Cascade ADRC-based fault-tolerant control for a PVTOL aircraft with potential actuator failures

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Abstract: This paper presents a novel reconfigurable control method for the planar vertical take-off and landing (PVTOL) aircraft with potential actuator failures. A cascade active disturbance rejection controller (ADRC) is used to counteract the adverse effects when the actuator failure occurs. The coordinate transformation is used for model decoupling due to the severe coupling between some variables. This approach does not require the accurate mathematical model of the controlled system and ensures that the reference input value can be tracked rapidly and accurately. The stability and safety of the aircraft is much improved in the event of actuator failures. Finally, the simulation results are given to show the effectiveness and performance of the developed method.

Keywords: cascade ADRC; planar vertical take-off and landing; PVTOL aircraft; coordinate transformation; fault-tolerant control; FTC; actuator failure.


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1 Introduction

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

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

A novel integral sliding mode control (ISMC) scheme was proposed for actuator outage (Li et al., 2016). For an uncertain nonlinear system, this scheme consisted of adaptive control method and matrix full-rank factorisation technique, and was synthesised with fuzzy logic systems to guarantee better robustness of the system 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 linearise the flight control system (Guo and Tao, 2015). Several issues were addressed on damaged aircraft, and the stability was also studied as well as asymptotic output tracking.

A robust control method which consists of H∞ and μ-synthesis control to optimise between the robustness and performance requirements was presented for a multi-variable aircraft (Saif and Nabil, 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 FTC. The fault was obtained by a fault detection and diagnosis (FDD) to use for 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. (2015b). In Ghodbane et al. (2016), a novel methodology was proposed for high-altitude flight control systems against cosmic rays and solar particle. The FDD was also designed to handle multiple actuator failures, which consisted of a geometric approach and a multiple-model (MM) algorithm.

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. (2015a), 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 (Mohammad et al., 2015). By virtue of model parameters and data, 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 nonlinearity 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 (V/STOL) aircraft, etc. (Fikret and Chingiz, 2015; Yu et al., 2016; Rose and Jinu, 2016).

In particular, the planar vertical take-off and landing (PVTOL) aircraft is gaining more attention during the last few years. It is in fact a simplified version of actual aircraft model and maintains the main characteristics (Carlos et al., 2015). Many control strategies have been studied in order to fulfill the increasing safety demand 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 Carlos et al. (2015), a control scheme based on output feedback is introduced for the regulation of a PVTOL craft. This work uses a novel SMC and an energy control approach to stabilise or balance the vertical variable and horizontal and angular variables, respectively. Alexander et al. (2015) presented a SMC approach for stabilisation of a PVTOL aircraft combined with super-twisting algorithms, and it focused on lateral motion of autonomous aircraft. In order to stabilise a model of PVTOL aircraft, an output feedback method was explored in Frye et al. (2010). In this work, the finite-time convergent control was used to construct a stabiliser, and a fast convergent observer was designed to stabilise the system.

In Ricardo and Luis (2011), a SMC scheme was focused on combining with output feedback technology to regulate the PVTOL aircraft including actuators dynamics. The velocity of the aircraft was estimated by a sliding mode observer (SMO) which was designed respectively, and the feedback control was also investigated. An adaptive control for the PVTOL craft could also be found in Soki et al.
(2015), which proposed minimum projection and dynamic extension algorithm based on Lyapunov function, and an optimal control method was also used.

In this paper, a novel reconfigurable control method-based cascade active disturbance rejection controller (ADRC) is proposed for the PVTOL aircraft with potential actuator failures. 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. Simulation is conducted to show its performance and effectiveness.

The rest of the paper is organised as follows. Section 2 is focused on the dynamic model of the PVTOL aircraft, the model decoupling 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 Dynamic models and problem statement
2.1 Dynamic model of PVTOL aircraft

The minimum number of state variables and input for hovering control of V/STOL aircraft is retained by using the PVTOL aircraft model as a benchmark model. Figure 1 shows the couple relationship between the roll moment and lateral thrust.

The roll torque $U_2$ of a V/STOL aircraft is generated by jet engines coordination control, which is under the both sides of wing tips. When the thrust that is generated by engines under wingtips is not vertical with horizontal direction one, a lateral thrust $\varepsilon_0 U_2$ will be generated with the roll torque. This is why a V/STOL aircraft has non-minimum phase characteristics.

