ICIC Express Letters
Part B: Applications
Volume **9**, Number **3**, March **2018**

ICIC International ©2018 ISSN 2185-2766
pp. 171–176

TRIAL PRODUCTION OF VERTICAL TAKE-OFF AND LANDING AIRCRAFT BASED ON Y4 QUADCOPTER WITH TILT COAXIAL ROTORS AND FIXED DELTA WING

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Received September 2017; accepted December 2017

Abstract. *The trial production of new concept vertical take-off and landing (VTOL) aircraft based on modified Y4 quadcopter was carried out for aerial, observation and research. The VTOL is made up of the reversed Y4 quadcopter with tilt mechanism of coaxial rotors and fixed-wing with elevon. Continuous transition from the rotorcraft to fixed-wing aircraft can be done with tilt of the coaxial rotors of the aircraft.*
Keywords: UAV, VTOL, Y4 quadcopter, Tilt coaxial rotors, Flying robot

1. **Introduction.** In recent years, with the reduction of size, weight and cost of the inertial measurement unit (IMU) that is applied MEMS (micro electro mechanical systems) technology, various unmanned aerial vehicles (UAVs) are developed for aerial, observation and research applications [1]. The multi-rotor helicopter is widely spread for the less mechanical parts, electrically controllable and small space of the take-off and landing. However, the time-of-flight and cruising distance is limited by the battery capacity. Although the fixed-wing aircraft has an advantage of wide range of flight area caused by the high-speed flight of energy efficiency compared with the rotorcraft, it takes a runway field to take-off and landing.

There are many kinds of vertical take-off and landing (VTOL) aircraft [2]. The tilt rotor system and tail-sitter aircraft are well known as VTOL aircraft. The tail-sitter takes off and lands on its tail, and then tilts horizontally for forward flight [3]. It is difficult to design the position of the center of gravity, because the attitude of the tail-sitter changes. Also, carrying payload is difficult. The tilt rotor system can be vertical and horizontal flight by changing the angle of rotors [4]. However, both attitude control is difficult in transition flight to vertical and horizontal at the time of take-off and landing.

The VTOL aircraft obtained by adding a fixed-wing to multicopter is already known [5-8], and it has structural stability because the aircraft has more than three rotors arranged at not on the same line. However, it is excessive to use the thrust of rotors for hovering as it is after transition to horizontal flight. The difference in thrust required for vertical flight and horizontal flight is better to be small.

In this study, trial production of a new concept VTOL aircraft based on modified Y4 quadcopter with wing added is presented. Continuous transition from rotorcraft to fixed-wing aircraft can be done with tilt of coaxial rotors of the aircraft. This aircraft has a structural stability because it hovers with three positions of rotors. The aircraft is considered to reduce the power difference between horizontal and vertical flight, and it can fly with at least 2 rotors after transition to horizontal flight.

2. Proposed Aircraft.

2.1. Concept of proposed aircraft. Figure 1 shows concept of the proposed aircraft. The aircraft has front coaxial rotors and two rear rotors. The front coaxial rotors can be tilted, and the angle of the rotors is changed from vertical to horizontal. When the coaxial rotors are vertical, the aircraft becomes vertical flight mode like a multicopter allowing VTOL and hovering. When the coaxial rotors are tilted forward, the aircraft becomes horizontal flight mode like an airplane, and moves to level flight. Since the aircraft is held by lift of the wing, the two rear rotors are unnecessary. The vertical flight mode of the aircraft is made by attaching wing to a modified Y4 quadcopter which will be described in the next section.

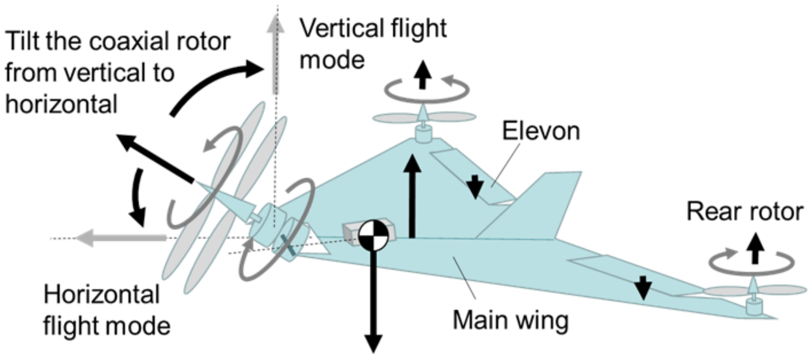
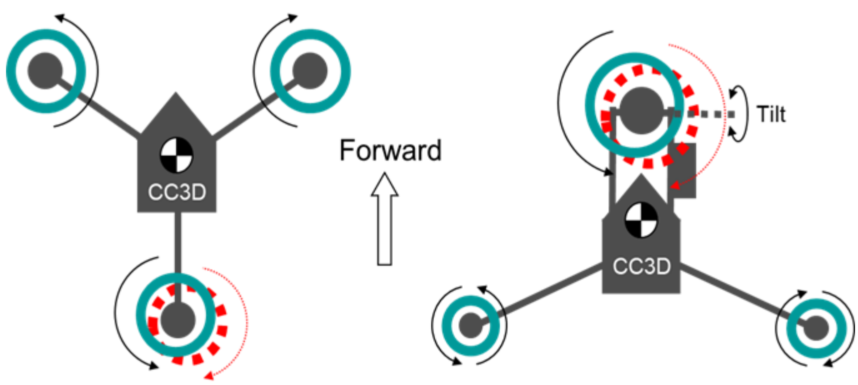


