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Radio Controlled "3D Aerobatic Airplanes" as Basis for Fixed-Wing UAVs with VTOL Capability

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Abstract

There are fundamental performance compromises between rotary-wing and fixed-wing UAVs. The general solution to address this well-known problem is the design of a platform with some degree of reconfigurable airframes. For critical missions (civilian or military), it is imperative that mechanical complexity is kept to a minimum to help achieve mission success. This work proposes that the tried-and-true radio controlled (RC) aerobatic airplanes can be implemented as basis for fixed-wing UAVs having both speed and vertical takeoff and landing (VTOL) capabilities. These powerful and highly maneuverable airplanes have non-rotatable nacelles, yet capable of deep stall maneuvers. The power requirements for VTOL and level flight of an aerobatic RC airplane are evaluated and they are compared to those of a RC helicopter of similar flying weight. This work provides quantitative validation that commercially available RC aerobatic airplanes can serve as platform to build VTOL capable fixed-wing UAVs that are agile, cost effective, reliable and easy maintenance.

Keywords

Aerobatics, Unmanned Aerial Vehicle, Fixed-Wing, VTOL, Hover

1. Introduction

Unmanned aerial vehicles (UAVs) are being recognized as cost-effective alternative to manned-aircraft in carrying out various civilian and military missions [1]-[5]. Among the important civilian applications of UAV are

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natural disaster prevention and management [6]-[8], as well as emergency response and aid delivery [9]-[12]. General statement regarding the choice of UAV platform is as follows: rotary-wing UAVs have the ability to hover, take off and land vertically and with agile maneuvering capability at the expense of high mechanical complexity, low speed and short flight range. On the other hand, fixed-wing UAVs are able to cruise efficiently at high speeds for longer duration though runway is required for take-off and landing [13]-[15]. The innovation of the tiltrotor was to take advantage of the VTOL capability of a rotor-wing and the speed and range of a conventional fixed-wing aircraft. It has a rotating engine nacelles to direct thrust but the aircraft design was vulnerable to dangerous aerodynamic phenomena and reliability issues [16] [17].

Any radio controlled (RC) airframe can potentially be used to create an UAV, whether it is in the form of a fixed-wing or a rotary-wing aircraft. An UAV generally has a higher level of sophistication in its navigation and auto-pilot system. Modern aerobatic fixed-wing aircraft, whether full-size or not, or RC models were designed to operate even under fully stalled conditions [18]-[23]. In particular, these fixed-wing aircraft can fly in trim at high angles of attack near 45˚ even with flight speed below the stall speed, a maneuver known as the "harrier" which is one of the popular "3D aerobatic maneuvers" within the RC flight community. Other 3D aerobatics that have been routinely performed by RC pilots are the hovering, flat-spin, blender, waterfall, tailslide and their derivatives [18] [20] [23]. Hallmarks of unlimited aerobatic airplanes are their relatively large control surfaces immersed in strong propeller wash and thrust-to-weight ratio that exceeds 1 [18] [19].

Large control surfaces with large deflections in the presence of strong propeller wash give adequate authority even when the airspeed of the aircraft is much lower than the stall speed (V_s). This enables an aerobatic model airplane to be maneuverable in the deep wing-stall condition. Many fixed-wing UAVs have been designed with relatively small control surfaces [24] especially those that have been inspired by the military UAVs such as the MQ-9 Reaper by General Atomics. Small control surfaces exert much weaker force even in strong propeller wash and this limits the ability of the airplane to make corrective input during hovering despite having an engine that can produce powerful thrust. **Figure 1** shows two RC fixed-wing airplanes belonging to the authors. The Cirrus SR-22 represented the more conventional airframe while the Katana-50 has features shared in common with any typical 3D aerobatic airplanes. Note that the percents of chord at tip and root of the large elevator on the Katana-50 were approximately 50%, in contrast to those of the Cirrus SR-22. This allows the elevator to continue having control over the pitch of the aircraft during the vertical hovering maneuver. Likewise, its large rudder and ailerons have authoritative control over the yaw and roll of the aircraft during hovering and other post wing-stall maneuvers.

This study employed a commercially available 25% scale RC Extra 260 (electric-powered) as the agile platform and validates quantitatively that hovering and VTOL maneuvers are well within the flight envelope of

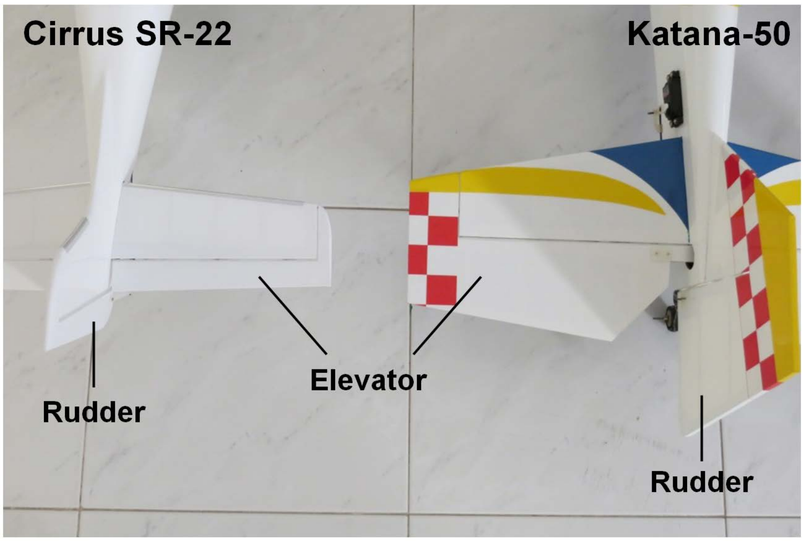

Figure 1. Comparison of flight control surfaces (rudder and elevator) on the Cirrus SR-22 and the Katana-50. Large control surfaces allow 3D aerobatic airplanes to easily perform post wing-stall maneuvers such as the "harrier".

