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Simulation verification of Flight Control of a tilt tri-rotor UAV Using X-plane

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Abstract: In order to realize the rapid verification of the control algorithm of the tilt tri-rotor UAV, this paper presents the design and implementation of the SIL(software in the loop) simulation system using X-plane software. Firstly, According to the actual parameters of the designed tilt tri-rotor UAV, a full scale digital model that can simulate actual flight dynamics is designed by Plane Maker. Secondly, the flight control scheme consists of mode transition strategy, hybrid controller and control allocation is illustrated and carried out using Matlab/Simulink. Then, using UDP protocol, the UAV model based on X-Plane and the controller based on MATLAB / Simulink are combined to form the SIL simulation system. Finally, the flight simulations are finished using the SIL system, and the results show that the designed simulation system is suitable for the verification of the flight control algorithm of the tilt tri rotor UAV.

Key Words: SIL simulation, tilt tri rotor UAV, flight control, X-plane

1 Introduction

Combining the characteristics of the multi rotor UAV and the fixed wing UAV, the tilt rotor UAV(TRUAV) has the advantages of long flight time, high speed and flight efficiency, while reducing the requirements for the take-off and landing sites. It has great application prospects in military applications as well as in civil fields [1]. Therefore, it has become a hot topic in the research field of UAV platform in recent years. According to the rotor number, the tilt rotor UAV can be divided into two types: Dual-TRUAV and Multi-TRUAV[2]. The Engle eye UAV is the representative and the first practical application of Dual-TRUAV[3]. However, it has the disadvantages of the complex tilt mechanism and serious interference between rotors and wings. To avoid this, many countries began to propose various Multi-TRUAV[4-6], which open another door for the development of technology and application of tilt rotor UAV.

For the Multi-TRUAVs, the mechanical structure is simplified. However, with the increase of actuators, the complexity of the controller design will increase. Especially in the transition mode, the aerodynamic characteristics of the Multi-TRUAVs change with the flight speed and the tilt angle. If the flight controller is not well designed, it easily cause the problem of large attitude shaking and height drop even flight instability, resulting in flight accidents. Therefore, how to achieve stable flight in transition mode is the most important research direction of the Multi-TRUAVs, which has been widely concerned by researchers. Because of the high risk for conducting a flight experiment, it is a very important method to verify the performance of the control algorithm in transition mode by simulations, before applying the designed controller to the actual flight.

There are two kinds of simulation methods for aircraft control algorithm verification: mathematical model based and software based[7]. The mathematical model based methods depend on building the accurate system model, including model parameters and aerodynamic parameters, etc. However, this kind of method needs great cost in obtaining model parameters and aerodynamic parameters, thus it will take a long time from modeling to flight simulation. With the development of X-Plane and other simulation software, the software based methods have been used to verify the flight control algorithm widely. These simulation software do not need the mathematical model and aerodynamic parameters, and has a large number of interfaces and good visualization effect, which is suitable for the rapid verification of the aircraft control algorithm [8,9]. Adriano et al.[10,11]developed a HIL simulation system consists of an academic autopilot and X-Plane which was used to simulate the aircraft dynamics, sensors and actuators. By using the HIL simulation system, the attitude control scheme of the fixed-wing was proposed and verified. Li [7] design a SIL simulation using X-Plane to develop the rapid prototyping and verification of cruise missile. Zhang[12] developed a test system including autopilot and X-Plane to verify the control structure and the results show that the controller is also effective in the actual flight.

Due to the variable structure of the Multi-UAV in transition mode, the aerodynamic model is too difficult to be acquired. Thus, the software based method is suitable to verify the flight control algorithm of Multi-UAV. In this paper, a tilt tri-rotor UAV is proposed. This kind of TRUAV has three rotors distributed in a triangle structure，and all rotors can be fully tilted. In order to promote the prototype design and control performance verification of the tilt tri-rotor UAV, this paper explores a SIL simulation by using X-Plane. The full scale model of the tilt tri-rotor which can be used to simulate the actual flight dynamics is developed using Plane Maker. A complete flight control scheme is also developed. And the control scheme is realized using

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Matlab/Simulink. Thus, the SIL simulation system of the tri tilt rotor UAV is completed. Through the results of the SIL simulations, the flight performance can be verified for further promotion.