FIGURE 1. Concept of the proposed aircraft

2.2. Modification of the Y4 quadcopter. Figure 2(a) shows configuration of normal Y4 quadcopter. There are two normal propellers and motors in front on separate arms and coaxial motors in the rear mounted to one arm. The Y4 quadcopter provides a better orientation visibility, and is more reliable than tricopter because there is no potential servo issues. In contrast, the modified Y4 quadcopter shown in Figure 2(b) has reversed configuration of front and back rotors. Furthermore, the front arm is shortened and the center of gravity is moved forward in order to use thrust of the coaxial rotors sufficiently and to downsize the rear rotors.

The CC3D (copter control 3D [9]) is commercially available flight controller (FC). The 3-axis acceleration sensor and 3-axis gyroscope are mounted on CC3D. The control board is



(a) Normal Y4 quadcopter (b) Modified Y4 quadcopter

FIGURE 2. Schematic view of the modified Y4 quadcopter

developed as open source/hardware project. We have used the CC3D for attitude control of the modified Y4 quadcopter. The configuration of the attitude and flight control are also possible by using a ground control software (LibrePilot). The general firmware was available for the modified Y4 quadcopter. The control board was installed back to front, and control signals for aileron and elevator are reversed.

2.3. **Additional fixed wing and vertical flight mode.** Figure 3 shows the schematic of the proposed aircraft and the vertical flight mode. A fixed delta wing with elevon (combining the functions of elevator and aileron) added to the modified Y4 quadcopter. The delta wing does not interfere with the air flow to avoid its influence during the take-off. During vertical flight for rise and descent gentry, the delta wing is ineffective.

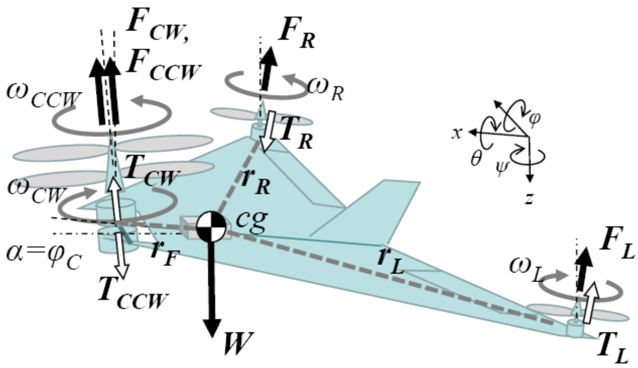


FIGURE 3. Schematic of the proposed aircraft at vertical flight mode with 90 degrees tilt coaxial rotors

The FC is installed slightly tilted with nose down φ_C. When hovering, the FC controls the attitude to be horizontal by itself, so that the angle of attack (α) of the aircraft becomes φ_C.

The thrust forces for front CW and CCW rotors, left and right rotors are $\boldsymbol{F_{CW}}$, $\boldsymbol{F_{CCW}}$, $\boldsymbol{F_L}$ and $\boldsymbol{F_R}$, respectively. To hover with vertical flight, total thrust forces and weight of the quadcopter ($\boldsymbol{W}$) are equal,

$$(\boldsymbol{F_{CW}} + \boldsymbol{F_{CCW}}) + \boldsymbol{F_R} + \boldsymbol{F_L} + \boldsymbol{W} = \boldsymbol{0} \tag{1}$$

Total pitch moment (around y-axis) is expressed by the following equation using position vectors from cg,

$$(\boldsymbol{F_{CW}} + \boldsymbol{F_{CCW}}) \times \boldsymbol{r_F} - \boldsymbol{F_L} \times \boldsymbol{r_L} - \boldsymbol{F_R} \times \boldsymbol{r_R} = \boldsymbol{0} \tag{2}$$

The total roll moment (around x-axis) is also expressed by the following equation,

