Design Of Vertical Take-Off And Landing (VTOL) Aircraft System

Win Ko Ko Oo, Hla Myo Tun, Zaw Min Naing, Win Khine Moe

Abstract: Vertical Take Off and Landing Vehicles (VTOL) are the ones which can take off and land from the same place without need of long runway. This paper presents the design and implementation of tricopter mode and aircraft mode for VTOL aircraft system. Firstly, the aircraft design is considered for VTOL mode. And then, the mathematical model of the VTOL aircraft is applied to test stability. In this research, the KK 2.1 flight controller is used for VTOL mode and aircraft mode. The first part is to develop the VTOL mode and the next part is the transition of VTOL mode to aircraft mode. This paper gives brief idea about numerous types of VTOLs and their advantages over traditional aircraftsand insight to various types of tricopter and evaluates their configurations.

Index Terms: VTOL, Dual Copter, Tri Copter, Helicopter, aerodynamic, Vertical take -off and landing and mathematical model.

1 Introduction

IN this paper, the VTOL UAV system design, build, and fly a tricopter mode and aircraft mode considered for use in military or commercial applications. These applications will development the appropriate operating envelope required to be incorporated into the design. Next the wing design is selected. And then, the dynamic stability check is calculated.

2 Overview of VTOL aircraft system

2.1 Review Stage

In firstly, VTOL aircraft system can be divided into two parts, VTOL mode and flight mode. The red region is flight mode system and the green region is VTOL mode system. The flight mode system, there are six servo motors must be used.

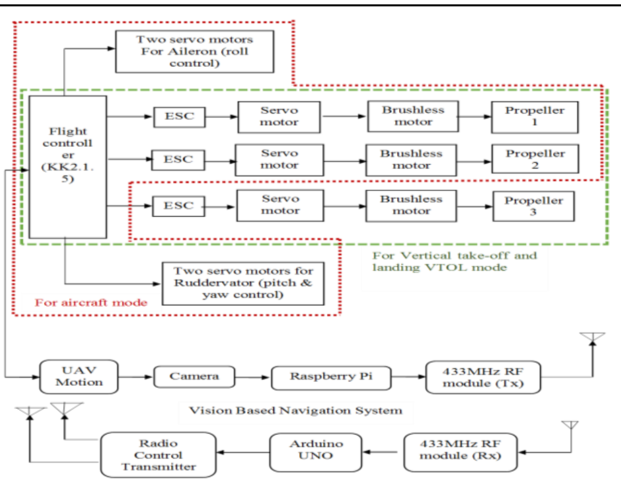

Fig. 1. *Block diagram of VTOL aircraft system.*

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The first two servo motors are used for aileron (roll control). The second two servo motors are used for ruddervator (pitch and yaw control). The last two servo motors are connected with the brushless motors, ESCs and battery respectively. The brushless motor can be drive the propellers at the left and right sides of the ailerons. This is the flight mode region. At the rear side of the fuselage, the servo motor is connected to the ESC, brushless motor and battery. And then, this brushless motor can derive the propeller at the rear side of the fuselage. This part and the propellers of the ailerons can be used to control the VTOL mode of the aircraft Figure: 1 shows the overall block diagram of our VTOL aircraft system. In vision based control system, we use Raspberry Pi3, Raspberry Pi Camera, 433MHz RC module (transmitter and receiver) and Arduino UNO board. Firstly, the Pi camera takes the photos and send the Raspberry Pi board to make image processing, when the user want to land. If the camera senses the knowing target, the 433MHz transmitter module transmits the signal by using Pi board. At the ground, the 433MHz receiver module receives the signal. And then, Arduino UNO board alarms the sound signal by joining the receiver module. By this method, the user knows, "This is the best time to land". He commands to land via RC transmitter. Finally, the landing function is operated.