The horizontal and vertical motion of aircraft mass centre $Y$ and $Z$ are normally treated as the output of the system, and the roll angle $\theta$ is used as internal state of the system, which is relative to the horizontal direction. The main thrust $U_1$ and roll torque $U_2$ on aircraft mass centre are used as the control variable of the system.

In terms of aircraft modelling, the aircraft will be considered as a rigid system and the bending effect of its fuselage and wings will be ignored. As shown in Figure 1, its motion equations can be established in the following form:

$$\begin{aligned}
   m\ddot{Y} &= -U_1 \sin \theta + \varepsilon_0 U_2 \cos \theta + \omega_1 \\
   m\ddot{Z} &= U_1 \cos \theta + \varepsilon_0 U_2 \sin \theta - mg + \omega_2 \\
   J\ddot{\theta} &= U_2
\end{aligned}$$

where $Y$ and $Z$ are the horizontal and vertical motion respectively; $\theta (|\theta| << \pi / 2)$ is the roll angle which is relative to the horizontal direction; $U_1$ and $U_2$ are the main thrust and roll torque; $g$ is the acceleration due to gravity which can be normalised to 1; $J$ is the mass moment of inertia; $\varepsilon_0$ is the coupling coefficient between the lateral thrust and roll torque; $\omega_1$ and $\omega_2$ are the bounded disturbance terms.

Figure 1  Schematic drawing of the PVTOL aircraft
To get a simplified form, the new variables are introduced below:
\[ x = -\frac{Y}{g}, y = -\frac{Z}{g}, \]
\[ u_1 = U_1 / (mg), u_2 = U_2 / J, \]
\[ \epsilon = \epsilon_0 J / (mg) \]

Then, we have the following motion equations:
\[
\begin{align*}
\dot{x} &= -u_1 \sin \theta + \epsilon u_2 \cos \theta + \omega_1 \\
\dot{y} &= u_1 \cos \theta + \epsilon u_2 \sin \theta - 1 + \omega_2 \\
\dot{\theta} &= u_2
\end{align*}
\]

(2)

where \( x \) and \( y \) are the horizontal and vertical motion of aircraft mass centre after simplification; \( \theta \) is the roll angle which is relative to the \( x \) axis; \( u_1 \) and \( u_2 \) are respectively the main thrust and roll torque control; \( \epsilon \in [0, 1] \) is the coupling coefficient between the lateral thrust and roll torque and immeasurable.

We can see that the main thrust offset the gravity to maintain the stable system when the aircraft is hovering, as shown in Figure 1.

**Remark 1:** \( u_1 \) and \( u_2 \) should be not too big due to the limitation of aircraft jet engines control and \( u_1 > 0 \). \( y(t) \) should have a very small amount of change or \( y(t) = 0 \).

### 2.2 Model decoupling and problem statement

The zero dynamic subsystem of a PVTOL aircraft is unstable due to coupling between the roll torque and lateral thrust. Though the reference input value can be tracked rapidly and accurately by the output \( x \), the vertical position and the roll angle \( \theta \) which are the key internal state indicator cannot be remained stable. Therefore, the decoupling between \( \epsilon \) and \( y(t) \) is studied by the coordinate transformation for the PVTOL aircraft model in this paper, and the Cascade ADRC is also designed in terms of the model after coordinate transformation.

Consider the control matrix with coupling characteristics of the actual PVTOL system (2), as follows:

\[
\begin{bmatrix}
-\sin \theta & \epsilon \cos \theta \\
\cos \theta & \epsilon \sin \theta
\end{bmatrix}
\]

(3)

From above, the last line of the control matrix of the system (3) should have nothing to do with \( \epsilon \) to make sure \( y \) is independent of \( \epsilon \). Now, multiplying (3) by a non-singular matrix on the right side one obtains:

\[
\begin{bmatrix}
-\sin \theta & \epsilon \cos \theta \\
\cos \theta & \epsilon \sin \theta
\end{bmatrix}
\begin{bmatrix}
1 & -\epsilon \tan \theta \\
0 & 1
\end{bmatrix}
\begin{bmatrix}
-\sin \theta & \frac{\epsilon}{\cos \theta} \\
\cos \theta & \frac{\epsilon}{\cos \theta}
\end{bmatrix}
\]

(4)

From above a new control variable \( \tilde{u} \) is defined below,

\[ \tilde{u}_1 = u_1 + \epsilon u_2 \tan \theta \]
\[ \tilde{u}_2 = u_2 \]

(5)

