Safety Landing Strategy Investigation for Urban-Air-Mobility Vehicles Using Inverse Simulation Approach

Ye Yuan	Douglas Thomson	David Anderson
Ye.Yuan@swansea.ac.uk	Douglas.Thomson@Glasgow.ac.uk	Dave.Anderson@Glasgow.ac.uk
Lecturer	Senior Lecturer	Senior Lecturer
Swansea University	University of Glasgow	University of Glasgow
Swansea, United Kingdom	Glasgow, United Kingdom	Glasgow, United Kingdom

INTRODUCTION

The UAM systems have recently become the focus in the rotorcraft academia and industry. The advent of the UAM could significantly reduce ground-level traffic and carbon emissions. NASA report indicated [1] that by 2030 there could be as many as 1.25 billion UAM flights a year. In anticipation of this increase, more than 150 UAM vehicles are currently under development (Fig. 1).

Fig 1 Typical examples of future UAM vehicle

The UAM vehicles are usually powered by electricity or hydrogen, and multiple autonomous systems are incorporated into the UAM vehicles to improve their performance and riding qualities. However, these additional components may lead to different risk situations, such as battery failures and critical actuator malfunction. These risks may require the vehicle to perform an emergency landing. Luckily, the redundant controllers widely equipped in the UAM vehicle, such as the cyclic pitch of the multi-rotor system, can provide additional freedoms to enhance the safety of the emergency landing. However, the control powers and stabilities of these vehicles depend on the flight status of the UAM, and consequently, the handling qualities are changed significantly during the flight. Thus, a high-accuracy flight simulation model to describe the UAM flight dynamics features is the basis for investigating the emergency landing strategy of the UAM vehicles.

Most UAM vehicles are still in the design phase, so no corresponding flight test data or simulation results are available. However, the relevant research on the tiltrotor aircraft is an ideal reference for this research as the tiltrotor aircraft shares multiple similarities with the UAM vehicles, including the conversion mode and the redundant control allocation. Researchers utilised various methodologies to investigate different risk conditions of the tiltrotor, including one engine failure[2], bird strike[3], and flight control system failure[4]. The outcomes would become the basis for evaluating the feasibility of our research. In these investigations, Yan [2] utilised the optimal control theory to analyse the landing strategy of the tiltrotor aircraft during the one-engine failure condition. The obtained results can be used to develop the emergency landing flight path.

On the other hand, the inverse simulation method is widely utilised to evaluate the handling qualities and safety of rotor-powered vehicles and aircraft. Recently, our research group has introduced the automatic differentiation algorithm to the inverse simulation, significantly improving its calculation efficiency. However, one critical challenge of the inverse simulation method is to deal with the non-minimum phase characteristics. The characteristics would lead to the additional oscillation of the inverse simulation results, or even worse, the calculation process has convergence problems. These non-minimum phase characteristics can be found in the UAM flight dynamics, especially when the vehicle is flying in a fixed-wing mode (the rotor is acted as a propeller to provide thrust). However, Giulio [5] initialised another idea for the Two Timescale Integration (TTI) method to tackle the right half-plane transmission zeros, i.e., the non-minimum phase system, for inverse simulation. However, the corresponding parameters need to be adjusted case-by-case, impeding its application.

In light of the preceding discussion, the safety landing strategy investigation of the UAM vehicles is analysed by incorporating the high-accuracy flight dynamics model and the inverse simulation method. First, a universal real-time flight simulation model is developed based on the existing multi-agent simulation engine, providing accurate flight dynamics estimates for different UAM configurations. Then, the inverse simulation method will be further developed to meet the requirement for the safety investigation. The inverse simulation algorithm will adopt the Two Timescale Integration (TTI) method to tackle the potential non-minimum phase system. Lastly, the tiltrotor configuration is utilised as an example to perform the emergency landing manoeuvre with a malfunctioning elevator to represent the battery failure condition.

METHODOLOGY

The methodology section has three components: the tiltrotor flight dynamics model, the inverse simulation model, and the emergency landing manoeuvre description.

A. Flight dynamics model

The flight dynamics model contains the following sections: multi-rotor, wing, controller, and actuator & sensor. The multi-rotor model is constructed using an individual blade method, and the Pitt-Peters dynamic inflow model is adopted to estimate the induced velocity on the rotor disk. Meanwhile, the fixed-wake projection method is developed based on the tiltrotor aircraft modelling method to calculate the rotor aerodynamic interference on other UAM vehicles' components. The aerodynamics of the wing components are calculated based on the lift-curve slope theory.

