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• LETTER •
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Control and dynamics analysis for miniature autogyro and compound autogyro

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Dear editor,
An autogyro is a type of aircraft achieving effective low-speed flight and short take-off and landing performance. A compound autogyro is a "pure" autogyro, designed with additional fixed wings. Its rotor ensures effective low-speed flight performance, and because the wings produce most of the lift at high airspeeds many problems associated with high-speed rotor dynamics in pure autogyros (and helicopters by extension) are circumvented [1]. However, to date there have been no good examples of fly-by-wire autogyros. This reflects a lack of in-depth research into autogyro dynamics and control [2]. Most existing research [3–5] is based on either costly full-sized rotors and aircraft or simulations. This study aims to verify flight controllers for low-cost miniature autogyros and compare the performances of "pure" and compound autogyro configurations.

Autogyro used for simulation and flight tests. A modified Hobbyking® Super-G pure autogyro is employed with fixed wings attached in the compound autogyro configuration. The aircraft has a rotor hub that can be tilted laterally for roll control, but not longitudinally. It also possesses an elevator and rudder for pitch and yaw control, respectively. A Pixhawk flight controller is employed for flight control. Table 1 lists the various parameters of this platform.

Rotor simulation model. The autogyro is modeled as a fixed-wing aircraft with an autorotating rotor. Careful attention must be paid to rotor modeling, as related literature is scarce. The rotor model used here is derived from actuator disk theory and an explicit form of the blade element method (hereafter referred to as EBEM) [6]. A major difference between the autogyro and helicopter rotor models is that the former does not maintain a constant rotation speed. Therefore, an iteration-based approach [7,8] is adopted to determine the rotor's angular acceleration.

In the solution algorithm, the rotor's induced speed v_i is first assigned with a reasonable starting value (e.g., 5m/s for the Super-G). Then, the rotor's thrust coefficient C_T can be derived from v_i via EBEM. A new value for v_i can then be obtained from C_T via the momentum method. By repeating this process, numerical solutions for C_T and v_i can be obtained that conform to both EBEM and the momentum theory model. Next, other rotor forces and moments are extracted from the solution process. The rotor's angular acceleration is used to obtain the rotor rotation speed for the next calculation step.

Roll and pitch controller design. The roll controller is a classical cascaded proportional-integral-derivative (PID) controller supplemented with feedforward control. The commanded roll rate p_d is proportional to the difference between the commanded roll angle ϕ_d and the actual roll angle ϕ: $p_d = k_{P_\phi} e_\phi = k_{P_\phi}(\phi_d - \phi)$. The output rotor hub tilt servo command is then given by

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Table 1 Aircraft parameters

Parameter	Unit	Value
Mass	kg	1.980
Length	m	1.223
Rotor diameter	m	1.08
Number of rotor blades	–	3
Blade length	m	0.518
Blade chord length	m	0.05
Blade airfoil	–	Clark Y (estimated)
Collective pitch	°	0
Fixed wing span	m	0.74
Fixed wing chord	m	0.11
Fixed wing airfoil	–	Selig S3010
Max thrust	kg	1.0 (approximated)

$$u_{A_1} = \underbrace{k_{F_p} k_S p_d}_{\text{Feedforward}} + \underbrace{k_{P_p} k_S^2 e_p}_{\text{Proportion}} + \underbrace{k_{I_p} k_S \int_0^t e_p \mathrm{d}t}_{\text{Integral}}$$
$$= k_{F_p} k_S p_d + k_{P_p} k_S^2 (p_d - p) + k_{I_p} k_S \int_0^t (p_d - p)\, \mathrm{d}t,$$

where k_S is the airspeed scaling factor, which is obtained by dividing the preset trim airspeed V_{trim} by the current airspeed V: $k_S = V_{\text{trim}}/V$. This is implemented as a simple form of gain-scheduling so that the controller's performance does not deviate too much from the design at different airspeeds. An integral controller is adopted to ensure that the autogyro's roll command in trimmed flight is not zero (this differs from most fixed-wing aircraft). The non-zero trim results from the rotor lift asymmetry, as the rotor blades experience different airspeeds on the left and right sides.

The pitch controller has a similar structure. The commanded pitch rate q_d is proportional to the difference between the desired pitch angle θ_d and the actual pitch angle θ: $q_d = k_{P_\theta} e_\theta = k_{P_\theta} (\theta_d - \theta)$. The elevator's servo command is then given by

$$u_{\delta_e} = \underbrace{k_{F_q} k_S q_d}_{\text{Feedforward}} + \underbrace{k_{P_q} k_S^2 e_q}_{\text{Proportion}}$$
$$= k_{F_q} k_S q_d + k_{P_q} k_S^2 (q_d - q)$$

with k_S similarly utilized.

Step input simulation and flight test results. The designed attitude angle controllers are verified via simulation. Step commands of 15° are given for the roll and pitch angles in both the simulation and flight tests, for both the pure and compound autogyros. The results are illustrated in Figure 1(a) and (b).

For the simulation, it can be observed that the cascaded PID controller can correctly track the desired roll and pitch angle commands with no overshoot. The perturbations in the pitch response are a result of nonlinearities in the rotor dynamics model. For the roll control, the compound autogyro exhibits slower responses, resulting from roll dampening caused by the fixed wings. The differences in pitch response can largely be attributed to the positioning of the fixed wings, which can induce significant changes in the longitudinal stability.

