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Tailsitter VTOL Flying Wing Aircraft Attitude Control

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***Abstract*—This paper introduces a flying-wing tail-sitter aircraft which can switch between vertical flight mode (rotary-wing mode) and level flight mode (fixed-wing mode). Equipped with two propellers and two elevons, the aircraft can fly by controlling these four actuators. The aircraft uses a microcomputer and various sensors to stabilize the attitude and to switch modes on command. Using the transition logic, it can receive and act on the signal sent by operator at any time, whether it is to switch modes or to retract the command. Using the target angle calculation algorithm, the aircraft can adjust its pitch angle during transition. PID feedback is used for attitude control both in vertical mode and during the transition. Test results show that the aircraft have the advantages of helicopters and fix-wing airplanes. It can hover midair and does not need runway to take off, and it can fly in high speed in fixed-wing mode.**

***Keywords*—vertical takeoff and landing; flight mode transition; attitude control**

I. INTRODUCTION

VTOL (vertical takeoff and landing) UAV (unmanned aerial vehicle) is a combination of VTOL technology and UAV. It has both capabilities of a helicopter hover and VTOL, but also has features of fixed-wing aircraft speed and long range, at the same time, it also has the basic characteristics of UAVs in general, to meet the need of performing specific tasks [1]. Before VTOL technology, conventional UAVs mostly divided into two categories, one is a fixed-wing UAV, the other is the unmanned helicopter. The former's flight speed is relatively fast, and task radius is larger, but runway to takeoff makes it more limited when takeoff and landing at small landing site, the latter can be flexible on a small landing site, and can work for a long time hovering over the target, but also showed the inherent shortcomings - the flight is relatively slow, small tasks radius [2]. VTOL UAV developed on the basis of the two kinds of drones, it can both takeoff and landing in small landing site with limited movements and quickly fly to the target and hover over the target. At the same time, a range of large, cruising distance makes it possible to carry out a variety of specific tasks.

There are many different kinds of testing machines in the early development, including tiltrotor [3], tilting ducted [4], tailsitter [5], lift jet engine [6] etc. Many countries tried dozens of VTOL aircraft only in the 1950s, but most failed, representative models include XFV-1of United States and SC.1 of the United Kingdom. With the rapid development of military technology, especially aviation engine technology, the British Hawker Siddeley company successfully developed the world's first aircraft come into use, VTOL UAV AV-8 "Harrier jet".

Fig. 1. Tiltrotor aircraft.

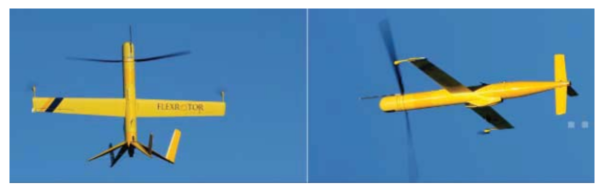

Fig. 2. Tailsitter aircraft.

Although VTOL has the advantages of both fixed-wing and helicopters, but it brought problems like complexity of structure, difficulty of control [4]. These factors have become the main reason for the slow development of VTOL aircraft after 1960s.

A kind of new VTOL brings VTOL field hope in the late 1980s. Through tilting the nacelles of wingtips, rotors of tiltrotor aircrafts, which are represented by the US V-22 Osprey, can switch between vertical and horizontal modes, it integrated the helicopter features with fixed-wing aircraft perfectly, and the actual aircraft flight performance proved that tiltrotor VTOL having a very promising.

In accordance with the thrust (pull) implementation, fixed-wing aircraft with vertical takeoff and landing capability is currently divided into two categories including tiltrotors (Fig. 1) and tail-sitter (Fig. 2).

This paper illustrates the characters and usefulness of the VTOL fixed-wing aircraft. Section II discusses the principles of the twin-engine flying wing aircraft and gives the definitions of attitude angles in the two modes. Section III introduces the components of the aircraft and gives the transition logic and the target angle calculation algorithm. Section IV presents the experimental results and Section V presents the conclusions.