2.2 Block diagram of KK flight controller for VTOL aircraft system

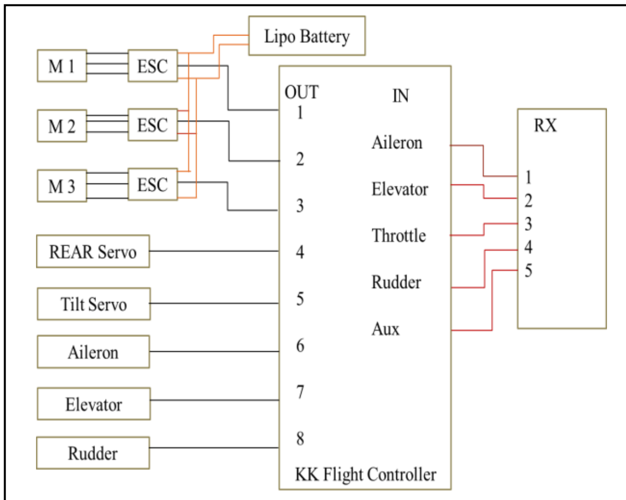

Fig. 2. *Block diagram of KK flight controller for VTOL aircraft system.*

2.3 Mechanical design of VTOL aircraft system

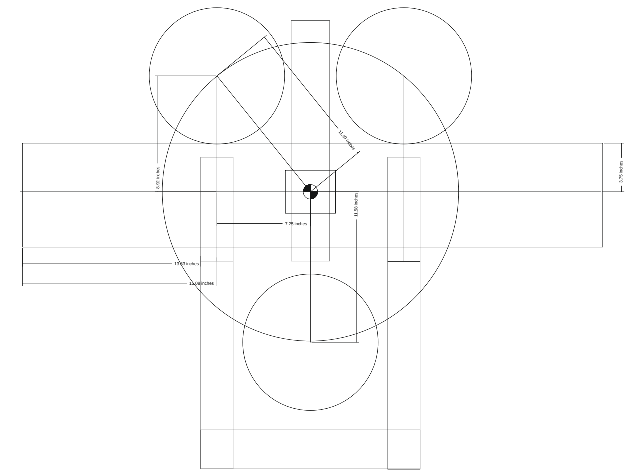

Fig. 3. *Diagram of VTOL aircraft system.*

2.4 Aerodynamic of an Aircraft equations

The equations of motion for a flight vehicle usually are written in a body-fixed coordinate system. It is convenient to choose the vehicle center of mass as the origin for this system.

- x-axis lies in the symmetry plane of the vehicle and points forward;
- z-axis lies in the symmetry plane of the vehicle, is perpendicular to the x-axis, and points down;
- Y-axis is perpendicular to the symmetry plane of the vehicle and points out the right wing.

The kinematics is concerned with the motion of the body without regarding the forces that cause the motion. The geometrical aspect of motion is based upon Newton's equation of motion. Kinematics equations from Newton's second law are as following:

$$\sum_{abs} F = ma$$
$$\sum_{abs} M = I\omega \circ$$

The velocity vector is related with six parameters: forward velocity, sideway velocity, vertical velocity, roll rate, pitch rate and yaw rate. The velocity vector, **v** in the body frame is defined as, where the angular velocity is expressed with respect to the north-east-down frame

Velocity vector, v= $\begin{bmatrix} \mathrm{u} \\ \mathrm{v} \\ \mathrm{w} \\ \mathrm{p} \\ \mathrm{q} \\ \mathrm{r} \end{bmatrix} = \begin{bmatrix} \text{forward velocity} \\ \text{sideway velocity} \\ \text{vertical velocity} \\ \text{roll rate} \\ \text{pitch rate} \\ \text{yaw rate} \end{bmatrix}$

6 DOF rigid-body forces and moments in the body frame are defined as follows:

$$\begin{bmatrix} X \\ Y \\ Z \\ L \\ M \\ N \end{bmatrix} = \begin{bmatrix} forwardforce \\ sidewayforce \\ verticalforce \\ rollmoment \\ pitchmonent \\ yawmoment \end{bmatrix}$$

Dynamic pressure, Q = $\frac{1}{2}\rho V_T^2$

Mass or Pitching Moment, m= $\frac{w}{g}$

Angle of attack, $\alpha = \tan^{-1}\left(\frac{w}{u}\right)$

Side Slip Angle, $\beta = \tan^{-1}\left(\frac{v}{\sqrt{u^2+w^2}}\right)$

Vertical Flight Path Angle, $\gamma = -\sin^{-1}\frac{w}{v}$

$$V_{eq} = \sqrt{u^2+v^2+w^2}$$

Rolling Moment Inertia, $I_x = \int_0^m \left(y^2+z^2\right)dm$

Pitching Moment Inertia, $I_y = \int_0^m \left(x^2+z^2\right)dm$

Yawing Moment Inertia, $I_z = \int_0^m \left(y^2+x^2\right)dm$

$$I_{xz} = \int_0^m (xz)dm$$

$$I_{yz} = \int_0^m (yz)dm$$

$$I_{xy} = \int_0^m (xy)dm$$

$$forceEquation, \begin{pmatrix} X \\ Y \\ Z \end{pmatrix} + mg_0 \begin{pmatrix} -\sin\theta \\ \cos\theta\sin\phi \\ \cos\theta\cos\phi \end{pmatrix} = m \begin{pmatrix} u'+qw-rv \\ v'+ru-pw \\ w'+pv-qu \end{pmatrix}$$