Hence, the PVTOL aircraft model (2) can be transformed to:

\[
\begin{bmatrix}
\dot{x} = -\tilde{u}_1 \sin \theta + \frac{\epsilon \tilde{u}_2}{\cos \theta} + \omega_1 \\
\dot{y} = \tilde{u}_1 \cos \theta - 1 + \omega_2 \\
\dot{\theta} = \tilde{u}_2
\end{bmatrix}
\]

(6)

We define

\[ u = [u_1 \ u_2]^T \]

\[ x = [y \ y' \ z \ z' \ \theta \ \dot{\theta}]^T \]

Then, equation (6) can be expressed, as:

\[
\dot{x} = Ax(t) + Bu(t) + d(t)
\]

(7)

where

\[
A = \begin{bmatrix}
0 & 1 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 1 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 1 & 0 \\
0 & 0 & 0 & 0 & 0 & 0
\end{bmatrix}
\]

\[
B = \begin{bmatrix}
0 & 0 & \frac{\epsilon}{\cos \theta} \\
0 & 0 & 0 \\
\cos \theta & 0 & 0 \\
0 & 0 & 0 \\
0 & 0 & 1
\end{bmatrix}
\]

\[ d(t) = \begin{bmatrix}
0 \\
0 \\
\omega_1(t) \\
0 \\
-1 + \omega_2(t) \\
0
\end{bmatrix}
\]

Generally, actuator failures of the aircraft include loss of effectiveness (LOE), hard over fault (HOF), float and lock in place (LIP), which can be described below:

\[
\dot{x} = Ax(t) + Bu(t) + d(t)
\]

(8)

where

\[ \sigma = \text{diag} \{\sigma_1, \sigma_2, \ldots, \sigma_m\} \]

\[ u_{ei}(t), \sigma_k = 1, \text{normal} \]
\[ k_i(t) \times u_{ei}(t), 0 < \sigma_k < 1, \text{LOE} \]
\[ u_{ci}(t), \sigma_k = 0, \text{LIP} \]
\[ 0, \sigma_k = 0, \text{float} \]
\[ u_{ci} \text{or } u_{cim}, \sigma_k = 0, \text{HOF} \]

where \( u_{ci}(t) \) denotes the actual output signal of the control surface; \( u_{ci}(t) \) is the control signal generated by the \( i \)th control surface; \( k_i \in (0, 1) \) is the actuator effectiveness coefficient; \( u_{ci} \) and \( u_{cim} \) are the minimum and maximum values, \( i = 1, 2, \ldots, m \).
can be described as follows:

The tracking value of the reference input can be described below (Wang et al., 2009):

\[ y^{(n)} = f(y, y', \ldots, y^{(n-1)}) + h_0 u + d(t) \]  

where \( f(\cdot) \) and \( d(t) \) are unknown; \( u \) and \( y \) denote the input and output of the system respectively; \( b_0 \) is a certain constant.

Then, the state variable can be represented as:

\[ [x_1, x_2, \ldots, x_n]^T = [y(t), y'(t), \ldots, y^{(n-1)}(t)]^T \]  

(10)

We define:

\[ a(t) = f(\cdot) + d(t), \quad b(t) = \dot{a}(t) \]

The extended states equation can be obtained:

\[
\begin{align*}
\dot{x}_1 &= x_2, \quad \dot{x}_2 = x_3, \ldots, \quad \dot{x}_{n-1} = x_n \\
\dot{x}_n &= a(t) + b_0 u \\
x_{n+1} &= b(t) \\
y &= x_1
\end{align*}
\]

(11)

Therefore, the extended states observer (ESO) of the plant is established as follows:

\[
\begin{align*}
\dot{z}_1 &= z_2 - b_1 \cdot g_1 (z_1 - x_1) \\
\dot{z}_2 &= z_3 - b_2 \cdot g_2 (z_1 - x_1) \\
&\vdots \\
\dot{z}_n &= z_{n+1} - b_n \cdot g_n (z_1 - x_1) + b_0 u \\
\dot{z}_1 &= -b_{n+1} \cdot g_{n+1} (z_1 - x_1)
\end{align*}
\]

where \( g_1, g_2, \ldots, g_{n+1} \) are the certain nonlinear function, and \( b_1, b_2, \ldots, b_{n+1} \) are the constant coefficient.

Through the parameter choice, the stability of ESO can be guaranteed and the system state can also be tracked. It can be described as follows:

\[
\begin{align*}
\dot{z}_1(t) &\rightarrow x_1(t), \ldots, \dot{z}_n(t) \rightarrow x_n(t), \\
\dot{z}_{n+1}(t) &\rightarrow x_{n+1}(t) = a(t)
\end{align*}
\]

(13)

The tracking value of the reference input \( v_0(t) \) and its derivatives \( v_1(t), v_2(t), \ldots, v_n(t) \) can be obtained by tracking differentiator (TD).

