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TRIAL PRODUCTION OF KITE WING ATTACHED MULTICOPTER FOR POWER SAVING AND LONG FLIGHT

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Abstract. *The trial production of a new concept vertical take-off and landing rotorcraft of flexible kite wing attached multicopter was carried out for power saving and long flight. The area and incident angle of the kite wing are changed in conjunction. Continuous transition from vertical to level flight can be done with automatically adjusting suitable angle of attack of the kite wing of rotorcraft. It was confirmed that the lift of kite wing during level flight was effective to reduce the power consumption less than 50% compared with that during hovering.*
Keywords: Flexible wing, Kite, Multicopter, Low power consumption, Flying robot, UAS

1. **Introduction.** The multi-rotor helicopter also called multicopter is widely spread for the less mechanical parts, electrically controllable and small space of the 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 wide range of flight area caused by the high-speed and long-time flight of energy efficiency compared with 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, a new flying machine is desired that has both feature of the rotorcraft for vertical take-off and landing (VTOL) and fixed-wing aircraft for wide range of flight. There are many kinds of VTOL [2]. It is well known of the tilt rotor system and tail-sitter aircraft. The tail-sitter takes off and lands on its tail, and then it tilts horizontally for forward flight [3]. The tilt rotor system can be vertical and horizontal flight by changing the angle of rotors [4]. However, attitude control for both aircraft is difficult in transition flight to vertical and horizontal at the time of take-off and landing.

In our previous research, trial production of a new concept VTOL based on variable pitch wing attached multicopter was carried out. Continuous transition from rotorcraft to similar to fixed-wing aircraft could be done with adjusting suitable angle of attack of the wing of the rotorcraft. It was confirmed that the lift of the wing during horizontal flight was effective to reduce the power consumption less than 66% compared with that without wing, and the flight area could be extended widely [5]. However, disadvantages of the rotorcraft are also derived. The rotorcraft is difficult to climb and descend rapidly. Lift of the wing cannot be obtained except for forward flight. It is investigated the main

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wing is affected by side wind and turbulence generated by own rotors, which is negative factor in stability during take-off and landing of the rotorcraft. The rotorcraft has poor portability because dividing the main wing has a limitation for the aspect of securing its strength, in contrast the multicopter can improve portability by folding the rod mounting rotors.

In this study, we propose a flexible kite wing attached multicopter to earn the advantage of the attachment of variable pitch wing. The flexible wing can be solved portability of the wing and avoiding the bad influence of turbulence by rotors during take-off and landing. Continuous transition from rotorcraft to similar to aircraft with flexible-wing can be done by adjusting suitable angle of attack of the kite wing. The lift of wing can be obtained during level flight, and causes the reduction of power consumption and extends the flight area.

2. Kite Wing Attached Multicopter.

2.1. Principle of the proposed multicopter.

Manned/unmanned aircraft with flexible wing such as kite, parafoil are already on the market. For example, a small unmanned aerial vehicle having kite wing called KitePlane (Sky Remote Inc.) has various usage performance as short-range take-off and landing aircraft (STOL aircraft) [6,7]. Although the kite wing is inferior to the fixed wing at the maximum airspeed, the wing area can be increased relatively easy. And the wing loading can be kept lower so that it can fly even at low airspeed.

For power saving or long-distance flight, the kite wing attached multicopter as shown in Figure 1(a) is devised in this study. We have designed the rotorcraft based on tricopter which consists of the minimum number of three rotors required for floating and attitude stabilization. The triangular kite wing with its apex at the front has an arrangement with few interferences with the rotors. The kite wing is made by a flexible sail connected to center and leading rods spreading right and left, and the trailing edge is free to deform under wind. The kite wing is fixed with rotatable to the front arm with support post.

When the control servo connected to the center rod by the link mechanism rotates, the mounting angle of the kite wing changes. The center rod slides back and forth, and the angles of both leading rods are also variable. The kite wing is designed to open and close in conjunction with the change of the mounting angle.

