based on an integral sliding mode (ISM), control allocation (CA) and the LPV method. The ISM/CA scheme was developed to accommodate actuator failures in (Chen et al., 2015). In (GHODBANE et al., 2016), a novel methodology was proposed for high-altitude flight control systems against cosmic rays and solar particle. The FDD consisted of a geometric approach and a multiple-model (MM) algorithm, and designed to handle multiple actuator failures.

SMC architecture was used to redistribute the control signals to the normal actuators combined with Lyapunov stability theory to guarantee the stability of system. In order to alleviate the chattering phenomenon and obtain good stability, (Samir et al., 2015) presented a FTC scheme used the interval type-2 fuzzy logic and sliding mode control methodology for coaxial tri-rotor helicopter. A MPC combined with FDD was used to address the actuator jamming caused by large aerodynamic forces, or a stuck faulty control surface (Laura et al., 2015).

In (Chen et al., 2015), an adaptive global sliding mode control approach was proposed to address the problem of actuator malfunction of helicopter, and the quantum logic was used to increase the system accuracy. This work has a good identification performance and little time delay. Considering the wing flutter when actuator failures occur, a robust FTC was used to deal with actuator failures, parameter uncertainties and external disturbances. It consisted of neural network and H∞, and could suppress the wing flutter with better stability (Gao and Cai, 2016).

A novel body-centric modelling approach was presented to a quadrotor UAV for the study of identification (Mohamad et al., 2015). By virtue of model parameters and data, an acceleration tracking control strategy was investigated using a linear-quadratic (LQ) algorithm. Though many algorithms have been developed, the research of FTC is still a challenging with the complexity and non-linearity of flight control system on air and space vehicles such as civil aircraft, combat aircraft, satellite, unmanned aerial vehicles (UAVs), vertical/short takeoff and landing (VSTOL) aircraft, etc. (Fikret et al. 2015, Yu et al. 2016 and Rose et al. 2016). (Zhang and Hu et al. 2016) presented a cascade control scheme for an inverted pendulum on a flying quadrotor. It also realized the tracking control for the aerial vehicle and the good performance was verified through a comparison analysis using simulation and experiments. A U-state space control method was proposed for F-16 aircraft dynamic model (Liu and Zhu et al. 2015). Combined with the LQR, a controller was designed through discretizing the linearized model.

In summary, many control strategies have been studied in order to fulfill the increasing demand on safety and flight performance. It is extremely important to guarantee system security and reliability in the event of various failures, namely uncertainties, parametric perturbations, and external disturbances, due to unmolded dynamics, control surface damage, actuator failures, and sensor failures, etc. In this paper, a novel reconfigurable control method based VS-MRAC combined with exponential reaching law is proposed for the aircraft with potential actuator failures. How to reduce or eliminate the chattering of system is difficult and it is also an important problem that guarantees the reaching condition and the stability of system. The purpose is mainly to use the proposed method to track the input instruction in the event of actuator failures and achieve the stability of the system. It does not require the accurate mathematical model of the aircraft and fault detection module. Combined with the exponential reaching law, the convergence rate is improved and the chattering is
reduced. Simulation is conducted to show its performance and effectiveness.

The rest of the paper is organized as follows. Section 2 is focused on the plant model of the aircraft and the statement of faulty aircraft. Section 3 describes the fault tolerant control strategy. Simulation results are presented and discussed in Section 4. Finally, a brief conclusion and future work are given in Section 5.