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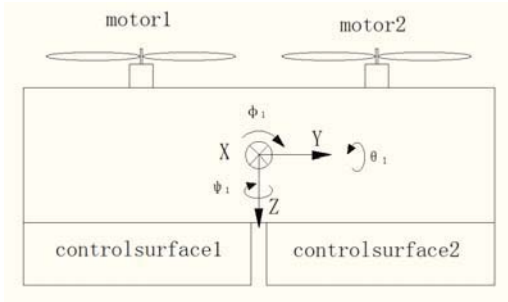

Fig. 3. Schematic diagram of the aircraft.

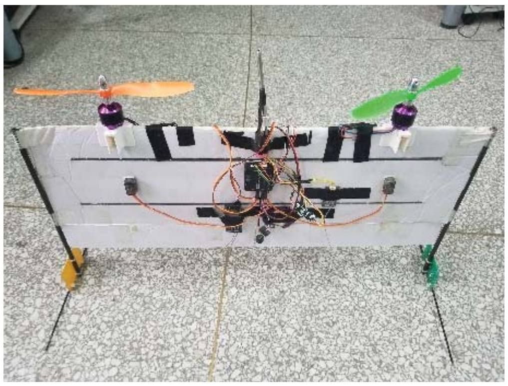

Fig. 4. Picture of real products.

II. PRINCIPLES OF TWIN-ENGINE FLYING WING AIRCRAFT

The aircraft structure diagram is shown in Fig. 3, and the real product is shown in Fig. 4. The fixed-wing fuselage's layout is blended wing body layout, on the top of the fuselage two brushless motors are installed for providing the hover lift in rotary-wing mode and pull in fixed-wing mode, at the bottom of the fuselage two control surfaces are installed for controlling the vehicle attitude.

To use the rotary-wing mode as a reference, the establishment of the body coordinate system F: OXYZ, the original point is the aircraft's center of gravity, OX axis perpendicular to the wing plane pointing to forward (perpendicular to the paper inwards), OY axis pointing to right in wing plane, OZ axis in wing plane perpendicular to the plane OXY pointing down.

The vehicle mounted two brushless motors side by side in the top of the fuselage, drives a pair of positive and negative propellers to provide an upward pull, balance each other their respective reaction torque, via motors differential rotation to achieve the body rotate around the OX axis (roll, right and left movement), define the right roll as the positive direction of roll angle; in addition, the surfaces at bottom of the body are two independent controlled control channels, two differential rudder deflection about OX axis's positive and negative directions can achieve body rotate around OZ axis (yaw control), define the right yaw as the positive direction of yaw angle; two simultaneous rudder deflection about OX axis's positive or negative direction can achieve body rotate around OY axis (pitch, front and back movement), define backward flight as the positive direction of a pitch angle.

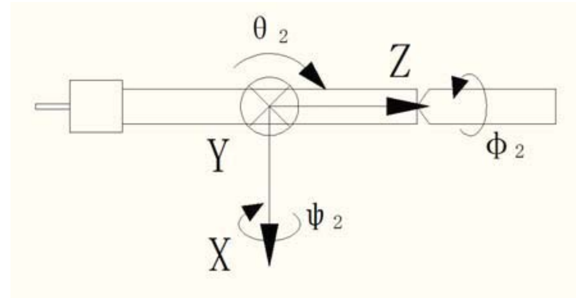

Fig. 5. Attitude angle definition in fixed-wing mode.

A. *Attitude Angle Definition in Rotary-wing Mode (Fig. 3)*

Pitch angle θ1: the angle between the OX axis and the horizontal plane, backward flight as the positive, range (-90 °, 90 °);

Yaw angle ψ1: the angle between north and the projection in horizontal of OX axis, projection in horizontal plane at the north east is positive, range [-180 °, 180 °];

Roll angle φ1: the angle between the horizontal plane and OY axis, the right motor sink, the left motor raise is positive, the range of (-90 °, 90 °).

