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DEVELOPMENT OF TILTED TRIPLE ROTORS ATTACHED FLYING WING VERTICAL TAKE-OFF AND LANDING AIRCRAFT

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Abstract. *The trial production of a new concept vertical take-off and landing aircraft of tilted triple rotors attached flying wing was carried out for power saving and long flight. The 45° tilted triple rotors are fixed at a position symmetrical to the center of gravity. Stabilization during hovering and level flight could be realized by a commercially available flight controller (FC) with custom settings. The FC is attached to the aircraft at an angle of 45°. The aircraft can hover at a pitch angle of 45°. The continuous transition from vertical to level flight can be done with only elevator operation. The attitude of the aircraft changes to tilt forward of the FC, and the aircraft flies horizontally as a fixed-wing aircraft. The attitude is controlled by the elevons rather than the thrust of the rotors. The lift of the wing during level flight caused the reduction of power consumption.*
Keywords: Tilted rotor, Tricopter, Flying wing, VTOL, Power saving

1. **Introduction.** The multi-rotor helicopter also called multicopter is widely spread for the less mechanical parts, electrically controllable and small space for take-off and landing, and is useful for aerial, observation, and research applications [1]. However, the time-of-flight and cruising distance is limited by the battery capacity. On the other hand, though the fixed-wing aircraft has an advantage of a wide range of flight areas caused by the high-speed and long-time flight of energy efficiency than the rotorcraft, it cannot hover in the air and takes a runway field to take off and landing. Assuming the exploration and observation at disaster sites, it is difficult to secure the airfield; therefore, vertical take-off and landing (VTOL) aircraft that combines the capabilities of both multicopter and fixed-wing aircraft is needed. There is a history of VTOL development in manned aircraft, and several aircraft such as the Osprey (V-22) have been developed for military use [2-4]. Recently, various VTOL unmanned aerial vehicles (UAVs) have been developed. It is well known of VTOLs of tail-sitter and tilt-rotor systems. The tail-sitter takes off and lands on its tail, and then tilts horizontally for forward flight [5]. The wingcopter is known as a highly stable VTOL with tilt rotors, which can hover with quad rotors, and transition to level flight with all tilting rotors [6,7]. The quadplane is also known as an open-source VTOL project, which is equipped with quad rotors on an airplane [8]. In these cases, the transition between horizontal and vertical flight during take-off and landing requires advanced attitude control [9,10]. The aircraft during transition becomes unstable and tends to avoid the state. Moreover, the disadvantage is that there are more electric parts than a regular airplane, which increases the weight of the aircraft. The VTOL consumes more electric power than normal aircraft, and a further improvement in efficiency is desired.

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In our previous research, we developed and compared several types of wing-attached multicopter to easily realize a VTOL in a small-scale unmanned aerial vehicle [11-13]. First, we examined a fixed-wing attached quadcopter with a large mounting angle that would provide an appropriate angle of attack when the airframe tilts forward when flying forward (Figure 1) [11]. The lift during level flight is effective for power saving. However, the aircraft could fly stably only within a narrow range of forward tilt angle and the flight speed was limited to not having too much lift force. The variable pitch wing attached multicopter was also developed as shown in Figure 2 [12]. The continuous transition from rotorcraft to similar to fixed-wing aircraft could be done by adjusting the suitable angle of attack of the wing. It was confirmed that it flew stably even if the mounting angle was tilted up to 35° and it saved less than 40% of power when hovering. However, when the lift is too much, the attitude control by the difference of thrust force of rotors becomes ineffective so the flight speed should be limited. For further power saving, it is desirable to add elevons to keep operability. As far as we know, there is only one model that has been produced based on the same concept, and the FIXAR has produced commercially available VTOL which is a tilted quad rotor attached aircraft in recent years [14]. However, this aircraft has no movable wings so it is thought to have similar limitations as our previous study of [11]. We considered that even if there is a large angle difference between the main wing and the thrust, it is possible to control the attitude and fly stably. Last year, we presented the trial production of a new concept vertical take-off and landing aircraft with 45° tilted quad rotor shown in Figure 3 [13]. The continuous transition from vertical to level flight can be done with only elevator operation. In spite of having the tilted rotors, this aircraft was completely transited to airplane mode. However, the quad rotor design produces too much thrust in level flight and is heavy and inefficient.