The paper is arranged as follows. Section 2 gives the description of the tilt tri-rotor UAV. In Section 3, the accurate 3D flight model of the prototype is designed using Plane Maker. Section 4 details the control scheme. In Section 5, the SIL simulation system is developed, and the flight simulation is completed. Finally, the conclusion and future research work are outlined in Section 6.

2 Description of Tilt Tri-rotor UAV

The proposed tilt tri-rotor UAV is shown in Fig.1. The tilt tri-rotor UAV adopts the layout of conventional double tail support, which is widely used in UAV. The rotors are connected with the main structural parts to make the aircraft stable. The rear part uses the tail strut instead of the traditional fuselage, which can reduce the wetted area and ensure enough tail arm length. The rotor of the aircraft is composed of a 13×6 inch propeller and a brushless motor.

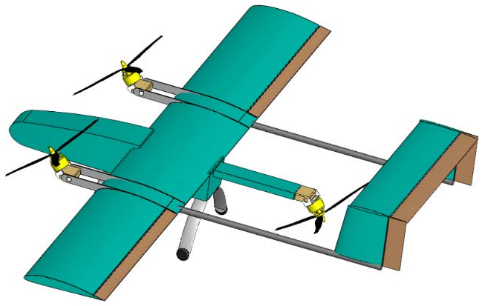

Fig.1 Prototyping of the proposed tilt tri-rotor UAV

Each rotor can be tilted by a designed tilt mechanism shown in Fig.2. The tilt mechanism is the most important part of the tilt tri-rotor UAV, including steering gear, link, mechanism support and motor nacelle. The steering gear is connected with multi links to drive the rotor, and the mode transition is realized through the tilt motion of the rotor. The two front rotors turn anticlockwise from top to bottom, and the tail rotor turns anticlockwise from bottom to top. In order to simplify the control strategy design, the tilt angle and the tilt speed of the three rotors are synchronized.

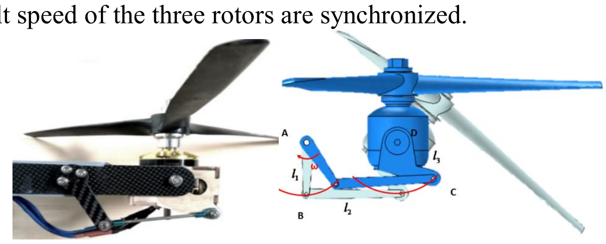

Fig.2 the tilt mechanism

The main parameters of the proposed tilt tri-rotor UAV are given in Table 1.

Table 1: main parameters of the tilt tri-rotor UAV

parameters	Value	parameters	Value
length	1.1m	Wing area	0.408m^2
weight	6kg	Aspect ratio	7.9
Wingspan	1.8m	Cruise speed	18m/s
Cruise time	1h	Payload	1kg

3 X-plane model implementation

For the tilt tri-rotor UAV, it is difficult to obtain the aerodynamic parameters, thus the flight simulation based on the mathematical model is not the suitable way for carrying out fast control algorithm verification. The X-plane software integrates the aerodynamic simulation function based on the "blade element" theory, and contains “Plane Maker” module by which the UAV can be modeled with precise physical dimensions and flight dynamics. Therefore, the simulation verification based on X-plane software can provide a high reliable simulation data. In this section, the digital mode of the tilt tri-rotor UAV is designed using Plane Maker.

3.1 Fuselage

The fuselage is the frame part of the UAV and viewed as the position reference of all other components. Using the geometric dimensions of the designed tilt tri-rotor UAV, the fuselage can be modeled by setting fuselage interface of Plane Maker (selecting “standard/fuselage”). The main parameters of the fuselage interface is given in Table 2. The UAV is of symmetrical structure, so the parameter setting is only about the cross-sectional view of the left/right half plane of the fuselage along the longitudinal direction.

Table 2: Fuselage parameters

parameters	Value
length	4.0ft
number station	8
number radii/side	9
body radius	0.3ft
Body coefficient of drag	0.05

3.2 Wings

The tilt tri-rotor UAV adopts the typical layout of the fixed wing UAV with two tail supports. The wings include the main wing, the horizontal tail and the vertical tail. The aerodynamic rudder surfaces to be controlled include ailerons, elevators and rudders.

The main parameters of the wings are given in table 3.The position in Table 3 represents the position of the horizontal / vertical tail from the center of gravity.