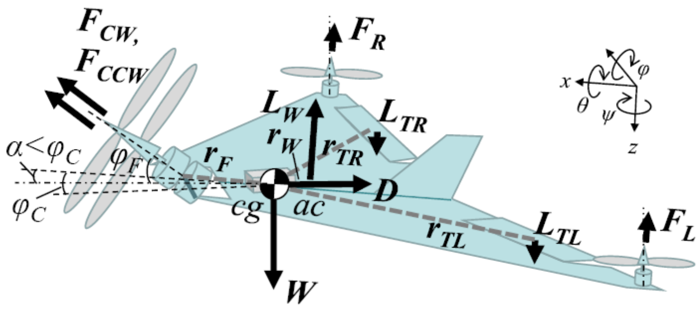
$$\boldsymbol{F_L} \times \boldsymbol{r_L} + \boldsymbol{F_R} \times \boldsymbol{r_R} = \boldsymbol{0} \tag{3}$$

The counter torques of rotors $\boldsymbol{T_F}$, $\boldsymbol{T_L}$ and $\boldsymbol{T_R}$ are also indicated with similar subscripts. Total yaw moment (around z-axis) is expressed by the following equation,

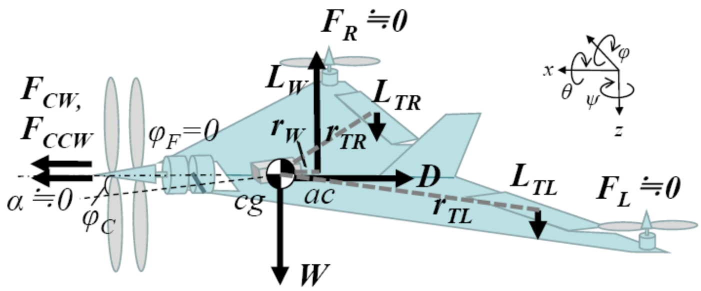
$$\boldsymbol{T_{CW}} + \boldsymbol{T_{CCW}} + \boldsymbol{T_L} + \boldsymbol{T_R} = \boldsymbol{0} \tag{4}$$

The left and right rotors are mounted symmetrically, and the outputs of both motors are almost the same. So the counter torques of $\boldsymbol{T_L}$ and $\boldsymbol{T_R}$ are canceled.

2.4. **Horizontal flight with the tilt coaxial rotors.** Figure 4 shows the schematic of horizontal flight of the proposed aircraft with tilt coaxial rotors. As a result of tilt of coaxial rotors, the aircraft has a forward thrust and flies forward. Then, the wing generates a lift by the wind. In the case of large angle of φ_C as shown in Figure 4(a), the attitude of the aircraft is mainly controlled by the thrust of the rotors similar to Y4 quadcopter. Here, part of the weight of the aircraft is supported by the lift of the wing. When the operation of the tilt of rotors and down elevator is linked, the controller tilts



(a) Tilt angle of 45 degrees



(b) Tilt angle of 0 degree

FIGURE 4. Horizontal flight with tilt coaxial rotors

forward according to the tilt rotors. Therefore, the front rotor is powered up and the rear rotor is powered down, and the α becomes smaller than the φ_C. The balances of forces around cg for vertical and horizontal direction are expressed as,

$$(\boldsymbol{F_{CW}} + \boldsymbol{F_{CCW}}) \cos \varphi_F = \boldsymbol{D} \quad (5)$$

$$(\boldsymbol{F_{CW}} + \boldsymbol{F_{CCW}}) \sin \varphi_F + \boldsymbol{F_L} \sin \alpha + \boldsymbol{F_R} \sin \alpha + \boldsymbol{L_W} \sin \alpha = \boldsymbol{W} \quad (6)$$

Here, the φ_F is tilt angle of coaxial rotors, and the $\boldsymbol{L_W}$ is lift of wing. Lift of elevon ($\boldsymbol{L_{TL}}$ and $\boldsymbol{L_{TR}}$) is negligible when the air speed is not so much.

As shown in Figure 4(b), when φ_F is further reduced and the coaxial rotors toward forward, the controller further tilts forward and causes increasing of the thrust of front rotors, and the aircraft gains the speed. When the aircraft speed is sufficiently high, lift of the wing becomes enough even if the α is almost zero, and the thrust of rear rotor is unnecessary. At this case, the balances of forces around cg are described as follows,

$$\boldsymbol{F_{CW}} + \boldsymbol{F_{CCW}} = \boldsymbol{D} \quad (7)$$

$$\boldsymbol{L_W} - \boldsymbol{L_{TL}} - \boldsymbol{L_{TR}} = \boldsymbol{W} \quad (8)$$

Control of the pitch axis of the aircraft can be taken with the elevon. The total pitch moment can be written using lift of wing and elevon.

$$\boldsymbol{L_W} \times \boldsymbol{r_W} - \boldsymbol{L_{TL}} \times \boldsymbol{r_{TL}} - \boldsymbol{L_{TR}} \times \boldsymbol{r_{TR}} = \boldsymbol{0} \quad (9)$$

3. **Prototype of the Proposed Aircraft.** Figure 5 shows the block diagram of the prototype of the proposed aircraft. The aircraft is operated by 2.4GHz radio control (R/C) system. The CC3D which installed general Y4 quadcopter firmware, was used for the FC above mentioned. Stabilization of both vertical and horizontal flight is carried out by CC3D.