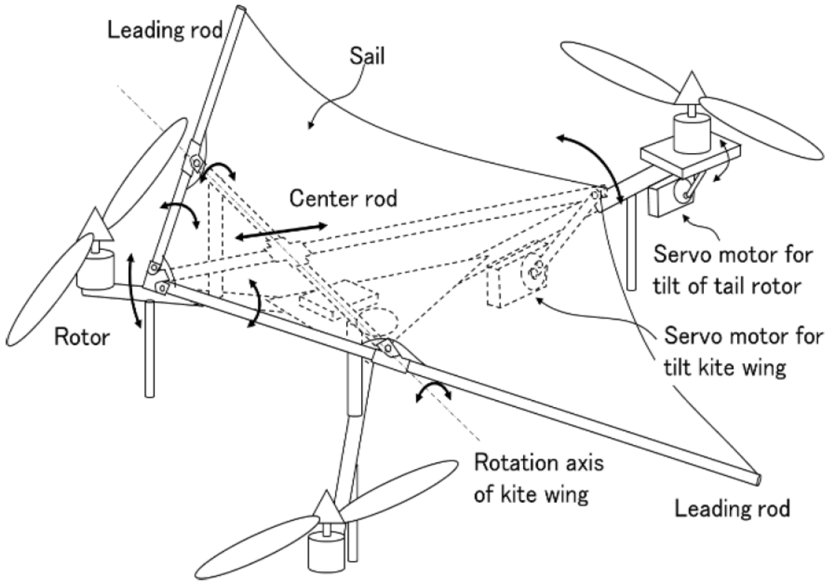
This rotorcraft can take off, land and hover the same as general multicopter with the kite wings closed. The rotorcraft is inclined forward when transition to level flight, and the kite wing is opening and automatically adjusting suitable angle of attack.

The kite wing generates lift which supports part of weight of the rotorcraft. Since the airframe is based on the multicopter, the efficiency in horizontal flight is inferior to the conventional KitePlane. However, the proposed rotorcraft has advantage that it is possible to move quickly to hover during flight, while it is impossible with the conventional KitePlane.

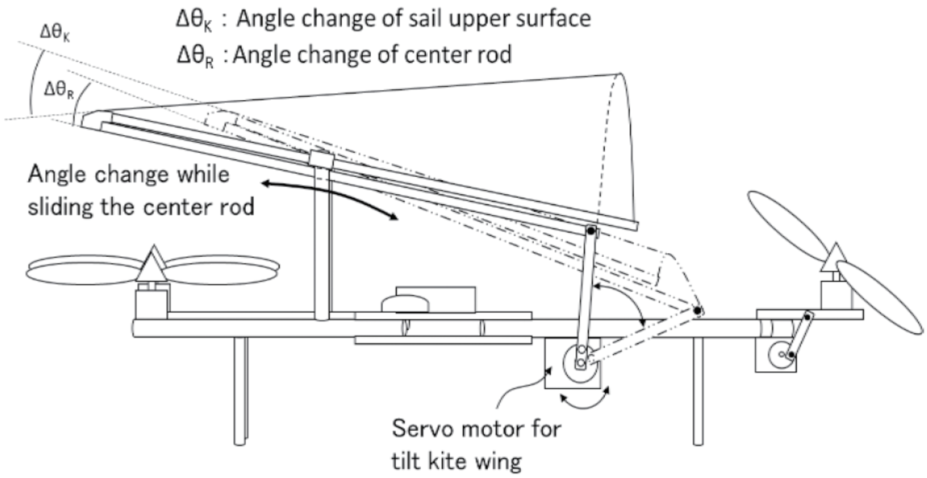
Figure 1(b) shows a side view of the proposed rotorcraft. Here, the $\Delta\theta_K$ and $\Delta\theta_R$ are angle change of upper surface of the sail and that of center rod when comparing the case where the kite wing is opened and closed, respectively. When the rotorcraft climbing and descending vertically, the kite wing can be closed. The inclination of the rod becomes small, and the sail has large slack. On the other hand, when the kite wing is fully opened, the inclination of the center rod becomes large and the sail is in a tensioned state. The change of effective angle of attack of kite wing (similar to $\Delta\theta_K$) is larger than the change of mounting angle of wing ($\Delta\theta_K$). This is a more advantageous feature than the case of our previous study of variable pitch wing attached multicopter [5].