Thus, the flight dynamics model can be represented as a set of nonlinear differential equations:

$$\dot{\boldsymbol{x}} = f(\boldsymbol{x}, \boldsymbol{u}, t) \tag{1}$$

where $\boldsymbol{x}$ and $\boldsymbol{u}$ are the state and control vectors, respectively, and t is the response time.

These aerodynamic components are incorporated into one multi-agent system, MAVERIC [6], along with the controller and, actuator & sensor components. The MAVERIC simulation package is a mathematical model based on a multi-fidelity simulation engine, initially for the RPG/Rotorcraft engagement simulation to evaluate the efficacy of various evasion strategies. This simulation engine could handle multiple dynamic agent models of differing fidelity and integrate them to provide an accurate, computational efficiency solution to a user-defined vignette. Thus, the multiple states of various components can be accurately simulated in this system, such as engine failure or actuator malfunction conditions. This software developed a Graphical User Interface (GUI) with user-point controls to demonstrate both the trajectory and the results, as shown in Fig. 2.

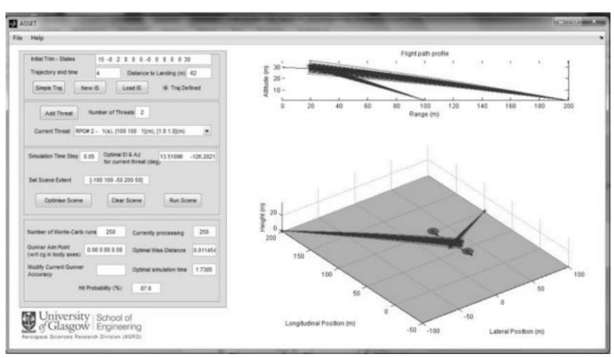


Fig. 2. MAVERIC Simulation package

B. Inverse Simulation Method

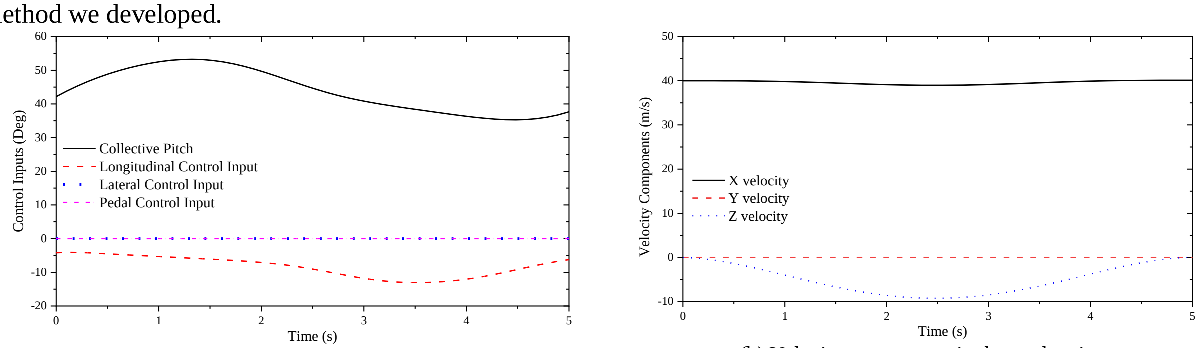
Inverse simulation is a widely used method for the manoeuvrability analysis of helicopter and fixed-wing aeroplanes. The so-called integration inverse simulation is utilised in this research, readily available when the flight dynamics model has been constructed. In order to process the inverse simulation algorithm, this article implements the three steps:

1). Calculate the trim control input

2). Define the manoeuvre

3). Calculate the control vector

The detail of the inverse simulation method can be found in references[7,8]. Fig. 3 is the simulation result of the XV-15 tiltrotor aircraft in the pop-up manoeuvre (helicopter mode), indicating the feasibility of the inverse simulation method we developed.



(a) Control input

(b) Velocity components in the earth axis

Fig .3 Inverse simulation results of XV-15 tiltrotor in the pop-up manoeuvre

On the other hand, the UAM vehicles may encounter non-minimum phase characteristics, which means that the system has right half-plane transmission zeros. The inverse simulation cannot be adequately implemented in these cases. Thus, the Two-Timescale-Integration (TTI) method is developed to tackle this risk[9].