The elevon operation does not include the Y4 quadcopter firmware, so that the elevon is directly controlled by R/C system. The elevon is implemented by the mixture of elevator and aileron signals using the R/C airplane parts of the v-tail mixer (BQ2020, Turnigy). Although the elevon is still working during the vertical flight mode but not applicable,

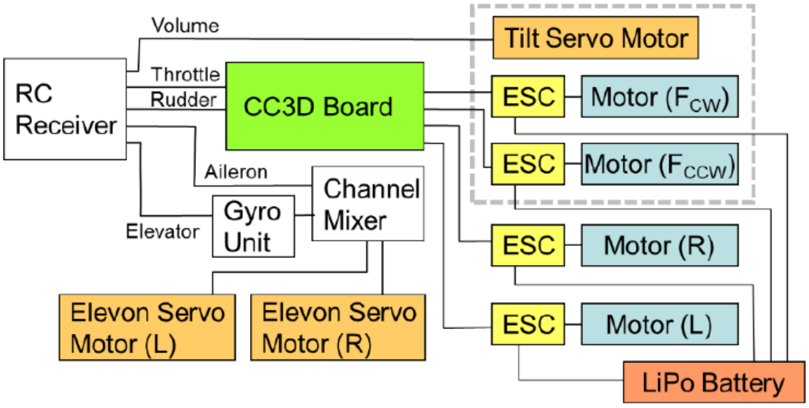


Figure 5. Block diagram of the proposed aircraft

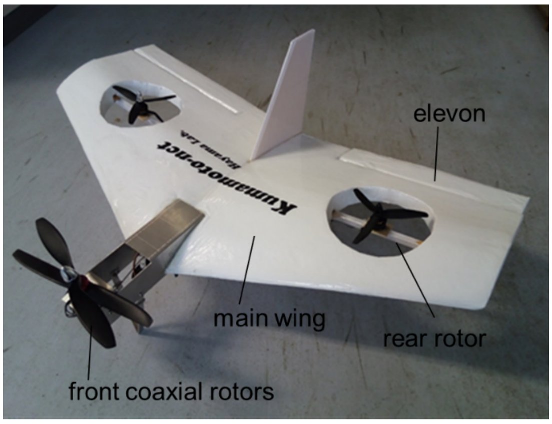


Figure 6. Prototype of the proposed rotorcraft

(a) Vertical flight with 90 deg. tilt coaxial rotors (b) Horizontal flight with 45 deg. tilt coaxial rotors

Figure 7. Flight image of the proposed aircraft

the effect of elevon is avoided because the elevon is attached outside of the left and right propellers of the wing. The gyro unit (PG-03, GWS) is also installed for stabilization of pitch angle for horizontal flight mode.

Figure 6 shows the photograph of the prototype of the proposed aircraft. The airfoil is an original flat bottom similar to the Clark Y [10]. The wing span and chord length are 0.77m and 0.38m, respectively. The total weight was about 0.65kg. The wing loading is estimated to 27.5N/m^2. This value is comparable to the commercial electric R/C airplane. It is confirmed the continuous transition of the flight mode from the vertical Y4 quadcopter to the horizontal tailless aircraft. Figures 7(a) and 7(b) show the flight images of the proposed aircraft at vertical and horizontal flight, respectively. Experimenting with the prototype of the aircraft, we confirmed the flight stabilization at hovering and low airspeed for the tilt angle of coaxial rotors up to around 45 degrees. However, the stable flight became difficult at lower tilt angle of front coaxial rotors. Because the adjustment of the many parameters during transition of the flight mode is difficult. Further work is necessary to complete the stable transition.

4. **Conclusion.** The trial production of new concept VTOL aircraft based on Y4 quadcopter was presented for aerial, observation and research. We are currently doing a transition of the flight mode and the flight control of tailless aircraft by radio control. We want to realize the stable transition of the flight mode and autonomous flight using GPS by the custom-made flight controller in the future.

Acknowledgment. This work is partially supported by Grant-in-Aid for Scientific Research (C) 17K06952 and for Challenging Exploratory Research 16K14314.

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