2.2. Trial production of the proposed multicopter.

Figure 2 shows a prototype of the proposed rotorcraft. The base flame is general Y3 tricopter, which is made by carbon



(a) Oblique view



(b) Side view

FIGURE 1. Schematic view of kite wing attached multicopter

FIGURE 2. Prototype of the proposed rotorcraft

rods mounted three blushless motors. Only tail motor has tilt mechanism with servo linkage for control of yow moment. The total weight including LiPo battery (3S-11.1V, 2200mAh) was about 1.06kg. The weights of the rotorcraft and the kite wing are 0.86kg and 0.20kg, respectively. In the present prototype, the weight of the battery occupies 16% and the kite wing occupies 19% of the total weight. The maximum thrust force and power consumption of the motor using 3 blade 9 inches propeller are 0.56kg and 180W each, respectively. There is enough thrust to lift the rotorcraft with three rotors.

Figure 3 shows the block diagram of the proposed rotorcraft. The rotorcraft is operated by 2.4GHz R/C system. We have used the APM (ArduPilot MEGA 2.5, 3D Robotics [8]) for attitude control of the rotorcraft. The APM is a commercially available flight controller. The control board is developed as open source/hardware project. The 3-axis acceleration sensor, 3-axis gyroscope, 3-axis geomagnetic sensor and pressure sensor are mounted in APM, and it is possible to utilize the attitude control that is developed in open source and flight control software (Arducopter). The configuration of the attitude and flight control are also possible by using a ground control software (APM Planner 2 [9]). The APM is installed of general tricopter firmware. Stabilization of both hovering and horizontal flight of the proposed rotorcraft is carried out by APM. The APM also has the output for control of camera gimbal, and the output is used for control of the kite wing.

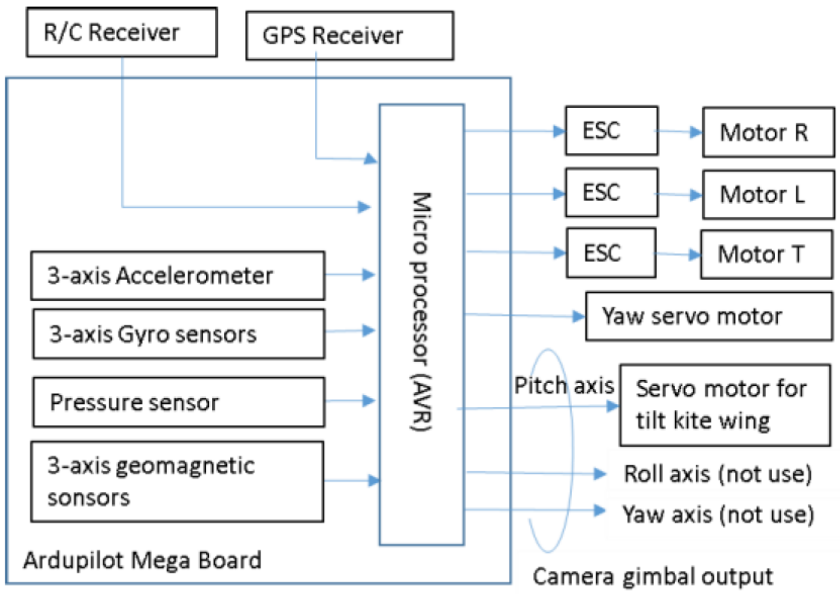


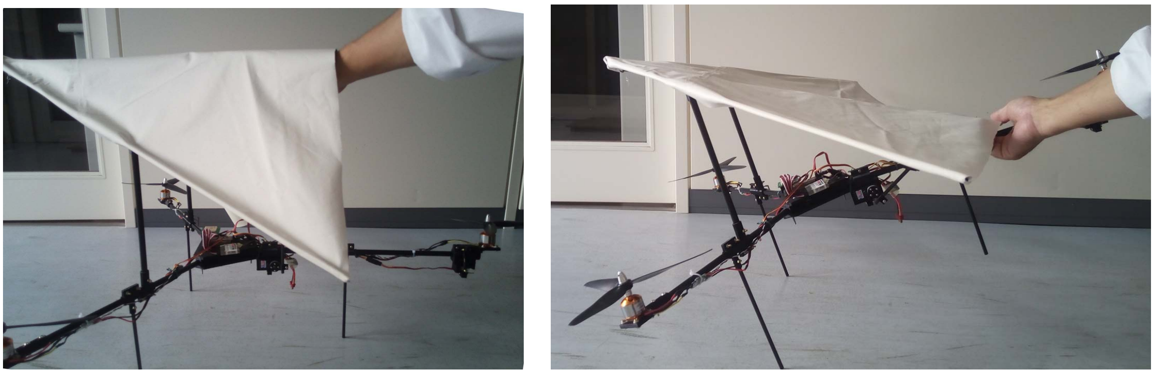
FIGURE 3. Block diagram of the proposed rotorcraft