The idea of the TTI method is to divide the inverse simulation into two calculation processes, the slow timescale and the fast timescale. The slow timescale is based on the intrinsic or Frenet coordinate system to obtain a fast and stable forward integration procedure of the aircraft equations of motion. Then, the movement of the centre of gravity is decoupled from the attitude dynamics over a time interval of the order of the long timescale. Therefore, two uncoupled inverse subproblems are formulated to solve the inverse simulation problem for the UAM system. Thus, the non-minimum phase characteristics can be forward simulated and would not influence the inverse simulation solving procedure.

Slow timescale

The state and control vectors for the slow dynamics are, respectively:

$$\boldsymbol{x}_s = (V, \chi, \gamma, \boldsymbol{R}) \tag{2}$$

$$\boldsymbol{u}_s = \left(\bar{\alpha}, \bar{\beta}, \bar{\mu}, \theta_0\right) \tag{3}$$

where $\bar{\alpha}, \bar{\beta}, \bar{\mu}$ can be regarded as pseudocontrols in the slow timescale inverse simulation process.

Eq. (2) can be used to combine with multiple flight trajectory descriptions, and then the inverse simulation method is applied here to calculate the time history of $\boldsymbol{u}_s$.

Fast timescale

In the fast timescale, the state and control vectors are shown below:

$$\boldsymbol{x}_f = (\bar{\alpha}, \bar{\beta}, \bar{\mu}) \tag{4}$$

$$\boldsymbol{u}_s = \left(\theta_{1s}, \theta_{1c}, \theta_T\right) \tag{5}$$

Combining Eqns (2-5), the fast timescale dynamics characteristics are required to track the pseudocontrols as computed in the outer solution. Meanwhile, in order to avoid a discontinuity in the vehicle angular velocity at the interface between each slow timescale calculation point, the commanded attitude in the fast time scale is given the following dynamics

$$\ddot{\boldsymbol{u}}_s + 2\omega_n \varsigma \dot{\boldsymbol{u}}_s + \omega_n^2 (\boldsymbol{u}_s - \boldsymbol{u}_{Des}) = 0 \tag{6}$$

where $\boldsymbol{u}_{Des}$ is the pseudocontrols in the next time step in the slow timescale, and ω_n and ζ are the bandwidth and damping coefficient to smooth the control inputs and avoid discontinuity. The values of these two parameters depend on the vehicle's flight dynamics characteristics.

C. Automatic differentiation embedded TTI inverse simulation

Different parameters should be determined in the TTI inverse simulation process, including the slow and fast timescale time interval and the bandwidth and damping coefficient in Eq. (6). These parameters are dependent on the vehicle flight dynamics characteristics at each time step. In theory, the stability eigenvalues and eigenvectors and the control derivative matrices can be utilised to decide these parameters to ensure their calculation efficiency and accuracy, but in practice, it is time-consuming to calculate the relevant parameters using the traditional modelling method.

The automatic differentiation (AD) based modelling method provides an alternative method to determine the parameters in the TTI inverse simulation. One advantage of the AD-based modelling method is the capability to output the stability and controllability matrices without any additional time cost, allowing the inverse simulation algorithm to adjust relevant parameters during the calculation. Therefore, the improved TTI inverse simulation process is shown below

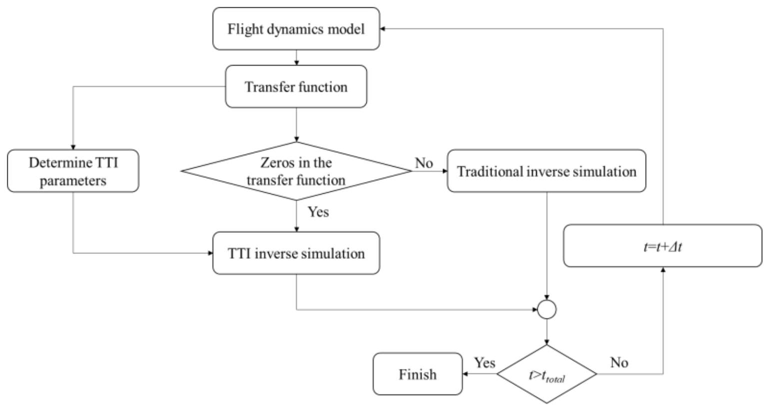


Fig .4 AD embedded TTI inverse simulation procedure

By combining with the AD algorithm, the TTI inverse simulation can autonomously change the time step and calculation procedure based on the flight dynamics characteristics at the local time step. Therefore, both calculation efficiency and accuracy can be enhanced.