Table 3: the wings parameters

Main wing			
Half of Wingspan	2.7ft	chord length of Wing root	0.79ft
mounting angle	2°	chord length of Wingtip	0.66ft
horizontal tail			
Half of Wingspan	0.7ft	chord length of Wing root	0.3ft
chord length of Wingtip	0.3ft	position	(2.4ft,0.0ft,0.6ft)
vertical tail			
Half of Wingspan	0.62ft	chord length of Wing root	0.48ft
chord length of Wingtip	0.3ft	position	(2.2ft,0.7ft,0.0ft)

According to the parameters in Table 3, the wings are designed in plane maker by selecting “standard/wings”. The airfoil of the main wing is set to be NACA2412, and the airfoil of the horizontal/vertical tail are chosen as NACA0012(selecting expert/airfoils). According to the proportion of each control surface to the winds of the aircraft, the size and number of the corresponding rudder, elevator and aileron can be designed by selecting "standard/control geometry". In addition, the angle limit and the change rate of the rudder surface are set to be 30° and 60°/s, which is consistent with the actual situation.

3.3 Motors and propellers

The tilt tri rotor UAV has three rotors, and each of the rotor composes of a brushless motor and a 13×6 propeller. The parameters of the motor and the propeller are given in Table 4, which is designed by selecting "standard/engine in Plane Maker.

Table 4: the parameters of the motor and propeller

parameters	Value	parameters	Value
rotating speed	10000rpm	Radius	0.54ft
Right Rotor Position	(0.72ft,0.85ft,0.0ft)	chord length of Wingtip	0.025ft
left Rotor Position	(0.72ft,-0.85ft,0.0ft)	chord length of Wing root	0.07ft
Rear Rotor Position	(-1.38ft,0.0ft,0.0ft)		

3.4 Tilting

The function of tilting is achieved by selecting "expert/vtol or helo controls", which is shown in Fig.3. The maximum tilting angle and tilting rate are set to be 100° and 90° /s.

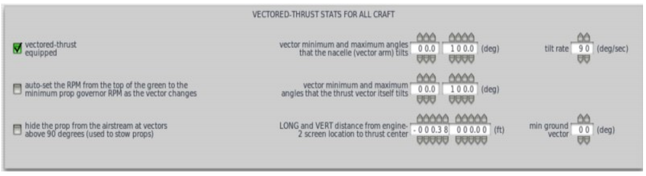

Fig.3 Tilt setting

Based on the above design process, the final digital model of tilt tri-rotor UAV in X-plane can be obtained, which is shown in Fig.4.

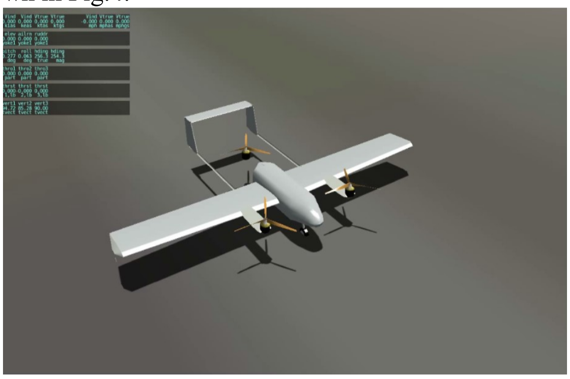

Fig.4 the digital model of the tilt tri-rotor UAV in X-plane

4 Flight Control

In this section, the flight controller for the tilt tri-rotor UAV is introduced. The design of flight controller consists of three parts: the mode transition strategy, hybrid controller and control allocation.

4.1 Mode transition strategy

The tilt tri-rotor UAV has three flight modes: the hover, transition, and forward modes. As for the hover and forward modes, the controller has been wildly studied and many mature controllers can be directly adopted in the two flight modes. The transition mode is a special intermediate state of the tilt tri-rotor UAV. By changing its structure or attitude, the aircraft can switch between the hover mode and forward mode. In the transition mode, the system model is complex and variable, the controller design is the key technology of the tilt tri-rotor UAV. The first problem to be solved in the design of modal transition strategy. The rotor controller and the fixed wing controller are both effective to the flight control in the transition mode. In order to ensure the attitude and altitude stability, it is necessary to design a reasonable mode transition strategy.

The mode transition process of the tilt tri-rotor UAV can be shown in Fig.5, which mainly includes the forward switching and the reverse switching. Forward switching refers to the transition from the hover mode to the forward mode, and the thrust vector direction changes from vertical to forward; reverse switching refers to the transition from the forward mode to the hover mode, and the rotor tilts in reverse direction.