The body rotate 90 degrees around the OY axis in the negative direction, the aircraft will transit into fixed-wing mode, the principles of body rotate around the three axis in fixed-wing mode is same as the rotary-wing mode, however, relative to traditional fixed-wing aircraft, roll angle of rotary-wing becomes yaw angle of fixed-wing (change nose pointing in airplane mode), yaw angle of rotary-wing becomes the roll angle of fixed-wing (and opposite), pitch angle in the two mode are similar, they are both rotate around OY axis (but there is a difference of 90 degrees), the motors provide lift in rotary-wing mode while provide pull for forward movement in the fixed-wing mode, the lift of the fixed-wing is produced by the relative motion between are and the wing.

B. *Attitude Angle Definition in Fixed-wing Mode (Fig. 5)*

Pitch angle θ_2: the angle between the plumb line and OX axis, the nose up is positive, Range (-90 °, 90 °), easy to see $\theta_2 = \theta_1 - 90$ °;

Yaw angle ψ_2: the angle between OZ-axis negative direction project in horizontal plane and the north, the projection at the north east is positive, range [-180 °, 180 °];

Roll angle φ_2: The angle between the Y axis and the horizontal plane, Sink on the right wing, Left wing elevation is positive, Range (-90 °, 90 °).

C. *Flight Process*

Aircraft takes off in the rotary-wing mode, it can fly like a helicopter, after obtaining the transition command, aircraft get into the transition flight mode, two control surfaces deflect synchronously to the positive direction of OX axis, body get rotation torque around the Y axis and lean forward and begin to accelerate and accumulate airspeed, until it reaches the vicinity of the pitch angle of -90 degrees and accumulate enough airspeed, then the aircraft complete the transition basically, the

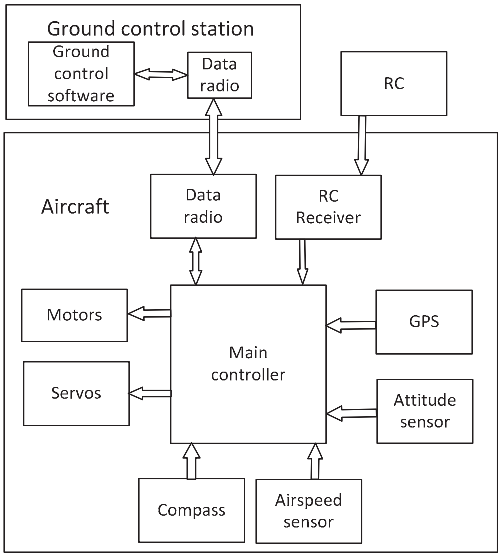

Fig. 6. Aircraft system components.

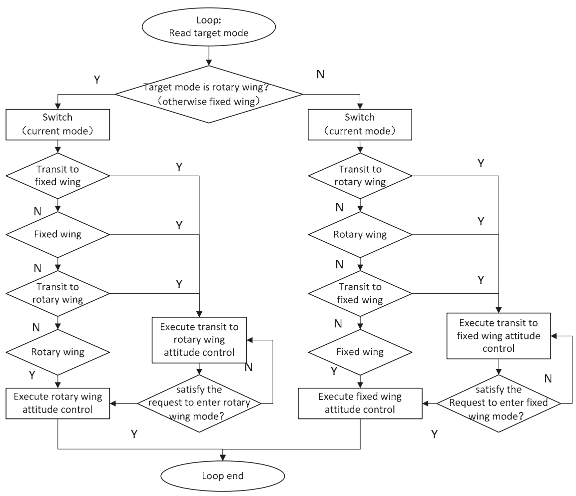

Fig. 7. Logic of transition.

aircraft will enter fixed-wing flight mode. In this process, the principle of the body to obtain the three axis angle motion is unchanged, but the definition of roll angle and yaw angle is different in the two control logics, so we need to achieve some conversion in the control logic. The transition from fixed-wing mode to rotary-wing mode is the inverse of the transition from the rotary-wing to the fixed-wing mode, two control surfaces deflects synchronously to the negative direction of OX axis, aircraft gain nose up torque, transit to rotary-wing mode.