Meanwhile, the non-minimum phase systems, which impede the application of the traditional inverse simulation method, are decoupled by the TTI algorithm. Therefore, the inverse simulation can be utilised in most aircraft manoeuvre control input estimations. Thus, with the incorporation of the TTI and the automatic differentiation, the inverse simulation can be utilised for the autonomous system and autopilot system development for UAM vehicles.

D. Trajectory Definition

The trajectory in this research was developed based on the landing manoeuvre defined in the rotorcraft handling qualities requirement, ADS-33 [10]. Thus, the mathematical description of the manoeuvres can be expressed using the following equations:

$$z_e(t) = h - h[6(\frac{t}{t_m})^5 - 15(\frac{t}{t_m})^4 + 10(\frac{t}{t_m})^3] \tag{7}$$

$$\ddot{x}_e(t) = \begin{cases} -a_{\max}[6(\frac{t}{t_1})^5 - 15(\frac{t}{t_1})^4 + 10(\frac{t}{t_1})^3], t < t_1 \\ -a_{\max}, t_1 \le t < t_m - t_1 \\ -a_{\max} + a_{\max}[6(\frac{t}{t_m})^5 - 15(\frac{t}{t_m})^4 + 10(\frac{t}{t_m})^3], t \ge t_m - t_1 \end{cases} \tag{8}$$

$$\dot{\psi}(t) = 0 \tag{9}$$

$$\dot{y}_e(t) = 0 \tag{10}$$

where x_e, y_e, and z_e represent distances in the earth coordinate, respectively; h is the initial altitude; $a_{\max}$ is the maximum acceleration in the X direction; t_m is the ending time of this manoeuvre; ψ is the yawing angle; t_1 is used to adjust the aggressiveness of the manoeuvre, which is set based on the flight dynamics characteristics of this vehicle.

The mathematical description derived from Eqns (7-10) could ensure that the velocities in the X and Z directions are equal to zero when the vehicle reaches the landing spot. Meanwhile, $a_{\max}$ in Eq (8) is determined by s, the distance between the vehicle and the nearest landing spot, and the flight performance limits.

This research will use the tiltrotor aircraft as an example to indicate the safety assessment, and the tiltrotor is required to land in helicopter mode (i.e., the nacelle incidence angle is equal to zero degrees). Thus, in the landing manoeuvre, the nacelle incidence angle is set following Eq. (11).

$$\dot{\beta}_m = \begin{cases} -\dot{\beta}_{m,\max}, \beta_m > 0 \\ 0, \beta_m = 0 \end{cases} \tag{11}$$

where $\dot{\beta}_{m,\max}$ is the maximum nacelle incidence angular velocity, which is 6 Deg/s for the example vehicle.

Meanwhile, the conversion mode is critical for the UAM vehicle as the flight dynamics characteristics are changed significantly. The pilot also needs a good Visual Cue Rating (VCR) to observe the surroundings to ensure safety. However, the deceleration mode always requires the vehicle to increase the pitching angle, which has a side effect on the pilot's view. Thus, the flight trajectory during the conversion is defined as follows.

$$z_e = 0 \tag{12}$$

$$\dot{\theta} = 0 \tag{13}$$

$$\dot{\psi}(t) = 0 \tag{14}$$

$$\dot{y}_e(t) = 0 \tag{15}$$

According to Eqns. (11-15), the flight trajectory ensures the vehicle maintains an ideal attitude during the conversion mode. Meanwhile, because the rotor-nacelle system is rolling back, the tangent deceleration is still increasing across the regime, and consequently, the forward speed is going down during the conversion. Then, the vehicle will follow the flight trajectory of Eqns. (7-10) after the nacelle incidence is equal to zero. However, the forward acceleration is no longer equal to zero when the nacelle angle is reduced to zero. The corresponding Eq. (8) needs to be revised as follows.

$$\ddot{x}_e(t) = \begin{cases} a_{ori} - (a_{\max} - a_{ori})[6(\frac{t}{t_1})^5 - 15(\frac{t}{t_1})^4 + 10(\frac{t}{t_1})^3], t < t_1 \\ -a_{\max}, t_1 \le t < t_m - t_1 \\ -a_{\max} + a_{\max}[6(\frac{t}{t_m})^5 - 15(\frac{t}{t_m})^4 + 10(\frac{t}{t_m})^3], t \ge t_m - t_1 \end{cases} \tag{16}$$

where a_{ori} is the forward acceleration when the nacelle incidence is reduced to zero.