In this study, we propose a new concept VTOL of a tilted triple rotor attached flying wing. By minimizing the number of components while keeping stability, we aim for highly efficient flight and continuous conversion from a rotorcraft to an airplane mode without a tilt mechanism. Unlike other VTOLs, it was also found that the aircraft can fly stably even in the middle state of transition. In the remainder of this article, the structure and

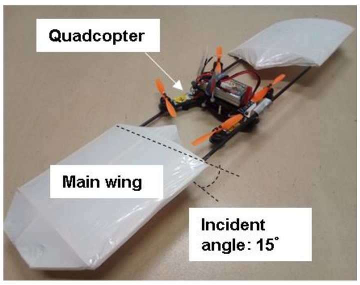


Figure 1. Quadcopter with fixed wing [11]

Figure 2. Variable pitch wing attached tricopter [12]

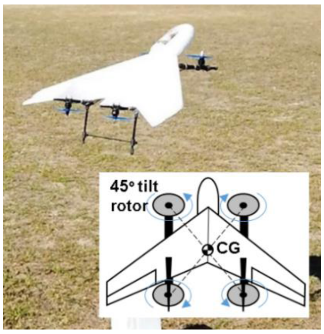


Figure 3. Tilted quad rotor attached flying wing [13]

theoretical power-saving performance of the proposed aircraft, details of the prototype aircraft, test flight, and their results are described.

2. Proposed Aircraft.

2.1. Principle of the proposed aircraft. As shown in Figure 4, we devised a new concept VTOL of tilted triple rotors attached flying wing. The rotors are installed at an angle of 45° from the horizontal of the aircraft, and these are symmetrical to the center of gravity of the aircraft. Counter-rotating propellers which turn in opposite directions to each other are used for front motors. The CW tail motor cancels out the counter torque of the tail rotor by tilting the mounting shaft.

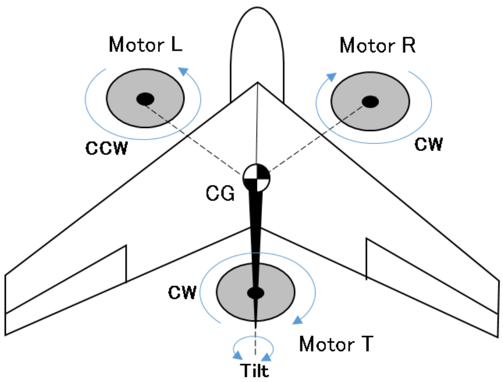


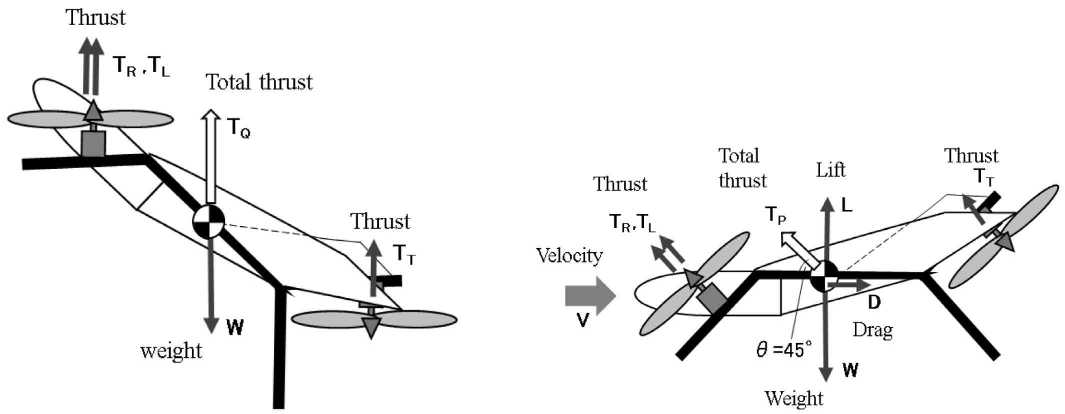
Figure 4. Schematic view of the proposed aircraft

Table 1 shows a comparison of the number of electrical components of VTOLs. The wingcopter and the quadplane have more components than normal airplanes and the weight increases. In the case of our recent study of the tilted quad rotor attached flying wing has 4 rotors, but a tilt servo is not needed. In the case of the proposed study, though a small servo is required to tilt the tail rotor, the number of motors could be reduced to three resulting in weight and power saving.

Table 1. The number of electrical components of VTOLs

	Wingcopter	Quadplane	Our recent study [13]	Proposed study
Motors	4	5	4	3
Tile servos	4	0	0	1
Control servos	4	4	2	2

Figure 5 shows the balance of forces during hovering and level flight. In Figure 5(a), when the aircraft is tilted at the angle of 45°, the rotors are horizontal and symmetrical concerning the center of gravity, even though they are on different levels. Therefore, take-off and landing can be performed with stability.