III. AIRCRAFT CONTROL SYSTEM

The aircraft system consists of three main parts: aircraft, ground control station, remote control, its composition is shown in Fig. 6.

Compared with ordinary UAVs, the layout of aircraft in this paper is special, flight mode is various, so the flight control logic and algorithm is different, motors and servo control output is also more complex, the two flight mode control schemes are shown in Table I.

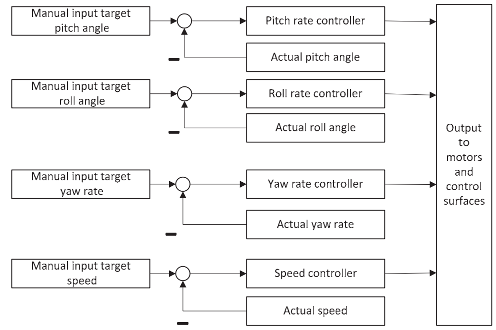

Fig. 8. Attitude control chart of rotary-wing and fixed-wing mode.

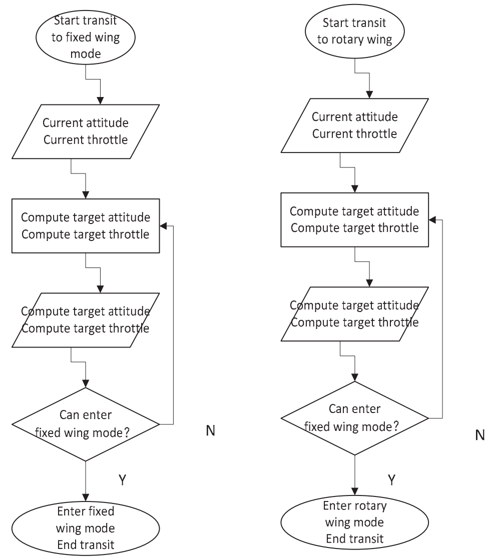

Fig. 9. Logic of transformation process.

TABLE I. CONTROL SCHEMES

Actuator	Rotary-wing mode	Fixed-wing mode
Two motors rotate synchronously	Height control	Speed control
Two motors rotate differentially	Roll control	Yaw control
Two control surface deflect differentially	Yaw control	Roll control
Two control surface deflect synchronously	Pitch control	Pitch control

A. Transition Logic of Flight Mode

We use a two-stage switch to input the desired flight mode, when the aircraft are in fixed-wing mode or in rotary-wing mode, the switch can switch target flight mode, the transition logic is shown in Fig. 7.

B. Attitude Control

In a single fixed-wing mode, we code the controller according to the corresponding relation of Table I to control the actuator (servos and motors) to reach the control target of attitude angle and speed, and we do not need to stabilize it

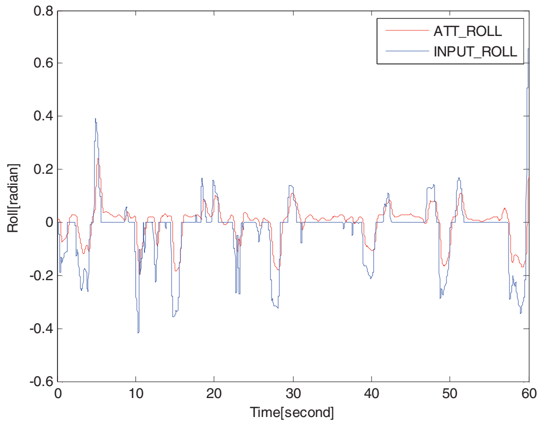

Fig. 10. Roll angle control.