RESULTS AND ANALYSIS

A. Normal landing in the helicopter mode

Fig 5 shows the landing control inputs of the tiltrotor aircraft in helicopter mode, where the initial speed is 60 m/s.

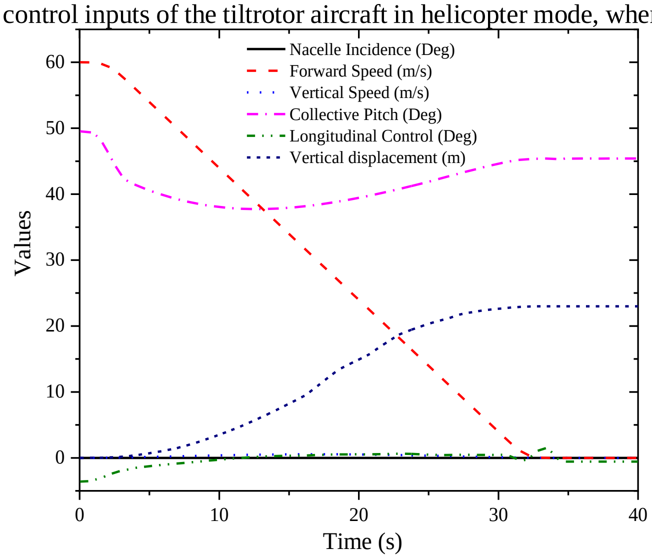
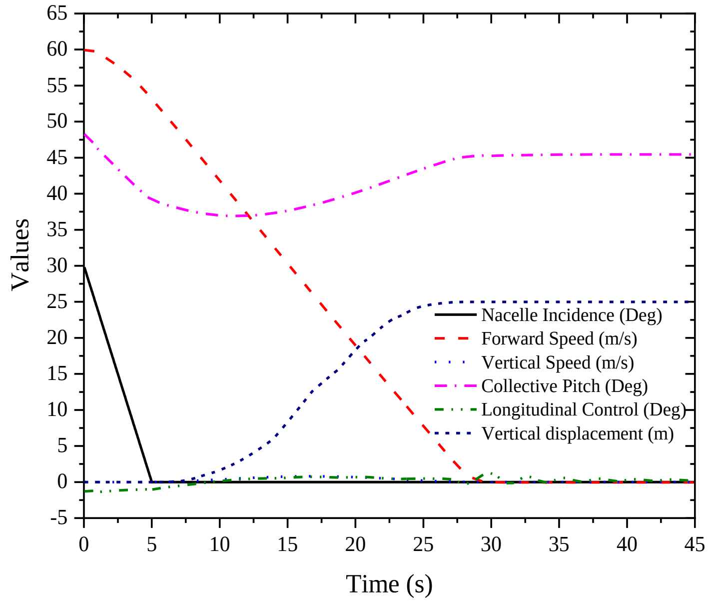


Fig. 5 Normal landing in the helicopter mode

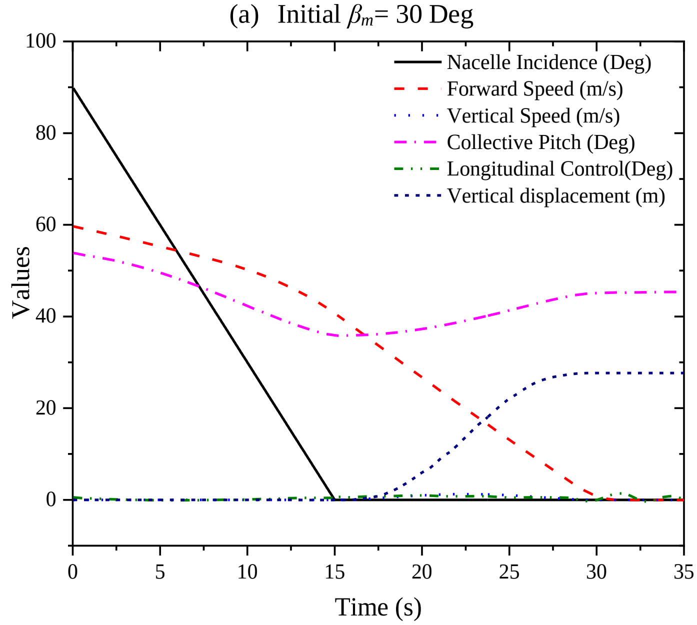
Fig. 5 indicates that the control input and flight states results in the helicopter mode are similar to that of the traditional aircraft. Meanwhile, it should be mentioned that the control oscillation in the longitudinal is because of the aerodynamic interference between the rotor and other components (i.e., fuselage, wing, and tailplane). Also, the initial forward speed, 60 m/s, is relatively high for the helicopter mode, which makes the trimmed pitching angle up to -15 Degrees. This phenomenon leads the tailplane to experience nonlinear aerodynamic characteristics, reducing the handling qualities. The rotor wake geometry tilts backwards with forward speed decreases. Thus, the effect of this aerodynamic interaction on the flight dynamics and corresponding control input calculated from the inverse simulation demonstrated significant non-linearity.