2 Problem Statement and Preliminaries

We consider the flight control system that will be influenced by external disturbance and perturbation, as follows:

\[
\begin{align*}
\dot{x}(t) &= Ax(t) + Bu(t) + d(t) \\
y(t) &= Cx(t)
\end{align*}
\]

and the reference model can be expressed as:

\[
\begin{align*}
\dot{x}_m(t) &= A_m x_m(t) + B_m u_m(t) \\
y_m(t) &= C_m x_m(t)
\end{align*}
\]

where \(x(t), x_m(t) \in \mathbb{R}^n\) and \(y(t), y_m(t) \in \mathbb{R}^r\) are the state vector and output vector of the system respectively; \(u(t), u_m(t) \in \mathbb{R}^m\) is the control input; \(A, A_m \in \mathbb{R}^{n \times n}\), \(B, B_m \in \mathbb{R}^{n \times m}\) and \(C, C_m \in \mathbb{R}^{r \times n}\) are the state, input and output matrices respectively; \(d(t)\) is the lumped effect of uncertainties and disturbances.

Assumption 2.1 \((A, B), (A, C), (A_m, B_m), (A_m, C_m)\) are completely controllable and observable, and \(A_m\) is a Hurwitz matrix.

Define the deviation vector:

\[
e(t) = x_m(t) - x(t)
\]

The object of the proposed scheme is to design a controller to make that:

\[
\lim_{t \to \infty} e(t) = 0
\]

and \(e(t)\) will be required to have good quality. Then we have the following equation:

\[
\dot{e}(t) = \dot{x}_m(t) - \dot{x}(t)
\]

After substituting (1) and (2) to (5), the differential equation of error with respect to the system can be obtained using the following equation.

\[
\dot{e}(t) = A_m e + (A_m - A)x + B_m u_m - Bu - d
\]

where \((A, B)\) and \((A_m, B_m)\) are completely controllable. Then we have an assumption below:

Assumption 2.2

\[
\text{rank}[B] = \text{rank}[B; (A - A_m)] = \text{rank}[B, B_m]
\]

Generally, the aircraft with actuator failures, disturbance and perturbation can be described as follows:

\[
\begin{align*}
\dot{x}(t) &= Ax(t) + (B + \Delta B)u(t) + d(t) \\
y(t) &= Cx(t)
\end{align*}
\]

where \(\Delta B \in \mathbb{R}^{n \times m}\) denotes actuator failures.

Assume that the condition (7) is satisfied, we define that:

\[
A_m - A = BK, \quad B_m = BK, \quad \Delta B = BK, \quad d(t) = BK
\]

After combining (8), (9), (10), (11), (12) and then substituting to (6) we have that:

\[
\dot{e}(t) = A_m e + B[K_x x + K_z u_m - (I + K_x)u - K_z]
\]

The following Theorem is useful for subsequent analysis. Moreover, it will be proved for a better understanding.

Theorem 1 There is control, which enables (8) to track (2), whose sufficient condition is the complete matching condition (7).

Proof: Obviously, the above Theorem also apply to (4), and the complete matching condition (7) is equivalent to (9) and (10).

From (13), we define:

\[
u = (I + K_x)^{-1}(K_x x + K_z u_m - K_z e)
\]

Then (13) can be expressed as:

\[
\dot{e}(t) = A_m e
\]

If \(A_m\) has desired stability characteristics, (4) can be fulfilled. Otherwise, we define:

\[
u = (I + K_x)^{-1}(K_x x + K_z u_m - K_z e) - K_x e
\]

where \(K_x\) is a non-singular matrix, then

\[
\dot{e}(t) = (A_m + BK_x e)
\]

Combined with (10), (17) can be expressed as:

\[
\dot{e}(t) = (A_m + B_m K_z^{-1} K_z) e
\]

where \((A_m, B_m)\) is completely controllable. So for any given set of pole \(\zeta\) in advance, there is a feedback matrix \(K = K_z^{-1} K_x\), which makes the set of pole of a linear
system $A_u + B_u K$ be $\Omega$. Therefore, the condition (4) can be fulfilled.

The proposed VS-MRAC approach aims to design a controller so that the actual output $y(t)$ can follow the reference output $y_r(t)$. That is to say, the error $e(t)$ between $x(t)$ and $x_r(t)$ should approach to zero asymptotically. The design consists of two steps.