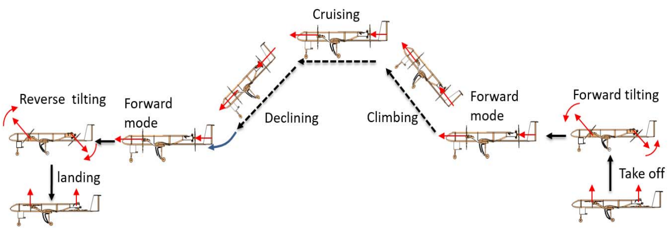

Fig.5 mode transition process of the tilt tri-rotor UAV

Reliable mode transition strategy is helpful to improve the stability of flight control. The transition mode is an acceleration flight process with variable structure. In this process, the aerodynamic characteristics are very complex, and the high control performance of the aircraft is required. A reasonable and simple transition strategy is helpful to reduce the control difficulty, and improve the reliability of mode transition. Commonly, the mode transition strategy can be divided into continuous switching and segmented switching.

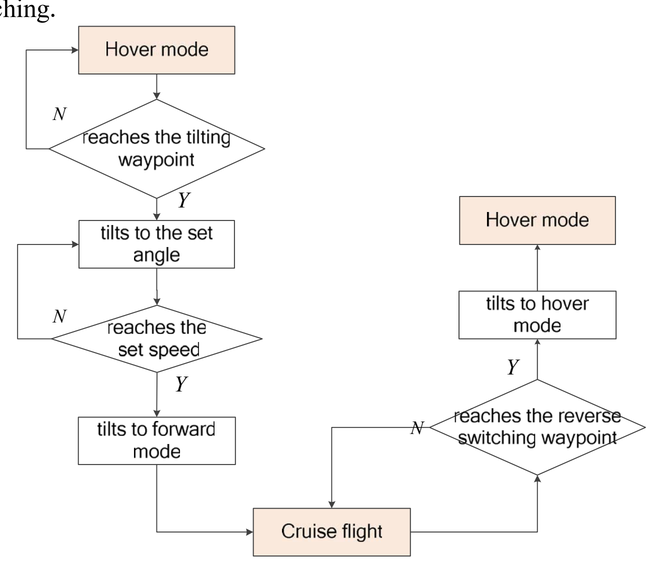

Fig.6 the block diagram of segmented switching

Because the aerodynamic force of the tilt tri-rotor UAV in transition mode is difficult to obtain accurately, the segmented switching strategy is widely used in practice. The main idea of the strategy is to divide the transition process into two stages. In the first stage, the UAV takes off vertically and keep hovering. Then, all the rotors tilts to a certain angle, and the aircraft will accelerate forward under the forward component of the rotor tension; in the second stage, when the speed reaches the set value (generally stall speed, for example), the rotors directly tilts to the final angle to complete the mode transition. The transition process is relatively simple. For the reverse switching, when the aircraft receives the reverse switching command, the rotors directly rotates to the hover mode if the attitude is stable. The specific block diagram of segment switching strategy is shown in Fig.6. In this paper, the segmented switching strategy is used in the controller design of the tilt tri-rotor UAV.

4.2 Hybrid controller

The tilt tri-rotor UAV has three flight modes. To reduce the difficulty of controller design, the hybrid control method is used to achieve good flight control in this paper. In hover mode, a multi rotor controller is designed. In forward mode, a fixed wing controller is designed. In the process of mode transition, the switching between the two flight modes is realized by adjusting the weight of the two controllers according to the weighting coefficient.

For the multi rotor controller and the fixed wing controller, it usually adopts a typical cascade feedback control structure. The position control is in the outer loop and the inner loop is the attitude control. Through making use of the internal physical relationship between the position control and the attitude control, this kind of control structure can achieve an effective position control by changing the body attitude. The input of the outer loop position controller is the desired position and the output is the desired attitude angle. Attitude control is the key part of the whole control system, which mainly realizes the stabilization control of the aircraft. Its control performance directly affects the tracking effect of the outer loop position. The input of the inner loop attitude controller is the desired angle and the output is the virtual control torque. The obtained virtual control quantity by the cascade control system is assigned to the rotors and the rudder surfaces, Based on this, it can realize the position and attitude control of the tilt tri-rotor UAV.