B. Normal landing in the conversion mode

Fig 6 shows the normal landing control input and flight state results in the conversion mode, in which the nacelle incidence angles are set to 30 Degrees and 60 Degrees, respectively, and the initial forward speed is 60 m/s.



(a) Initial β_m= 30 Deg



(b) Initial β_m= 60 Deg

Fig. 6 Normal landing in the conversion mode

According to Fig.6, the landing time in the conversion mode is similar to that in the helicopter mode. This is because that tilting back the nacelle would provide significant deceleration to the vehicle, allowing the forward speed to reduce continuously across the manoeuvre. Meanwhile, the longitudinal control channel's handling qualities are improved in the conversion mode compared to the helicopter mode. This is because the initial forward speed, which is 60 m/s, is far away from the margin of the conversion envelope of this vehicle, and the initial pitching attitude is close to zero in the conversion mode. That makes the aerodynamic characteristics of the tailplane and other components more linear. Also, the control oscillation still happens in the low-speed regime of the conversion mode due to aerodynamic interference and the lack of stability at this flight range.

C. Normal landing in the fixed-wing mode

Fig. 7 shows the normal landing procedure of the exampled vehicle during the fixed-wing mode (β_m= 90 Deg), in which the initial forward speed is still 60 m/s.

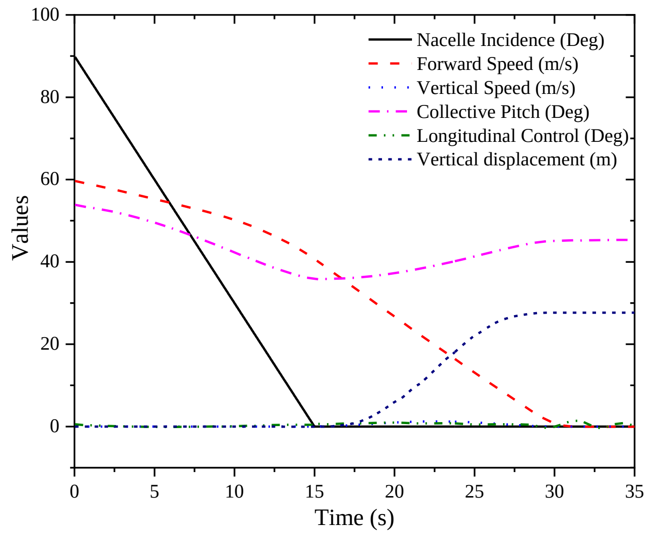
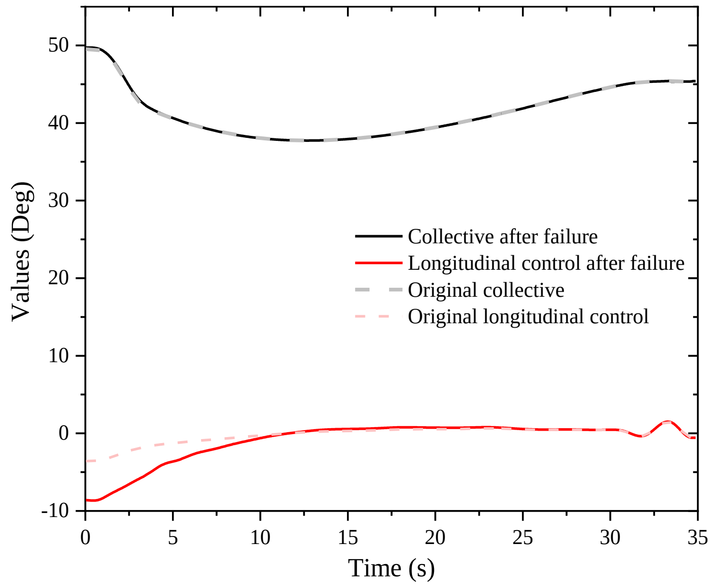