- The first step is to set up the model following deviation system, and then the sliding surface is constructed using $e(t)$ as the state variable.
- At the second step, the SMC is designed to make the model reference deviation system reach the sliding surface, and then the variable structure control law is obtained. Finally, the Lyapunov stability theory is used to guarantee the stability of system.

## 3 Control Strategies

In this section, the VS-MRAC scheme is designed based on exponential reaching law. The sliding surface and control law are deployed to make the system reach the sliding surface and the balance point in order to yield asymptotic stability.

### 3.1 The Sliding Surface Design

The switching function is expressed as:

$$s(t) = C_{o} \hat{e}(t)$$ (19)

where $C_{o} \in \mathbb{R}^{m \times m}$. The sliding mode $s(t) = 0$ and $\dot{s}(t) = 0$ is satisfied.

From (19) and $\dot{s}(t) = 0$, we have:

$$\dot{s}(t) = C_{o} \hat{e}(t) = 0$$ (20)

Assume $C_{o}B$ is a $m \times m$ non-singular matrix. We substitute (6) into (20), and obtain:

$$\dot{s} = C_{o} \hat{e}$$

$$= C_{o} [A_{u}e + (A_{u} - A)x + B_{u}u_{a} - Bu - d]$$ (21)

Then we can obtain the equivalent control:

$$u_{e} = (C_{o}B)^{-1} C_{o} [A_{u}e + (A_{u} - A)x + B_{u}u_{a} - d]$$ (22)

### 3.2 Design of Control Law

According to (13), the linear transform is applied to $e$ as below:

$$\bar{e} = Fe$$ (23)

where $F$ is satisfied with:

$$\bar{B} = FB$$

$$= [0 \quad B^{'\top}]$$ (24)

where $B^{'}$ is a $m \times m$ non-singular matrix.

We define:

$$FA_{u}F^{-1} = \hat{A}_{u}, \quad C_{o} = C_{q}F^{-1}$$ (25)

After transformation, we have:

$$\bar{e}(t) = \hat{A}_{u}\bar{e} + \bar{B}[K_{s}x + K_{u}u_{a} - (I + K_{s})u - K_{s}u]$$ (26)

$$\dot{s}(t) = \bar{C}_{o}\bar{e}$$ (27)

We define:

$$C_{o} = \begin{bmatrix} C_{o1} \\ C_{o2} \end{bmatrix}, \quad \bar{e} = \begin{bmatrix} e_{1} \\ e_{2} \end{bmatrix}$$ (28)

Then we can obtain the following form:

$$s(t) = \bar{C}_{o1}\bar{e}_{1} + \bar{C}_{o2}\bar{e}_{2} = 0$$ (29)

In general, we can assume $C_{o2}$ is a $m \times m$ non-singular matrix, then:

$$\bar{e}_{2} = \bar{C}_{o2}^{-1}(s - \bar{C}_{o1}\bar{e}_{1})$$ (30)

and through the linear transform

$$\begin{bmatrix} \bar{e}_{1} \\ \bar{e}_{2} \end{bmatrix}^{\top} = \begin{bmatrix} I & 0 \\ C_{0} & C_{01} \end{bmatrix} \bar{e},$$

Note that (26) and (27) can be expressed as:

$$\dot{\bar{e}}_{1} = \hat{A}_{u11}\bar{e}_{1} + \hat{A}_{u12}\bar{e}_{2} + \bar{C}_{o2}^{-1}C_{o1}\bar{e}_{1} + \hat{A}_{u12}\bar{e}_{1}$$ (31)

$$\dot{s}(t) = \bar{C}_{o}A_{u}\bar{e} + \bar{C}_{o}B[K_{s}x + K_{u}u_{a} - (I + K_{s})u - K_{s}u]$$ (32)

According to $s(t) = 0$, the motion equation of sliding dynamics can be obtained:

$$\dot{\bar{e}}_{1} = (\hat{A}_{u11} - \hat{A}_{u12}\bar{C}_{o2}^{-1}C_{o1})\bar{e}_{1}$$ (33)

$\bar{C}_{o2}$ can be obtained using the pole assignment or optimal control method. Obviously, according to (7), the sliding mode is fully adaptive against the uncertainty of the system, which is only related to $A_{u}$ and $C_{o}$, and irrelevant to the uncertainty of the system.