Finally, the input vector can be obtained:

\[
u(t) = k_1 \cdot h_1 (v_1 - z_1) + k_2 \cdot h_2 (v_2 - z_2) + \cdots + k_n \cdot h_n (v_n - z_n) + z_{n+1} / b_0 \]

(14)

where \( h_1, h_2, \ldots, h_n \) are the certain nonlinear function, \( k_1, k_2, \ldots, k_{n+1} \) are the constant coefficient.

The effect of disturbances can be compensated by the feedback \( z_{n+1} / b_0 \) timely so that the strong robustness of the system can be realised.

### 3 Control strategies

#### 3.1 Theoretical grounding

The uncertainty plant with unknown disturbance can be described below (Wang et al., 2009):

\[ y^{(n)} = f(y, y', \ldots, y^{(n-1)}) + h_0 u + d(t) \]  

where \( f(\cdot) \) and \( d(t) \) are unknown; \( u \) and \( y \) denote the input and output of the system respectively; \( b_0 \) is a certain constant.

Remark 2: For convenience, it is assumed that only one failure occurs on each control surface in a certain period of time. It cannot be certain when the fault occurs or how severe the fault is due to \( \sigma_k \in [0, 1] \) is unknown.

#### 3.2 Control strategies

The PVTOL aircraft is called a non-minimum phase system, which is a nonlinear systems with the asymptotically stable zero dynamics system. Owing to the unstable zero dynamic system, the output \( x \) and \( y \) of a PVTOL system can track the given instruction with a fast and accurate capacity, but the roll angle will roll around periodically after the output has stabilised.

The hovering control of a PVTOL aircraft is to guarantee that the lateral manoeuvre is achieved and the vertical position is unchanged at the same time. When the aircraft arrives at a given location, the horizontal position has to be maintained. The FTC is to guarantee the certain robustness for the perturbation of coupling coefficient or failures. That is to say, the controller is designed to ensure that the expression (8) is stable and has a good dynamic performance.

The vertical position of a hovering PVTOL aircraft is not affected by the transverse thrust caused by the roll torque since the vertical motion \( y(t) \) of the aircraft model (6) after coordinate transformation is no longer affected by the perturbation of the coupling coefficient \( \varepsilon \) directly.

However, the horizontal motion \( x(t) \) still has a strong coupling with the roll angle \( \theta \) to make the PVTOL aircraft generate periodic tumbling during lateral manoeuvre. For the hovering control of a vertical take-off and landing aircraft, it is difficult to make the hovering aircraft keep unchanged hovering height and have no rolling during lateral manoeuvre when the fault occurs. That is the reason that many researchers use the emerging FTC method for the PVTOL aircraft constantly.

In this paper, for the system (8), the cascade ADRC is designed in the channel where \( x(t) \) has a strong coupling with \( \theta \), to sustain the stability of the hovering aircraft during lateral manoeuvre when the fault occurs. Figure 2 shows the system block diagram of the cascade ADRC method.

The cascade ADRC has a strong ability for decoupling and is adaptable to disturbance as it is independent of the accurate mathematical model of the controlled plant. It uses the external disturbance and the internal uncertainty of the control system as a disturbance while compensating the total disturbance for tracking in real-time.

When the actuator failure occurs, the circuit change can be estimated by ESO, and used to compensate for the system dynamically since it includes the actuator fault and external disturbance. Then, the dynamic and steady-state performance of the circuit can be obtained by the nonlinear configuration of the state feedback.
Assuming that the control system can be approximated to a second order model under the effect of cascade ADRC, it can be expressed as:

\[
\begin{align*}
\dot{x}_1 &= x_2 \\
\dot{x}_2 &= f + b_0 u \\
y &= x_1
\end{align*}
\]

(15)

where \( u \) and \( y \) are the control signal and the output of the system respectively; \( b_0 \) is the parameters of cascade ADRC.

Then we have that the following equation:

\[
\dot{y} = f + b_0 u
\]

\[
f = g(t, y, \dot{y}, \omega) + (b - b_0)u,
\]

(16)

where \( b \) is the parameter of a controlled plant; \( g \) represents comprehensive characteristics combining with internal dynamics and external disturbances of the system; \( \omega \) is the external disturbances as the two external signals in the control loop; \( f \) is the extended state of the controlled plant, whose specific form of the expression is unknown.