Fig. 7 Normal landing in the fixed-wing mode

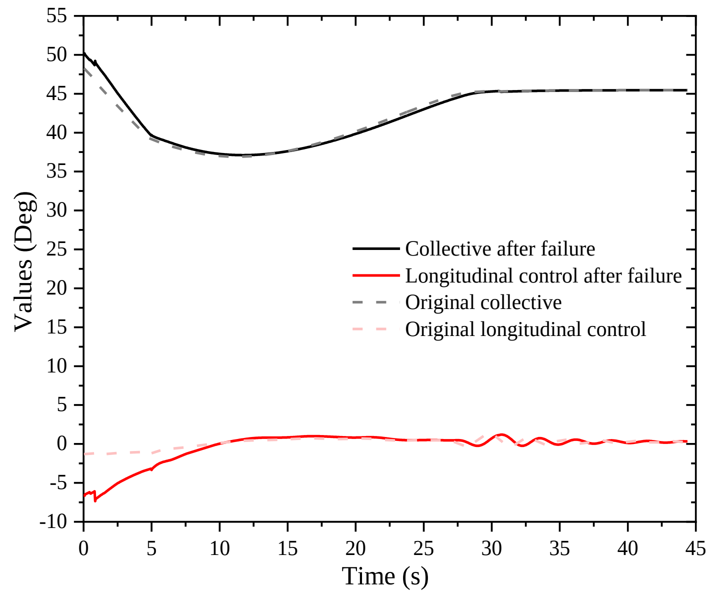
Compared to the fixed-wing mode results with other modes, the handling qualities are not degraded significantly, especially in the longitudinal channel. This is due to the flight trajectory we defined in the Eqns. (12-15) which ensures a smooth aerodynamic atmosphere across the transition procedure. Also, the landing manoeuvre can be finished in 30 seconds, which is similar to the landing strategy in other modes.

D. Emergency case: Elevator struck at a given value

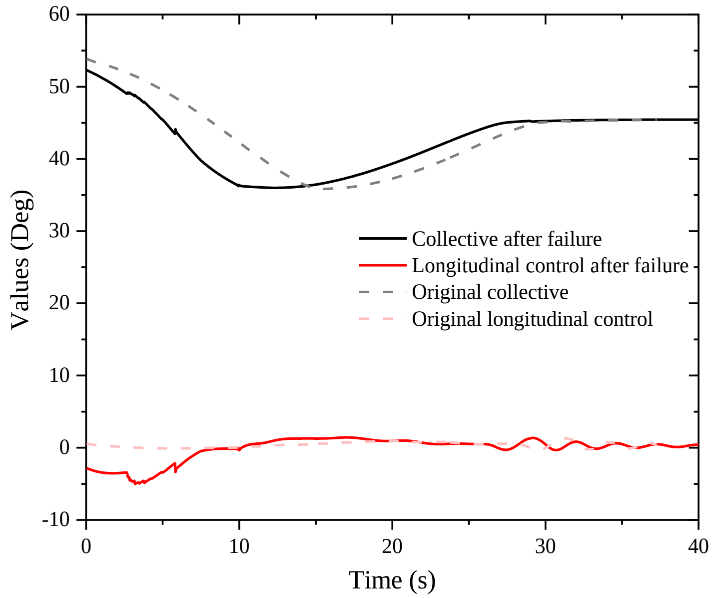
In this section, a case study is implemented to investigate the safety characteristics of the exampled UAM vehicle in an emergency case. In this emergency case, the elevator is assumed to be struck at a given value, zero, across the flight range. Then, the aircraft will perform a landing considering the malfunctioning elevator. Thus, the control inputs during the emergency landing in different nacelle incidence angles are shown in Fig.8, in which the corresponding normal landing control actions are also added to these figures as a comparison.