When the center rod is driven by the servo motor, mounting angle and area of the kite wing are controlled in conjunction. Holding torque of the servo motor is 10kg·cm, which is enough to support the estimated maximum weight at rear edge of the kite wing. The apex angle of the kite wing is 85 degrees during hovering (Figure 4(a)) and the angle expands to maximum of 105 degrees during level flight (Figure 4(b)). Each wing areas are 0.36m^2 and 0.43m^2, respectively, and the wing area can be varied continuously. The wing loading is estimated to 23.2N/m^2 during level flight. This value is comparable to the commercial electric R/C airplane. In particular, to prevent the influence of turbulence during take-off and landing, it is possible to further close the apex angle to 65 degrees and the wing area down to 0.28m^2 by mixing to the pitch axis signal of the R/C transmitter using switching operation.

Figure 5 shows the side view for checking slack of the sail and change of mounting angle when the kite wing is opened and closed. As mentioned in previous section, the

(a) Kite wing opened (b) Kite wing closed

Figure 4. Variation of the area of kite wing



(a) Hovering (b) Level flight

Figure 5. Variation of the shape and the mounting angle of the kite wing

sail is largely slacked when the rotorcraft is hovering as shown in Figure 5(a). When moving from hovering to level flight, the sail fills out by wind and the effective angle of attack of the kite wing is about 15 degrees. When the rotorcraft transitions to level flight by inclined forward as shown in Figure 5(b), the center rod and leading rod are further inclined from the rotorcraft and the sail is opened to increase the wing area. The effective angle of attack is about 5 degrees, which results in lift supporting the rotorcraft.

3. **Test Flight.**

3.1. **Flight impression.** We conducted a test flight of the prototype of rotorcraft. After take-off vertically, the rotorcraft kept level and stable hovering was possible as shown in Figure 6(a). The sail did not flutter during hovering and there was little influence of the air flow of the rotors.

Figure 6(b) shows a photograph when the rotorcraft transited to level flight. It is seen that the kite wing is keeping suitable angle of attack although the rotorcraft is inclined forward. The tensioned sail is bellying in the wind and keeping low incident angle during level flight. As the airspeed increases, the rotorcraft rises the altitude by the lift of the kite wing. In order to keep the altitude, the throttle should be down resulting in power saving.

Operability was almost the same as general multicopter. There is no discontinuity operation when flight transition from vertical to level flight. Backward flight and quick turning behaviors are different from general multicopter, but it is not to make operation so difficult.

(a) Hovering

(b) Level flight

FIGURE 6. Flight image of the proposed rotorcraft

In case of level flight, increasing airspeed caused a flutter at the trailing edge of kite wing. For this reason, the drag increased and the flight efficiency decreased. In order to prevent deterioration of flight efficiency due to flutter, it is necessary to optimize the material of kite, the slackness, the angle of attack and the airspeed.

3.2. **Power saving of the rotorcraft.** In order to evaluate the power saving performance of the rotorcraft, the test flight had done with logging the flight parameters. Table 1 shows the result of typical power consumption calculated from the flight logs of battery voltage and current. To clarify the effect of the kite wing, we compared the case with kite wing and without wing (removed wing). The flight speed during level flight was about 8m/s.