$$m(u'+qw-rv+g\sin\theta) = X$$
$$m(v'+ur-pw+g\cos\theta\sin\phi) = Y$$
$$m(w'+pv-qu+g\cos\theta\cos\phi) = Z$$

$$
\begin{aligned}
&I_x p' + I_{xz}(r' + pq) + (I_z - I_y)qr = L \\
&I_y q' + I_{xz}(p^2 - r^2) + (I_x - I_z)pr = M \\
&I_z r' + I_{xz}(p' + qr) + (I_y - I_x)pq = N
\end{aligned}
$$

$$
\begin{aligned}
&X_0 + \Delta X - mg_0 \sin(\theta_0 + \theta) = m(u' + qw - rv) \\
&Y_0 + \Delta Y + mg_0 \cos(\theta_0 + \theta)\sin\phi = m(v' + r(u_0 + u) - pw) \\
&Z_0 + \Delta Z + mg_0 \cos(\theta_0 + \theta)\cos\phi = m(w' + pv - q(u_0 + u))
\end{aligned}
$$

Translational Velocity can be derived from Equation:

$$
\begin{aligned}
u' &= \frac{X}{m} - g_0 \sin\theta - qw + rv \\
v' &= \frac{Y}{m} - g_0 \sin\phi \cos\theta - rv + pw \\
w' &= \frac{Z}{m} + g_0 \cos\theta \cos\phi - pv + qu
\end{aligned}
$$

Some terms are neglected in equation:

$$
\begin{aligned}
&\Delta X - mg_0 \cos\theta_0 \theta = mu' \\
&\Delta Y + mg_0 \cos\theta_0 \phi = m(v + ur) \\
&\Delta Z + mg_0 \sin = m(w' - u_0 q)
\end{aligned}
$$

3 THE TIP MECHANISM FOR VTOL AIRCRAFT DESIGN

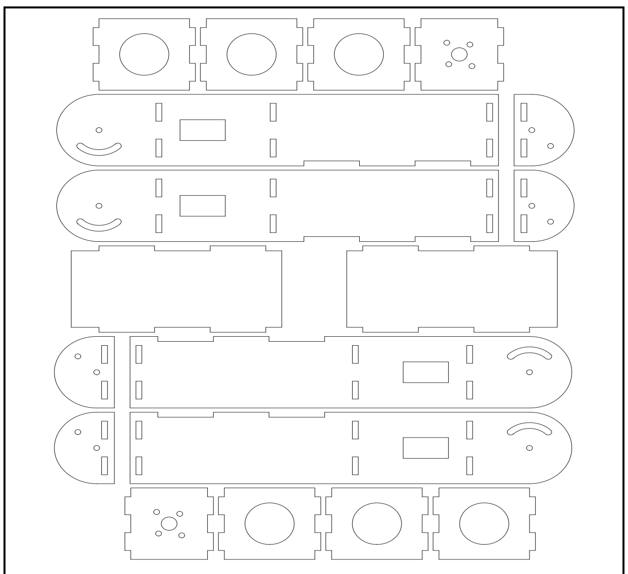

Fig. 4. *Tip mechanism design of VTOL aircraft.*

4 TRANSITION METHOD OF VERTICAL TAKE-OFF AND LANDING (VTOL) MODE TO AIRCRAFT

Open Aero VTOL (OAV) supports 2 "Profiles" also known as Flight Modes. Profile 1, (P1) is generally assumed to be for hover mode. Profile 2 (P2) is generally used for Fast Forward Flight (FFF) or airplane mode. The process of getting from P1 to P2 and back again is called a "transition". The transition from hover mode to FFF is called an "outbound transition". The reverse transition from FFF back to hover mode is called an "inbound transition". Various points on the transition curve between P1 and P2 are sometimes called "P1.n" where the "n" is sometimes replaced by a number. There is an intermediate flight mode sometimes called "Slow Forward Flight" (SFF). Hover mode (P1) and FFF mode (P2) often involve very different flight characteristics and control systems. Hover mode usually requires active stabilization in two or all 3 axis. FFF mode, or airplane mode, generally does not require stabilization, but even fixed wing aircraft can sometimes benefit from some stabilization. The stability feedback parameters for P1 and P2 are often very different, and the transition between P1 and P2 benefits from a smooth transition of stability feedback parameters. OAV uses the same PID feedback parameters as are commonly used for tricopters. In addition to the Gyro based stability feedback, the KK2 board also has accelerometers that can measure acceleration in all 3 axis, X, Y, and Z. This includes the constant acceleration due to gravity. The accelerometers and gyros are combined to create an IMU (Inertial Measurement Unit) which provides what is sometimes called an "Auto-Level" function. The Z axis accelerometer can also be used for "altitude damping" which helps the pilot to hold a more constant altitude in a hover. Lateral acceleration can also be used to detect and compensate for an uncoordinated turn, also known as a "slip". As VTOL aircraft transition between P1 (hover mode) and P2 (Fast Forward Flight or FFF) the control systems often vary dramatically. Hover control is often by direct control of various lift motors. It can also be accomplished by servos that drive collective or cyclic pitch on rotors and it also sometimes involves Aerodynamic surfaces in the powered air stream. In FFF control often depends on aerodynamic surfaces, including elevator, rudder, and ailerons, as with any typical airplane. In intermediate flight modes like Slow Forward Flight (SFF), all the methods of control are often simultaneously somewhat effective. The transition control often changes some important aspect of the aircraft configuration. Tilt rotors, or tilt propellers, often tilt motor pods to redirect the angle of thrust. Tilt wings, tilt the entire wing, motors and all. Tail sitters also do not change configuration but simply tilt the entire aircraft. It is not uncommon for the frame of reference to change for VTOL aircraft during transition. Roll often becomes Yaw and Yaw becomes Roll. The aircraft that do not change physical configuration there is often a marked change in the control system dynamics. Trim points will change, control throws need to change, and stability factors need to be modulated. The flight controller (FC) needs an input from the pilot telling it what flight mode, or percentage of transition is desired.