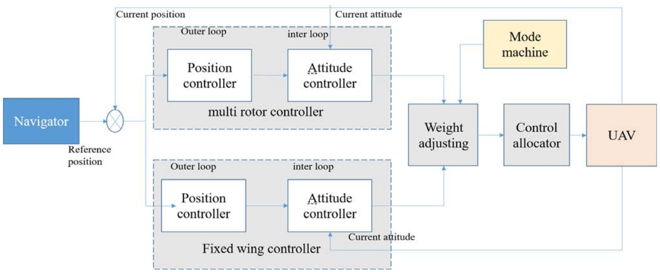

Fig.7 the block diagram of segmented switching

The block diagram of the hybrid controller is shown in Fig.7. All the position controllers and the attitude controllers in Fig.7 are carried out based on PID controller.

4.3 control allocation

The control allocation provides the mapping from the virtual control inputs to the manipulated inputs of the aircraft. It should be pointed out that the control allocation under the forward mode is the same as the traditional fixed-wing. Therefore, only on the control allocation in the hover mode and the transition mode are discussed.

a. control allocation in the hover mode

In hover mode, there are six control variables, including three motor speeds and three tilt angles. Reasonable distribution of rotation speed and tilt angle can achieve effective attitude and position control. The yaw is controlled by the differential of the two front rotor tilt angle, and the pitch, roll and height are controlled by the distribution of the three motor speed. Denote *R*, *P*, *Y*, *N* and *T* as the virtual control inputs calculated by the hybrid controller, *R* is directly linked to roll control, *P* is used for pitch control, *Y* is related to yaw control, the altitude is controlled by *T*, the flight speed is controlled by *N*.

For yaw control, the virtual control quantity is allocated to the tilt angle of the two front rotor by using formula (1),

$$\begin{cases} \alpha_1 = k * Y \\ \alpha_2 = -k * Y \end{cases} \tag{1}$$

where *k* is a positive coefficient, α_1 and α_2 is the tilt angle of the two front rotors .

By adjusting the rotating speed of the three rotors, the control of pitch, roll and height is realized. Formula (2) gives the relationship between the rotating speed of the three rotors and the virtual control inputs *R*, *P*, *T*.

$$\begin{bmatrix} \omega_1^2 \\ \omega_2^2 \\ \omega_3^2 \end{bmatrix} = \begin{bmatrix} -b*r_{1y}\cos\alpha_1 + d\sin\alpha_1 & b*r_{1y}\cos\alpha_2 - d\sin\alpha_2 & 0 \\ b*r_{1x}\cos\alpha_1 & b*r_{1x}\cos\alpha_2 & b*r_{3x}\cos\alpha_3 \\ b\cos\alpha_1 & b\cos\alpha_2 & b\cos\alpha_3 \end{bmatrix}^{-1} \begin{bmatrix} R \\ P \\ T \end{bmatrix} \tag{2}$$

where b and d is thrust coefficient and torque coefficient, respectively. ω_i is the rotating speed of the three rotors, α_3 is the tilt angle of the two rear rotor.

b. control allocation in the transition mode

According to the mode transition strategy shown in Fig.6, the control allocation in the transition mode can be divided into two stages named s1 and s2. In stage s1, the rotors tilts to a certain angle, only the multi rotor controller works and it adopts the same control allocation in the hover mode. In stage s2, taking the forward switching as an example, the flight speed first reaches the given value and continues to increase as the tilt angle increases. Therefore, the control efficiency of the rotors decrease while the control efficiency of the wings increase. The hybrid controller is adopted in stage s2. The weight of the multi rotor controller and the fixed wing controller is distributed.

For yaw control, the virtual control quantity is also allocated to the tilt angle of the two front rotor by adjusting the formula (1) to be

$$\begin{cases} \alpha_1 = \alpha_0 + k * Y \\ \alpha_2 = \alpha_0 - k * Y \\ \alpha_3 = \alpha_0 \end{cases} \tag{3}$$

where α_0 is the tilt angle which is relevant to flight modes, and $\alpha_0 = 0$ in the hover mode.