ESO satisfies the following form:

\[
\begin{align*}
e &= y - z_1 \\
z_1 &= z_2 + l_1(y - z_1) \\
z_2 &= z_3 + l_2(y - z_1) + b_0 u \\
z_3 &= l_3(y - z_1)
\end{align*}
\]

(17)

where \( l_1, l_2 \) and \( l_3 \) are the parameters of observer which need to determine. \( z_1, z_2 \) and \( z_3 \) are the input variables of ESO. \( y, \dot{y} \) and \( f \) will be tracked by \( z_1, z_2 \) and \( z_3 \) when the ESO in (17) is tuned properly.

From (17), the controller is defined as the third order cascade ADRC. Therefore, the control law \( u_0 \) can be expressed as:

\[
u_0 = b_1 (r - z_1) - b_2 z_2
\]

(18)

where \( r \) is the reference input variable of the system. \( b_1 \) and \( b_2 \) are the parameters of cascade ADRC.

Then, the control signal of cascade ADRC can be expressed as:

\[
u = (u_0 - z_3)/b_0
\]

(19)

Substituting (19) to (16), when the ESO in (17) is tuned properly and \( z_3 \approx f \), the control system is converted to a double integral serial link:

\[
\dot{y} + b_3 \ddot{y} + b_5 y = b_5 r
\]

(21)

From above, the parameters of the controller \( b_1, b_2, b_0, l_1, l_2 \) and \( l_3 \) have to be tuned.

The characteristic equation of (21) can be expressed, as:

\[
D(s) = s^3 + l_1 s^2 + l_2 s + l_3
\]

(22)

Defining: \( D(s) = (s + \omega_0)^3 \).

Then \( l_1, l_2 \) and \( l_3 \) can be converted to the function of the observer bandwidth \( \omega_0 \):

\[
\begin{align*}
l_1 &= 3\omega_0 \\
l_2 &= 3\omega_0^2 \\
l_3 &= \omega_0^3
\end{align*}
\]

(23)

Hence, we will obtain a good performance for Cascade ADRC by tuning \( b_1, b_2, b_0, \omega_0 \).

4 Simulation results

In this section, an example of a PVTOL aircraft model is presented to demonstrate the feasibility of the proposed control method, as shown in Figure 3, a cascade ADRC is used to counteract the adverse effects when the actuator failures occur. For convenience, a simplified version of the actual aircraft model, namely, the PVTOL is used to deal with the potential actuator failures.
The MATLAB software is used for a couple of numerical simulations. For comparison, the results under normal and fault are presented simultaneously. The initial condition of the aircraft is $x(0) = 0$, and the control parameters are used as the following:

$$b_0 = 0.9, 0.9, -18 \quad b_1 = 0.8, 387, 0.17$$

$$b_2 = 1.8, 39, 0.8 \quad \omega_0 = 85, 1, 88$$

Two scenarios are considered in the numerical simulations: a loss of 30% control effectiveness and a loss of 60% control effectiveness in elevator. As shown in Figure 4, the fault is injected at the 20th second, which may lead to transient loss of horizontal motion and roll angle, while the vertical motion is affected little. Using the proposed method, the system stabilises asymptotically quickly.

**Figure 3** The model of VTOL aircraft (see online version for colours)

From above pictures, a loss of 60% control effectiveness occurs at the 20th second, which may lead to transient partial loss of aircraft. The aircraft is manoeuvred by the developed approach back to the anticipated position after a transient volatile period.

**Figure 4** (a) The horizontal output with respect to loss of 30% control effectiveness ($x$) (b) The vertical output with respect to loss of 30% control effectiveness ($y$) (c) The roll angle with respect to loss of 30% control effectiveness ($\theta$) (see online version for colours)
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5 Conclusions and future work

A cascade ADRC is presented to accommodate partial loss fault for the PVTOL aircraft. It does not require the accurate mathematical model of the aircraft and fault detection module. For convenience, the coupling between variables is decoupled by coordinate transformation. Two scenarios are considered with respect to loss of 30% and 60% control effectiveness in an elevator and the resulting control law is validated in the numerical simulations. The results demonstrate the satisfactory performance and robustness of the proposed method in the event of actuator failures.

The future work is to apply the presented method in a VTOL aircraft which is no longer a simplified version. The performance and effectiveness will be tested in an actual aircraft model and then it could be used in real aircrafts for a variety of tasks.

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