45°state, P1.n mode

0°state, P2 mode

5 Flowchart diagram of VTOL aircraft system

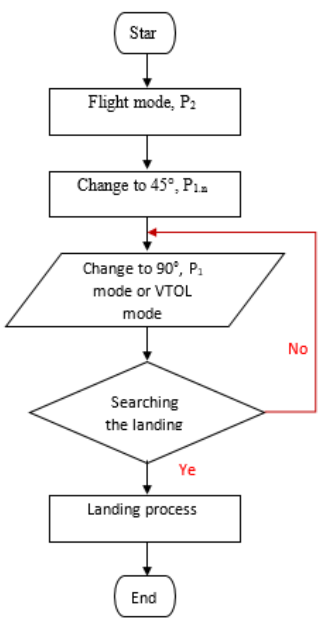

Fig. 5. *Flowchart diagram of VTOL landing position.*

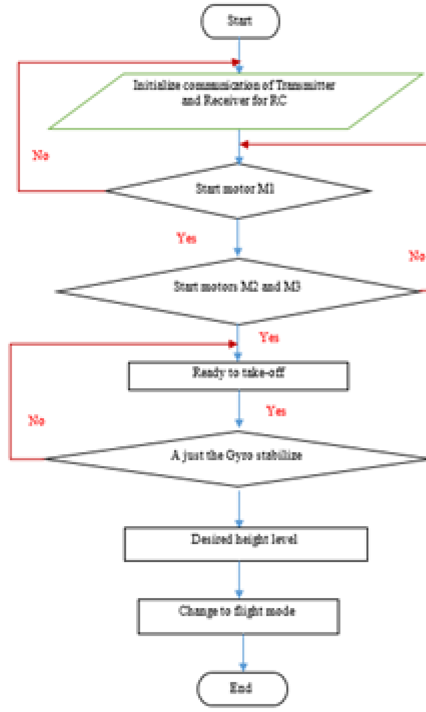

Fig. 6. *Flowchart diagram of VTOL take-off position.*

6 Testing the vertical take-off and landing process

6.1 Testing Figures and Tables of aerodynamic values

Stability of ground state control

Front view of VTOL aircraft

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Yawing state

Stability of the upper state

TABLE 1

Units for VTOL aircraft values

Notations	Values	Properties
b	3.75ft	Wing span
c	0.6667 ft	Chord
S	$2.5ft^2$	Wing area
m	0.1243lb	Empty weight
u	31.726 ft/s	Forward velocity along the X-axis
v	4.568 ft/s	Horizontal velocity along the Y-axis
w	3.806 ft/s	Vertical velocity along the Z-axis
ρ	0.002378 slug.ft^{-3}	Air pressure density
α	6.841 Degrees	Angle of attack
θ	6.9 Degrees	Pitch angle
δ_e	1.6 Degrees	Elevator deflections angle
δ_t	0.01 Degrees	Throttle angle
AR	5.625	Wing Aspect Ratio
k	20	Engine constant
I_x	6.144 slug ft^2	Rolling moment of inertia
I_y	7.823 slug ft^2	Pitching moment of inertia
I_z	8.094 slug ft^2	Yawing moment of inertia
Q	5.024 lb ft^{-2}	Dynamic pressure

7 Conclusion

In this research, I have showed the design and implementation of the VTOL aircraft and carried out to bring out the Mathematical Model of the VTOL aircraft. The VTOL UAV has been tested successfully in both manual and automatic flight operations.

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