In the transition mode, only the attitude control is considered. Denote the weight coefficient of the multi rotor controller as η, then, the weight coefficient of fixed wing controller is $1-\eta$. By adopting the direct control allocation method, it can obtain the control allocation of the virtual control inputs R, P, N in stage s2 as

$$\begin{cases} br_{1y}(\omega_2^2\cos\alpha_2-\omega_1^2\cos\alpha_1) \\ +d(\omega_1^2\sin\alpha_1-\omega_2^2\sin\alpha_2+\omega_3^2\sin\alpha_3)=\eta R \\ b(\omega_1^2\cos\alpha_1+\omega_2^2\cos\alpha_2)r_{1x}+b\omega_3^2 r_{3x}*\cos\alpha_3=\eta P \\ -b\omega_1^2\sin\alpha_1-b\omega_2^2\sin\alpha_2-b\omega_3^2\sin\alpha_3-D=N \end{cases} \tag{4}$$

$$\begin{cases} P(1-\eta)=k_e\delta_e \\ R(1-\eta)=k_a\delta_a \end{cases} \tag{5}$$

Where D is the aerodynamic drag, δ_e is the elevator deflection, δ_e is the aileron deflection, and k_e and k_a is the corresponding rudder gain. By solving equations (4) and (5), the flight speed, roll and pitch can be controlled.

In the transition mode, the weight of rotor controller and fixed wing controller is a function of the airspeed. The control ability of the two controllers under different flight speeds is synthetically used to ensure the stability of the attitude and finally realize stable mode transition.

5 SIL Simulation system and Results

5.1 Simulation system

In order to verify the control algorithm, this paper constructs a SIL simulation system, in which the controller is realized by Matlab / Simulink, the tilt rotor UAV adopts the digital model based on Plane Maker of the X plane software, and the communication adopts UDP protocol. The SIL simulation system is shown in Fig.8.

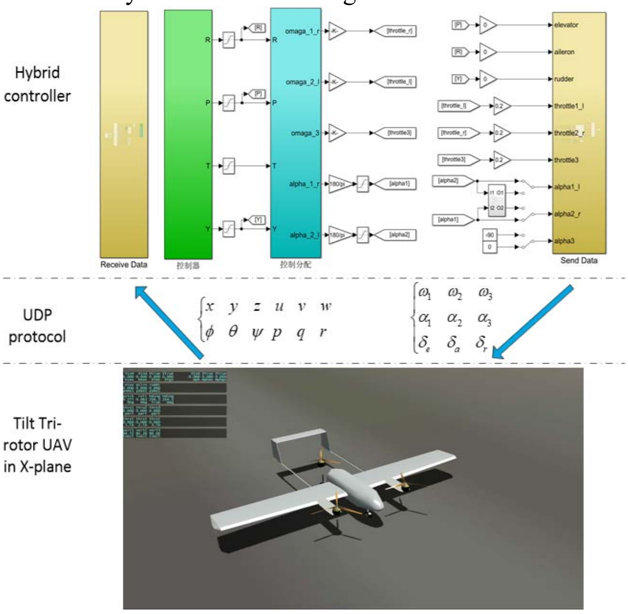

Fig.8 SIL simulation system

5.2 Simulation reslults

The simulation results obtained by using the SIL system are shown in this section. Fig.9 gives the computer screenshot of the actual simulation system.

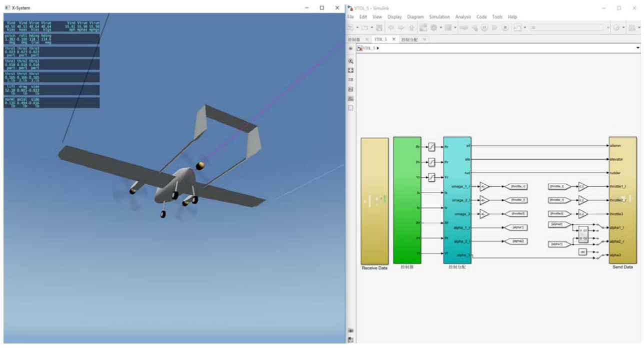

Fig.9 the interface of the SIL system

The simulation which contains the forward switching and reverse switching is completed within 23 seconds. In the first 10s, the aircraft takes off and climbs to the height of 30m under hover mode. The forward switching consists of stage s1 and s2 is completed within the next 6 seconds. Once the aircraft flights to the predefined altitude, it enters into the stage s1 and starts to accelerate. While the airspeed increases to the given value, the three rotors are tilted forward during stage s2, and the airspeed continues to increase to complete the forward switching. The reverse switching process is simpler than the forward switching, the rotors are shut down first and tilted backward to vertical position within 1s. The change of tilting angles that describes the whole flight process including the hover, transition, and forward modes are shown in Fig.10.