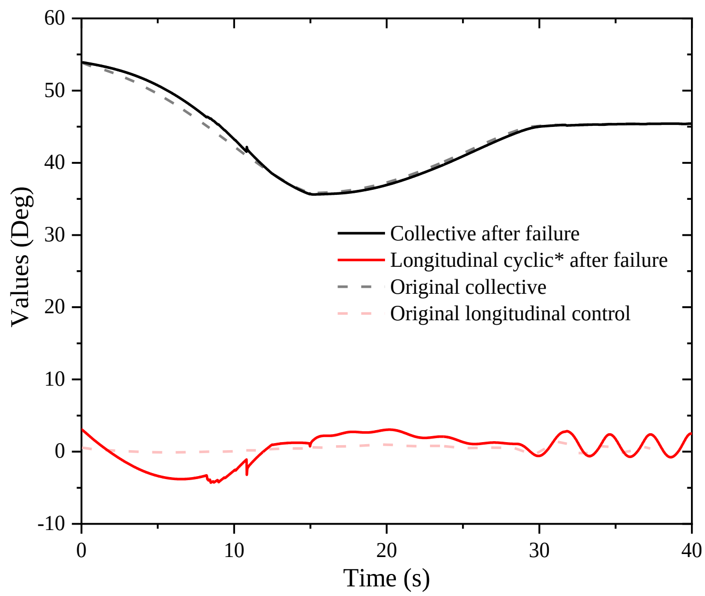
(a) Helicopter mode



(c) Conversion mode (Initial β_m= 30 Deg)



(c) Conversion mode (Initial β_m= 60 Deg)



(d) Fixed-wing mode

Fig. 8 Control inputs during the emergency landing

According to Fig. 8, the elevator malfunction would not influence flight safety in the helicopter and conversion modes. The nacelle incidence angle determines the rotor longitudinal cyclic and elevator control allocation according to the setting of the example vehicle. The cyclic control will be phased out when the vehicle is converted to the fixed-wing mode. When the vehicle is in helicopter mode, the longitudinal control is directly related to the longitudinal cyclic. Thus, although the elevator malfunction may cause additional control input, which may exceed the control limit, the vehicle can still achieve a successful, safe landing.

When the vehicle is in the conversion mode, the vehicle is more struggling to control the pitching attitude due to the lack of control power. However, the control power increases as the nacelle incidence angle reduces. Thus, the handling qualities are improving with time development. Meanwhile, as the tailplane with a changeable elevator can provide some lift to the vehicle, the elevator malfunction can lead to an additional change in the collective pitch results slight.

When the exampled vehicle is in the fixed-wing mode, the vehicle cannot achieve a safe landing considering the elevator malfunction. This is because the elevator is the only control channel used to provide the pitching control moment at this flight range. In reality, it would be very challenging for the UAM vehicle to recover from the elevator malfunction as the longitudinal cyclic is washed out at this flight range.

Thus, in order to assess the safety and handling qualities in the fixed wing mode, the control allocation strategy has to be changed. The longitudinal cyclic is re-introduced here as an additional control input for the pitching channel, and its time history is shown in Fig. 8 (d). This figure shows that the longitudinal control changed significantly to provide the required pitching moment across the flight time. Meanwhile, the longitudinal control (rotor cyclic) oscillation amplitude is much higher than that in the normal case due to the lack of control power.

CONCLUSIONS

In this research, a universal flight simulation model was developed for UAM vehicles to investigate their flight dynamics, handling qualities, and flight safety. Meanwhile, a Two-Timescale-Integration method incorporated inverse simulation method is developed to tackle the non-minimum phase characteristics that may happen during the UAM flight. This method further improves the feasibility of the inverse simulation method to allow it to be capable of investigating all manoeuvres. The conclusions of this research are shown as follows.

1) The flight dynamics model is fully developed and incorporated into the MAVERIC multi-agent simulation engine. The model can be used to simulate and assess the flight dynamics characteristics of different UAM vehicles. The aerodynamic interaction between different components in various flight ranges is considered in the modelling method to improve its accuracy.
2) A TTI embedded inverse simulation is developed incorporating the automatic differentiation method to improve its feasibility for different scenarios. The improved approach allows the non-minimum phase characteristics to be calculated with satisfactory accuracy and computing efficiency.
3) The exampled tiltrotor-like UAM is utilised to evaluate the feasibility of the modelling and novel inverse simulation. Flight status and controls in the normal landing and pop-up manoeuvre of different flight modes are calculated and analysed.
4) The normal landing results indicated that developed methods could be utilised to investigate the UAM flight dynamics and handling qualities in different flight ranges, especially for the system with non-minimum phase characteristics. The emergency landing calculations demonstrated that the exampled UAM could land safely with elevator malfunction in helicopter and conversion modes. However, elevator malfunction would lead the vehicle to struggle to land in the fixed-wing mode. Thus, the pilot needs to have priority to controlling the longitudinal cyclic across the flight to ensure vehicle safety, which is vital in the fixed-wing mode.

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