(a) Hovering (b) Level flight

FIGURE 5. Weight and balance acting on the aircraft

The total thrust of rotors (T_Q) during hovering and the weight of the aircraft (W) are balanced,

$$T_Q = W \tag{1}$$

The thrust forces of the front right and left rotor are T_R and T_L, and the thrust force of the tail rotor is T_T, respectively. Since the three rotors are symmetrical, the thrust is expressed by the following equation.

$$T_R = T_L = T_T = \frac{T_Q}{3} \tag{2}$$

During level flight, the outputs of 45° tilted rotors are varied to keep the aircraft horizontal as shown in Figure 5(b), while the aircraft flies with the lift of the main wing and part of the thrust of rotors. The thrusts of the three rotors are almost equal in level flight, and the total thrust in level flight (T_P) is expressed,

$$T'_R = T'_L = T'_T = \frac{T_P}{3} \tag{3}$$

Since the motors are 45° tilted in level flight, the vertical component of thrust partly supports the weight of the aircraft. So the weight of the aircraft is supported by both part of the thrust and lift of the wing.

$$\frac{T_P}{\sqrt{2}} + L = W \tag{4}$$

The horizontal component of the thrust of 45° tilted rotors becomes forward thrust and it balances with drag (D).

$$\frac{T_P}{\sqrt{2}} = D \tag{5}$$

The ratio of thrust during level flight and hovering is

$$\frac{T_P}{T_Q} = \frac{\sqrt{2}\ D}{W} = \frac{\sqrt{2}\ D}{D+L} = \frac{\sqrt{2}}{1+\frac{L}{D}} \tag{6}$$

Here, if the lift-to-drag ratio (L/D) is sufficiently large, the power consumption during level flight is much lower than that during hovering.

2.2. **Prototype of the proposed aircraft.** Figure 6 shows the prototype of the proposed aircraft. The airframe is made by combining with carbon pipe base frame and a reinforced Styrofoam wing. The main wing is a swept wing of an original airfoil, and the dihedral angle is 5°. The wingspan and wing area are 1.2m and 0.28m^2, respectively. The 45° tilted triple rotors are mounted at a position symmetrical to the center of gravity. The maximum thrust force and power consumption of the motor (A2212/10T, 1400KV) using 3 blades 9×5 inches propeller are 0.91kg and 210W, respectively. There is enough thrust to lift the aircraft with triple rotors. The total weight including LiPo battery (3S-11.1V, 1600mAh) was about 0.96kg.

Figure 6. Prototype of the proposed aircraft

Stabilization during flight can be realized by a commercially available flight controller (FC) with custom settings. As shown in Figure 7, the FC is mounted on the nose of the aircraft at a 45° tilt. So the aircraft can hover at the pitch angle of 45° when the transmitter sticks are neutral position.

Figure 7. Tilting FC mount

Figure 8 shows the block diagram of the proposed aircraft. The aircraft is operated by 2.4GHz R/C system. We have used the CC3D for attitude control of the aircraft. The CC3D is developed as an open source/hardware project [15]. The 3-axis acceleration sensor and 3-axis gyroscope are mounted in CC3D. The configuration of the attitude and flight control are possible by using a LibrePilot. The general tricopter firmware is installed in CC3D. Stabilization of hovering and transition to level flight are carried out with the custom setting as shown in Table 2. The value of 127 means the maximum value for mixing channels. Two elevon servos are added to link the roll and pitch operations.

After take-off, the nose can be lowered to level flight by down operation of the elevator but maintaining level flight and turning while giving down operation is not easy to operate. To solve this problem, the proportional volume at the center of the transmitter is added in the custom setting, which is inverting the elevator operation. The angle of attack of the aircraft is adjustable by the volume operation. This means the flight transition can be performed by the volume operation, allowing the plane to maintain level flight with the stick in the neutral position, which improves the operability of the plane.