For reducing the chattering, the exponential reaching law is used here:

$$\dot{s} = -\varepsilon sgn s - ks$$ (34)

where $\varepsilon = diag[e_{1}, \ldots, e_{m}], \varepsilon > 0, k > 0, sgn s = [sgn s_{1}, \ldots, sgn s_{m}]^{\top}, i = 1, 2, \ldots, m$.

Assume $\bar{C}_{o2}B^{'}$ is a $m \times m$ non-singular matrix and $I + K_{s}$ is invertible matrix. We substitute (34) into (32) to obtain:

$$u = (I + K_{s})^{-1}[(\bar{C}_{o2}B^{'\top})^{-1}(\varepsilon sgn s + ks + \bar{C}_{o}A_{u}\bar{e})$$

$$+ K_{s}x + K_{u}u_{a} - K_{s}u]$$ (35)
After substituting $e \rightarrow e^{-T}$ into the above expression, we obtain the following control law:

$$u = (I + K_I)^{-1}[(C_0B)^{-1}(e \, sgn \, s + ks + C_0A_m e)] + K_f x + K_f u_m - K_b$$

(36)

where $K_p = (I + K_f)^{-1}K_i$, $K_f = (I + K_f)^{-1}K_z$, $K_h = (I + K_f)^{-1}K_s$.

### 3.3 Analysis of Stability and Chattering Reduction

This section will discuss the stability and of the system (8) and how to reduce the chattering.

**Theorem 2** Combined with the switch surface (19), the system (8) will reach the sliding surface in a limited time and be asymptotically stable under the control law (36).

**Proof** The Lyapunov function is chosen as follows:

$$V = \frac{1}{2} e^T e$$

(37)

Substituting (34) into (37), we have that:

$$\dot{V} = \frac{1}{2} \dot{e}^T \dot{e} + \frac{1}{2} e^T \ddot{e}$$

$$= e^T \dot{e} + \frac{1}{2} e^T \ddot{e}$$

$$= e^T (-e \, sgn \, s - ks)$$

$$= -\sum_{i=1}^{m} [s_i (e_i \, sgn \, s_i + ks_i)]$$

$$= -\sum_{i=1}^{m} (e_i \mid s_i \mid + ks_i) < 0$$

(38)

where $sgn \, s = \begin{cases} 1, & s > 0 \\ -1, & s < 0 \end{cases}$

As above, $V = \frac{1}{2} \dot{s}^T \dot{s}$ is positive definite and $\dot{V} = \dot{s}^T \dot{s}$ is negative definite, so the reaching condition is satisfied and the system is asymptotically stable.

Actually, the exponential reaching law can reduce the chattering.

We define $s = 0$, then

$$\dot{s} = \left\{ \begin{array}{ll} -e, & s > 0 \\ +e, & s < 0 \end{array} \right.$$  

(39)

That is to say, $e$ means the approach speed when reaching the switch line. The distance through the switch line will be short if $e$ is small enough to guarantee the approach speed is low, thus the lag of switching is little and it ensures the chattering is weak. Otherwise, the chattering is strong. Although the chattering is weaken greatly, the approach speed will be low and lead to the bad quality if $e$ is reduced. For reducing the chattering and approaching fast, $k$ should be increased and $e$ be reduced. The ability to resist the perturbation and interference will be also eliminated while the chattering is eliminated, so it is advisable by means of reducing chattering.

### 4 Simulation Results

In this section, an aircraft model is presented to demonstrate the feasibility of the proposed control method. As shown in Figure 1, the VS-MRAC approach is used to
counteract the adverse effects when the actuator failures occur. The MATLAB software is used for a couple of numerical simulations.