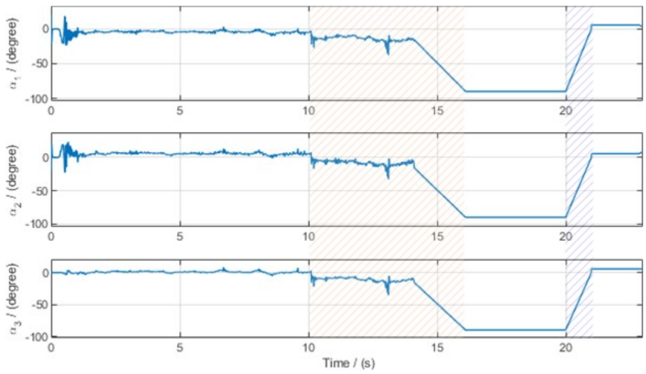

Fig.10 The change of three tilting angles

During the flight, attitude and altitude are two key aspects to reflect the control performance of the flight controller and mode transition strategy. The altitude in the simulation is shown in Fig.11. Note that the yellow shaded area is used to mark the forward switching, and the purple shaded area denotes the reverse switching.

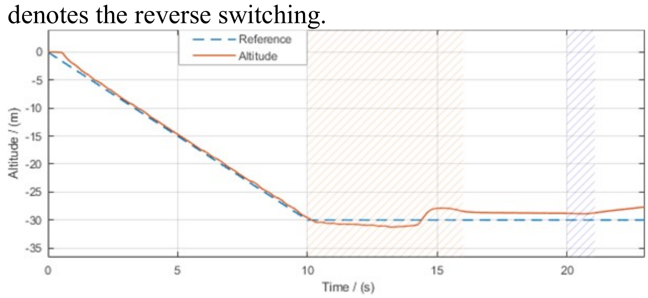

Fig.11 Altitude tracking results.

In the hover mode, the UAV gradually climbs to 30m. In the process of forward switching, there is a height change which is consistent with the actual flight. The maximum drop height is about 2m and the altitude is almost unchanged. The simulation result proves that the proposed control algorithm can effectively reduce the height change.

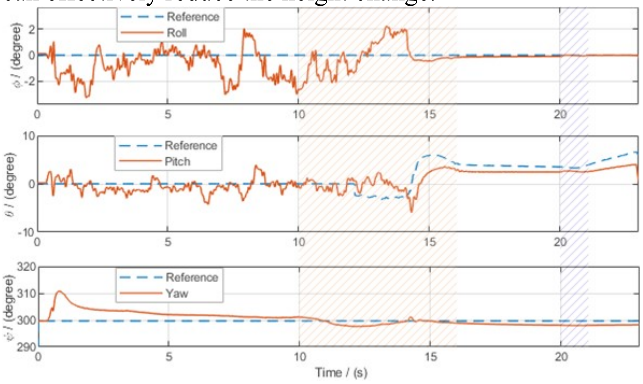

Fig.12 Attitude tracking results

The tracking results of attitude are depicted Fig.12. In the whole flight process, the attitude is well controlled. Even in the transition mode, the changes of roll, pitch and yaw angles are less than 10 degrees. The simulation results show that the proposed control algorithm can ensure the stable flight of the tilt tri-rotor UAV.

The X-plane software can quickly build the digital model of the tilt rotor UAV. By combining with the controller based on MATLAB/Simulink, it builds a SIL simulation system for the tilt tri-rotor UAV. Using the SIL simulation system, it can realize the rapid control performance verification of the tilt tri-rotor UAV.

6 Conclusion and Future Work

This paper focuses on the rapid simulation verification of the flight control of a tilt tri-rotor UAV. A SIL simulation system consisting of the UAV model based on X-Plane and the controller based on MATLAB / Simulink is built. Through the simulation flights of the tilt tri rotor UAV, it proves that the designed simulation system is effective. Taking the advantages of fast model building, good visualization effect and reliable simulation data, the present simulation method benefit to the preliminary design and rapid verification of flight control algorithm.

In the future work, we will implement the flight control algorithm in the autopilot and build the HIL (hardware in the loop) simulation system using X-Plane software. Then, further verification of the control algorithm can be finished in the HIL simulation system.

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