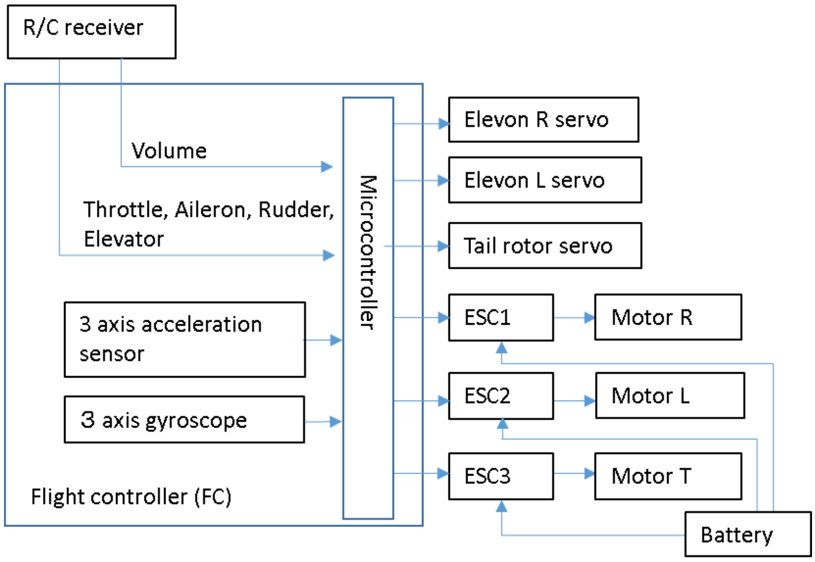


FIGURE 8. Block diagram of the proposed aircraft

TABLE 2. Custom FC setting for stabilization

	Motor R	Motor L	Motor T	Servo T	Elevon R	Elevon L
Throttle	127	127	127	0	0	0
Roll	127	−127	0	0	64	64
Pitch	64	64	−127	0	64	−64
Yaw	0	0	0	127	0	0
Volume	−64	−64	127	0	−64	64

3. Test Flight.

3.1. **Flight performance.** Figure 9 shows the photographs during a test flight of the proposed aircraft. After take-off vertically, the aircraft kept 45° tilted and stable hovering was possible as shown in Figure 9(a). When hovering, the yaw motion was controlled by the tilt of the thrust of the tail rotor due to the rudder operation. Figure 9(b) shows the flight image after the transition to the level flight. The continuous transition from hovering to level flight was done with only volume (elevator) operation. Conventional VTOL aircraft require advanced attitude control for transition flight due to its difficulty [16], but the proposed aircraft does not include a tilt mechanism and has a simple structure, so no special controls are required.

When the aircraft tilts forward, it flies horizontally as a fixed-wing aircraft. Operability was also gradually changed from multicopter to airplane. During level flight, the attitude was controlled by the elevons rather than the thrust of the rotors. As the airspeed increased, the aircraft increased the altitude by the lift of the wing. To keep the altitude, the throttle should be adjusted downward, resulting in power saving. For landing, the attitude should be changed to hovering while increasing the thrust of the rotors. Then lower the altitude of the aircraft. When the landing legs touch the ground, all the motors should be down immediately.

It was possible to take off even when the aircraft was installed horizontally without using a launcher, but since the thrust is tilted, there is a risk of failing to take off by catching on rough ground. When gliding on smooth ground or with wheels, it was possible to take off as an STOL (short take-off and landing) aircraft. If the tail rotor can be reversed, it will be possible to take off temporarily nose up with the rear legs as a support.

(a) Hovering (b) Level flight

Figure 9. Flight image of the proposed aircraft

3.2. **Comparison of power consumption.** To evaluate the power saving of the aircraft, we measured the amount of power used during flight. Table 3 shows the results of converting the power consumption in different flight attitudes from the remaining battery capacity by battery checker (AOK CellMeter 8) using a fully charged LiPo battery and assuming that the flight time is about 1 minute. In the case of outdoor level flight, sufficient lift was obtained for the reduction of power consumption down to 25% compared with that of hovering at this time. Further power savings can be expected depending on the adjustments of airframe and flight conditions.

Table 3. Power consumption of the proposed aircraft at different conditions

Flight attitude	Power consumption (W)	Power ratio
Hovering	266	1
30° tilted flight (indoor test)	138	0.52
Level flight (outdoor)	66.7	0.25

Particularly different from other VTOLs is the flight stability in the middle state of transition. When the turning flight with a radius of about 5m was performed indoor test flight at the tilting angle was around 30°, even though the main wing was in a stall, it was possible to fly with 52% power saving compared with that during hovering. Therefore, the proposed aircraft can achieve continuous stable and power-saving flight from hovering mode to fixed-wing aircraft mode.

4. **Conclusion.** The trial production of a new concept VTOL of tilted triple rotors attached flying wing was carried out. The aircraft can hover at the pitch angle of 45°, and a continuous transition from hovering to level flight can be done with only elevator operation. The lift of the wing during level flight caused the reduction of power consumption down to 25% compared with that of hovering. In the future, more detailed flight data and the advantages of the wide-range observations will be demonstrated. We will develop the control interface for the seamless transition between multicopter and airplane mode on the FC side.

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