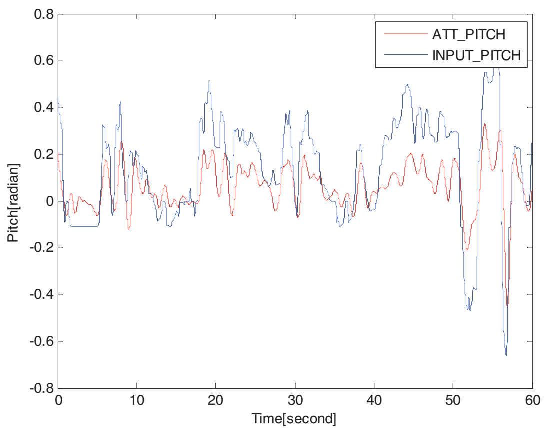

Fig. 11. Pitch angle control.

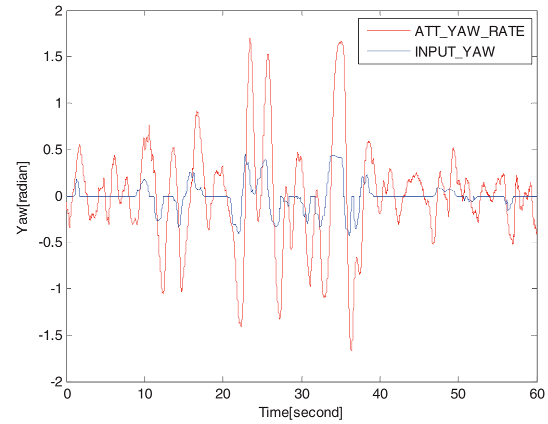

Fig. 12. Yaw rate angle control.

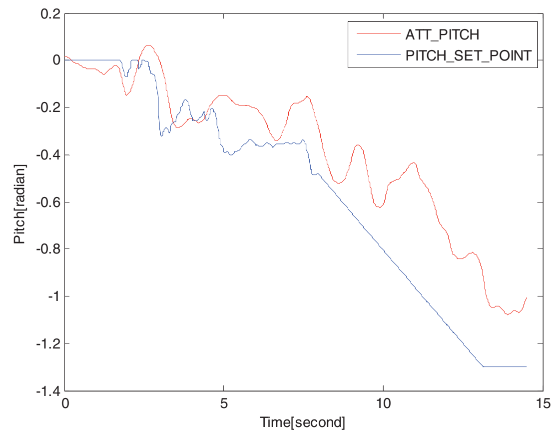

Fig. 13. Pitch angle control in transition mode.

because fixed-wing is a stable system. But rotary-wing is not a stable system, an experienced model airplane expert may control it but it is almost impossible for a normal person to control it. Therefore, we need to stabilize it so that a normal model amateur can control it.

Fig. 8 is logical block diagram of attitude control for rotary-wing mode, the controller use a radio controller to input target attitude angle, the main controller will read the data from different channels and compute the output data to control the attitude. The paper use PID controller to control the attitude angel [7].

Attitude control is much more complex in the transition. First of all, a rudder surface action is corresponding to the different roll and yaw control in the two flight modes, transition mode need to blend them together. Secondly, under different flight speeds, aerodynamic efficiency of the rudder surface is also very different, so we need to find a suitable transition algorithm automatically transit the two flight mode without affecting the aircraft flight status. Based on the above analysis, in the automatic transition process, the main work is to realize an aircraft rotation 90 degrees around the Y axis, that is the pitch angle from 0 degrees to -90 degrees in rotary-wing mode, in this process, the output of the controller to the rotary-wing and the fixed-wing is required to be added to the actuator (servos and motor), we will sum the weights of the rotary-wing and the fixed-wing in a weighted sum according to the transition duration, then output to the corresponding servos and motors, specific weight calculation method will be given later in the paper. The main logic transition process shown in Fig. 9.