From the flight tests, it can be observed that the controller can track the attitude angles correctly in flight. The high-frequency (approximately 50 Hz) sawtooth-shaped fluctuations in the curves are a result of rotor force oscillations. Compared with the pure autogyro, the compound autogyro exhibits a slower roll response. It reaches the command angle of 15° around 1.5 s after the command is given, compared to approximately 0.7 s for the pure autogyro. The pitch responses of both configurations are reasonably similar, with the compound autogyro responding slightly faster. The overall curve trend differences between the pure and compound autogyros are similar to those exhibited in the simulations. It is also worth noting that there is a slight delay of 0.1 to 0.2 s in the step control response, which can be attributed to controller, servo, and linkage delays.

Short takeoff and landing performance. Both the pure and compound autogyros exhibit notably short take-off and landing processes, as shown in Figure 1(c) and (d). Pilot remarks indicate that the control input used during short take-offs is quite similar to that in fixed-wing aircraft. However, this is not the case for short landings. To perform a short landing, the autogyro is usually first maneuvered into a dive to build up speed. When close to the ground, the desired pitch angle is abruptly increased. The rotor rotation speed will increase very quickly, and allow the autogyro to perform a near-hover touchdown.

Reduction of drag in the compound configuration. Data points and moving average value curves for the cruise thrust command and rotor rotation speed are plotted against the airspeed (Figure 1(e) and (f)). It can be observed that the overall trends are as follows:

(1) The compound autogyro requires less thrust to maintain a level flight. For example, to fly at 13 m/s, the pure autogyro requires a thrust command of approximately 0.84 on average, whereas that required for the compound autogyro is approximately 0.68 (Figure 1(e));

(2) The compound autogyro has a lower rotor rotation speed, especially at higher flight speeds. For example, when flying at 15 m/s, the average rotor rotation speeds are 1292 and 1127 RPM for the pure and compound autogyros, respectively

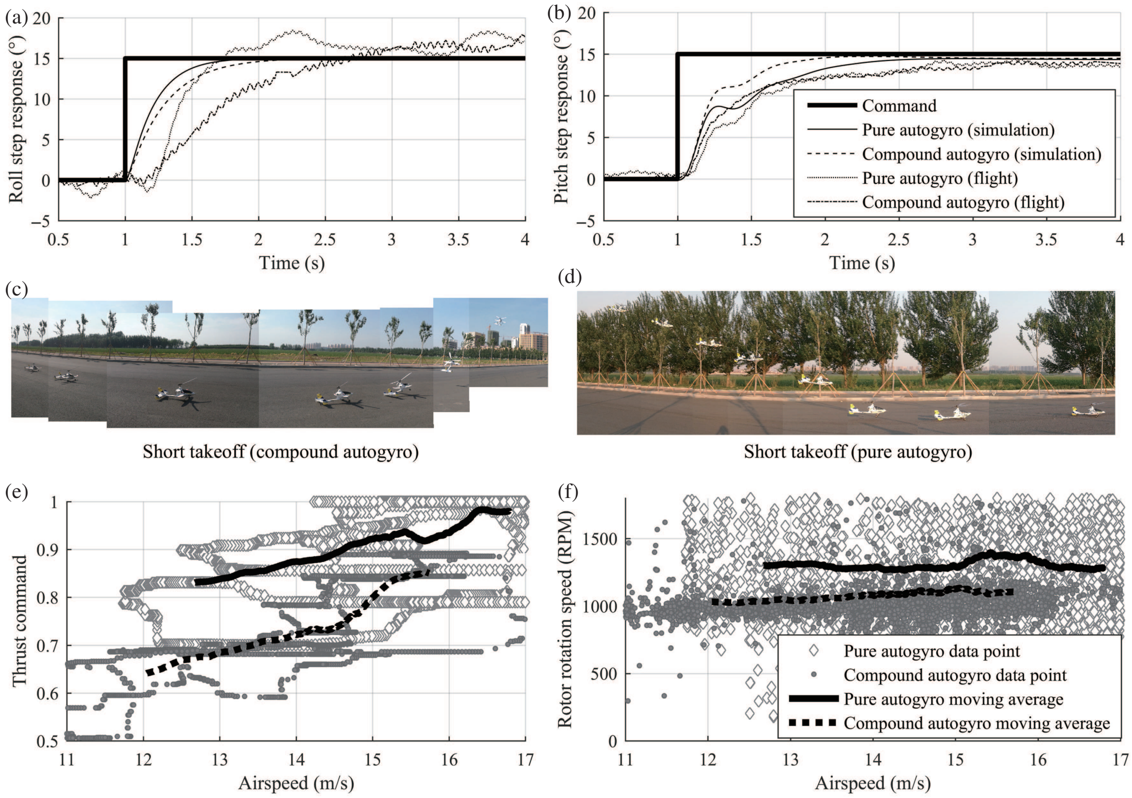

Figure 1 (Color online) (a) Roll step response; (b) pitch step response; (c) short takeoff (compound autogyro); (d) short landing (pure autogyro); (e) thrust command given at different airspeeds; (f) rotor rotation speed at different airspeeds.

(Figure 1(f)). The calculated rotor drags for the two configurations are 8.2 and 7.2 N, respectively (approximately 12% less rotor drag in the compound configuration).

These results show that the rotor is partially unloaded in the compound configuration, leading to a reduction in the rotor rotation speed and overall drag.

Conclusion and future work. Cascaded-PID-style roll and pitch angle controllers have been designed for autogyros, and a simulation model was constructed to evaluate the effectiveness of the controllers. Simulation results demonstrate that the controller can control the roll and pitch in flight for both the pure and compound autogyros, and that their flight dynamic characteristics are different. Flight tests were conducted, and the results demonstrate the effectiveness of the controllers, as well as the differences between the pure and compound autogyros in terms of dynamics and performance. Future work will include enhancing the fidelity of the simulations, expanding the quality and scope of the automatic flight control, and further exploitation of the performance potential of the compound autogyro configuration.

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