TABLE 1. Typical power consumption at different flight conditions

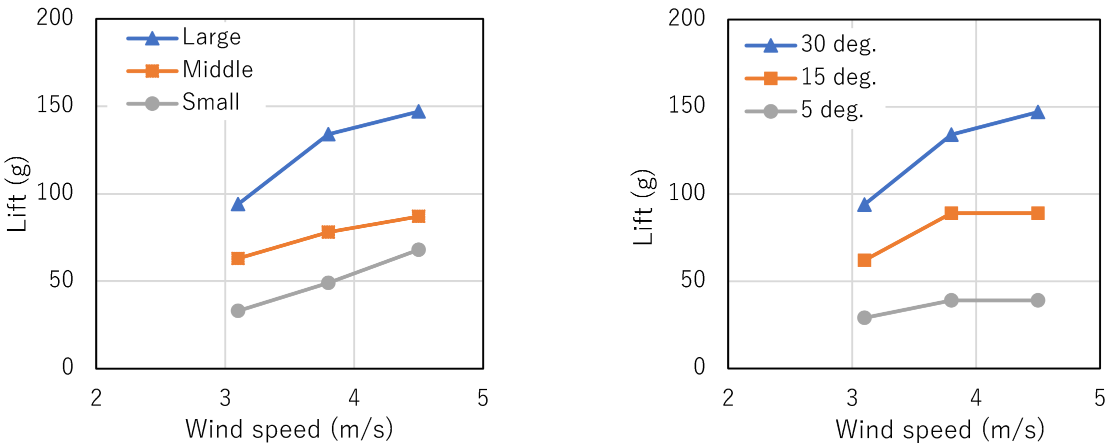
Flight condition	Without wing	With kite wing
Hovering	110W	133W
Level flight	126W	67W
Power ratio (level flight/hovering)	1.15	0.50

In general multicopter (without wing), the rotorcraft tilts forward during level flight and part of the thrust is used for forward flight. Therefore, the power consumption was increased to keep the altitude. On the other hand, compared with the hovering and level flight at the case with kite wing, it was possible to fly by 50% electric power by the lift of the kite wing. Taking this into consideration, it can be said that the power saving of the kite wing is more effective.

Maximum flight time of the presented rotorcraft at level flight can be estimated around 30min. This is comparable value from the specification of the similar scale of KitePlane. However, considering that the KitePlane weighs 1.5kg and has enough strength and payload, flight efficiency of our rotorcraft should be improved.

For wide range of aerial survey, it often takes a repeat straight flight and change of direction. So, our proposed rotorcraft has an advantage for power saving during straight flight. For drone delivery to remote areas, fixed wing aircraft is advantageous of the flight efficiency, but there is difficulty in take-off and landing. We believe that the proposed rotorcraft is useful for drone delivery to middle range areas that becomes difficult for normal drone. The rotorcraft is also advantageous for observing dangerous parts that cannot enter surroundings like volcanoes.

3.3. **Wind tunnel experiment.** To investigate the lift of kite wing, provisional wind tunnel experiment was carried out using industrial fan. Figure 7(a) shows the results of measuring the lift of kite wing at the rotorcraft placed horizontally by changing wing area and wind speed for three steps. The angle of center rod is about 30 degrees at horizontally placed rotorcraft with fully opened kite wing. As shown in the figure, the lift increases with increasing wing area and wind speed.



(a) Different wing areas at horizontally placed rotorcraft

(b) Different placed angles of rotorcraft with fully opened kite wing

Figure 7. Relations of the lift of kite wing and wind speed for the prototype of rotorcraft

Figure 7(b) shows the result of measured lift at different setting angles of fully opened kite wing at 5, 15, and 30 degrees. The lift increases with increasing the setting angle of kite wing and wind speed. When the kite wing is fully open, the flutter becomes easy to occur with increasing wind speed.

Compared to our previous study of variable pitch wing attached multicopter, though large lift cannot be expected from the kite wing caused by the shape of airfoil, the flight speed can be optimized according to the flight purpose by changing the wing area and angle of attack. Furthermore, as long as a flutter does not occur, the flight speed can be increased with small angle of attack, and the effect of kite wing can be obtained in a wide speed range.

4. **Conclusions.** The trial production of flexible kite wing attached multicopter was presented for power saving and long flight. The following conclusions are obtained.

1) Continuous transition from vertical to horizontal flight can be done with automatically adjusting suitable angle of attack of the kite wing of rotorcraft.
2) The lift of kite wing during horizontal flight causes the reduction of power consumption.
3) The lift of the kite wing was investigated at various wing area, wind speed, and setting angles by wind tunnel experiment, and the effect of kite wing is discussed.

Further study to optimize the material of kite, slackness, the angle of attack and the airspeed to prevent fluttering the kite wing is desired in near future.

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