In the process of transiting to fixed-wing, set the transition duration parameter T_1, the transition time has pasted Δt_l ($\Delta t_l \leq T_1$), weighted superposition of a rotary-wing controller and a fixed-wing controller, the rotary-wing controller weight is $1\text{-}\Delta t_l/T_1$, fixed-wing weight is $\Delta t_l/T_1$, decoupling control each channels, the rotary-wing controller output X_1, airplane controller output X_2, actuator output values Y,

$$Y= (1-\Delta t_l/T_1) * X_1 + \Delta t_l/T_1 * X_2 . \quad (1)$$

The initial pitch angle θ_0, Target pitch angle θ ,

$$\theta = \theta_0 - \left|-90° - \theta_0\right| * \Delta t_1 / T_1 \left(\theta \geq -70°\right). \quad (2)$$

Because the yaw control in rotary-wing corresponds to the roll control in fixed-wing, the roll control in rotary-wing corresponds to yaw control in fixed-wing, so the channels of remote control will have a channel jump, and in the process of transition, it needs to maintain a fixed roll angle and yaw angle. Setting airspeed parameters V_1 and V_2, when the airspeed is greater than V_1 and less than V_2, keep the target roll angle and target yaw angle; when airspeed V_a is greater than V_2, open the target roll angle and yaw angle, reading the target roll angle and the target yaw angle from the remote control channel.

The thrust to weight ratio is 1: 1 when hovering, initial throttle $THRO_0$, the maximum throttle during transition $THRO_{max}$ will ensure that the pull of the motor is greater than

the vertical component, so the aircraft will not lead to lose height, target throttle denoted by $THRO_1$,

$$THRO_1 = THRO_0 + \left(THRO_{max} - THRO_0\right) * \Delta t_1 / T_1$$

$$(THRO_1 \leq THRO_{max}). \quad (3)$$

Until aircraft accumulate enough airspeed threshold value V_3, read the target throttle from the remote control;

Using the above method to calculate the target throttle angle and target attitude value, when $\theta \leq$ -70 °, airspeed $Va \geq V_3$, enter fixed-wing mode, set the fixed-wing weight to 1, rotary-wing weight to 0.

The transition process of from fixed-wing to rotary-wing and rotary-wing to fixed-wing is similar, but the main control target is pitch angle, after the pitch angle reaches the stall angle, body wind resistance increases rapidly, forward speed decreases rapidly.

Set the transition duration parameter T_2, the transition time has pasted Δt_2 ($\Delta t_1 \leq T_2$), rotary-wing controller weight is $\Delta t_2/T_2$, fixed-wing weight is 1- $\Delta t_2/T_2$, actuator output values Y,

$$Y = \Delta t_2 / T_2 * X_1 + (1 - \Delta t_2 / T_2) * X_2. \quad (4)$$

The initial pitch angle denoted by θ_1, target pitch angle θ,

$$\theta = \theta_1 + \left|\theta_1\right| * \Delta t_2 / T_2. \quad (5)$$

When the transition starts, keep the target roll angle and target yaw angle zero, when the pitch angle reaches -10 °, enter rotary-wing flight mode, set fixed-wing weight to 0, set rotary-wing weight of 1.

IV. EXPERIMENTAL RESULT

The flight test has achieved the success in the vertical takeoff and landing process and in the rotary-wing mode. In rotary-wing mode, we can control the aircraft to move upward or downward, front or back and left or right. In transition mode, we use the method given above to compute target pitch angle. The following is the results analysis of attitude control.

Figs. 10-12 are the three channels of the input target attitude and the actual attitude output. The results presents the aircraft can achieve the desired results through the control method. Fig. 13 is the transition pitch angle, the attitude pitch angle diminish along with target pitch angle and get into fixed-wing mode.

V. CONCLUSION

The rapid development of sensor technology and computer technology makes it possible to realize the micro automatic control system. This paper, based on a flying wing aircraft, uses PID feedback control to control the attitude. A flight mode transition control logic and a method for calculating the target pitch angle based on time are presented. The actual flight test was carried out, according to the test results, this kind of aircraft is able to achieve stable flight and hovering through the automatic control system.

Due to the advantages of both fixed wing and helicopter, the new aircraft is able to complete the mission of the ordinary aircraft can not do. In order to achieve a more reliable and highly reproducible system, some advanced control and more perfect constraint conditions will be studied and tested in the future.

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