For comparison, the results under normal and fault conditions are presented simultaneously. The state vector of the aircraft is $x = [V \; \alpha \; q \; \theta]^T$, where $V$ denotes the velocity, $\alpha$ denotes the attack angle, $q$ denotes the pitch rate, $\theta$ is the pitch angle. $u = [\delta_e \; \delta_t]^T$ is the control vector, where $\delta_e$ denotes the elevator deflection, $\delta_t$ denotes the thrust. $y = [\alpha \; q]^T$ is the output vector. The plant parameters matrices are given below:

$$A = \begin{bmatrix} -0.0121 & 5.678 & 0 & -9.681 \\ -0.0011 & -0.5712 & 1 & 0 \\ 0.0027 & -2.2132 & -1.0118 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix},$$

$$B = \begin{bmatrix} 0 & 0.0027 \\ -0.0727 & 0 \\ -2.2725 & 0 \\ 0 & 0 \end{bmatrix},$$

$$C = \begin{bmatrix} 0 & 1 & 0 & 0 \end{bmatrix}.$$

The reference model parameters matrices are chosen as follows:

$$A_r = \begin{bmatrix} -0.0122 & 5.888 & 0 & -9.791 \\ -0.0013 & -0.6762 & 1 & 0 \\ 0.0035 & -2.2232 & -1.0129 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix},$$

$$B_r = \begin{bmatrix} 0 & 0.0033 \\ -0.0837 & 0 \\ -3.3225 & 0 \\ 0 & 0 \end{bmatrix},$$

$$C_r = \begin{bmatrix} 0 & 1 & 0 & 0 \end{bmatrix}.$$

![Figure 2 The command input and control input](image)

![Figure 3 The attack angle and pitch rate with respect to loss of 10% nominal value](image)
In the simulation, the first-order inertia unit \( -30s + 10 \) is used as the elevator model and the elevator surface is limited to \( \pm 5 \). Considering the constant wind disturbance at the 50th second, the throttle input is ignored and the simulation time is 120 seconds.

Two scenarios are considered in the numerical simulations: a loss of 10% control effectiveness and a loss of 30% control effectiveness in elevator. As shown in Figures 2-5, the fault is injected at the 30th second, which may lead to transient loss of the pitch rate, while the attack angle is affected little.

In the output curve, the dotted line is the ideal reference model output, and the solid line is the controlled system output. Using the proposed control method, the aircraft is able to maneuver back to the anticipated position after a transient volatile period and the system can stabilize asymptotically quickly.

For testing the performance of the investigated control method that is described above, an actual model aircraft is constructed to deal with the potential actuator failures, as shown in Figure 6. More specifically, Figure 6(a) shows the aircraft construction process; Figure 6(b) shows the laptop PC and joystick used for controlling the model aircraft; Figure 6(c) presents the human-machine interface displayed on the screen of the laptop PC. Experimental results and analysis will be gathered during our next stage of research and presented in the future paper.

5. Conclusion and Future Work

A Variable Structure Model Reference Adaptive Control (VS-MRAC) method is presented in this paper to accommodate potential actuator failures of aircraft. It does not require the accurate mathematical model of aircraft and the fault detection module. Combined with exponential reaching law, the convergence rate of the aircraft control system is improved and the chattering is reduced.

Two scenarios are considered in simulation, with respect to loss of 10% and 30% control effectiveness in an elevator.
and the resulting control law is validated in the numerical simulations. The simulation results demonstrate that the proposed method can achieve the satisfactory performance and robustness in the event of actuator failures.

Our future work is to apply the presented control method to an actual aircraft model with unexpected fast disturbance and strong uncertainties. The performance and effectiveness will be tested in and then it could be used in real aircrafts for a variety of tasks. The approach developed in this paper could also be used for hypersonic vehicle or missile control to overcome the system uncertainty, nonlinearity or parameter perturbation, improving both the tracking accuracy and the manoeuvrability.

References