fixed-wing UAV without resorting to configuration involving rotating nacelles while retaining common advantages shared with conventional fixed-wing aircraft such as efficient cruising. The motivation for this work is that if such simple yet robust platform proves to be a viable option, then the approach will expedite the development and deployment of VTOL-capable fixed-wing UAVs without the formidable costs and mechanical complexities. Low cost and ease of mass production of such platform will indirectly promote the practical implementation of large-scale multi-agent UAVs with unique emergent collective behaviors. Power consumptions at different phases of flight are investigated in this work via experimental field testing.

What is related to this research work is the recently revealed Project Wing by Google X [25]. The advantage of 3D airplane proposed in this work is the maturity of its production process. Furthermore, the flight performance, robustness and reliability of such airframes have put to test in international competitions such as the prestigious Fédération Aéronautique Internationale (FAI) Class F3M. They also have been indirectly tested by RC pilots around the world during their weekend flying sessions since the concept was conceived along with the introduction of lithium batteries for RC applications about 10 years ago. These resulted in tremendous accumulated hours of rigorous testing and technical know-how.

2. Materials and Methods

A 3D aerobatic airplane was used in this study and a pod-and-boom helicopter was included as comparison. Both of them were electric powered. The airplane was a 25% scale Extra 260 from Hobby King [26] and the helicopter was a Logo-10 by Mikado Model Helicopters [27] with custom stretched tail-boom to accept 600 mm main rotor blades. The Extra 260 and the stretched Logo-10 are as shown in **Figure 2(a)** and **Figure 2(b)**, respectively. Both the wing and the rotor blades have symmetrical airfoils. Maximum deflections of ailerons, elevator, and rudder were 40˚, 40˚ and 45˚, respectively for the Extra 260. Setup details of the models were tabulated in **Table 1**. Chemistry of batteries used for all the model aircraft was lithium polymer (Li-po). Additional mass was added to the Logo-10 so that both aircraft have identical flying weight of 4.5 kg. 5.8 GHz telemetry system by Guilin Feiyu Electronic Technology Co., Ltd. was employed in this study to relay real time data for

(a) (b)

Figure 2. RC model aircraft employed in this study: (a) 25% scale Extra 260; (b) Logo-10 with stretched tail-boom to accept 600 mm main blades.

Table 1. Key setup of the model aircraft.

	25% scale Extra 260	Logo-10
Manufacturer	Hobby King	Mikado Model Helicopters
Airframe type	Fixed-wing	Rotary-wing
Wing span/main rotor diameter (mm)	1754	1340
Wing/disk loading ($g{\cdot}dm^{-2}$)	71.8	31.3
Total flying weight (kg)	4.50	4.50

monitoring and the data were stored on a nonvolatile memory card for subsequent analysis. The primary sub-components of the telemetry system were the GPS sensor, overlay screen display (OSD) unit, and current sensor. The current sensor chip was the ACS758LCB-100B by Allegro Microsystems and was pre-calibrated at factory up to 100 A and the unit was also capable of measuring the input voltage to the electric motor. Electrical power was obtained by multiplying the current and voltage developed across the motors. The flying weight of the models was gauged using a digital weighing scale with a resolution of 10 g. Experimental flights were performed in calm air (wind speed < 5 km·h^{-1}) and "straight and level flight" was maintained with near-zero vertical speed during data acquisition. Radio transmitter used for the flight control was the Futaba 10CG.

3. Results and Discussion

Hovering and VTOL capabilities were clearly demonstrated for the Extra 260 and these attributes were typical of any RC 3D airplanes with thrust/weight ratio that exceeds unity. It achieved a vertical climb rate of about 5 m·s^{-1} and it also demonstrated a maximum stable descent rate of 3 m·s^{-1} without any adverse characteristics. These vertical rates enabled the airplane to perform VTOL with good margin of safety. Moderate deflection of the ailerons (not exceeding 18˚) was adequate to counteract the propeller torque effect during the VTOL and the "harrier" maneuver. Concept of co-axial counter-rotating propellers could be implemented to reduce the propeller torque effect and the P-factor to an almost negligible level. This would, to a large extend, eliminate the need to apply ailerons during harrier or VTOL. Counter-rotating propeller systems, such as the contra-drive system by SebArt-Hacker, are currently available for high-end competition F3A models [28].

The electrical power consumption at steady level flight and in trim at high angles of attack for the Extra 260 was plotted in **Figure 3**. The flight power for Logo-10 was included for comparison. The Extra 260's power curve was nonlinear and displayed a minimum. The point on the curve tangent to a horizontal line is the minimum power value, and the corresponding airspeed is the minimum power airspeed $\left(V_{mp}\right)$. A line drawn from the origin and tangent to the curve will produce the airspeed of minimum drag $\left(V_{md}\right)$ at the point of tangent. Power curve for the Extra 260 also exhibited the well-known "Region of Normal Command" and "Region of Reverse Command" [29]. As evidenced from **Figure 3**, a unique characteristic of such platform was that the large control surfaces continued to have authority even in the "Region of Reverse Command" down to zero airspeed (vertical hovering). This very characteristic enabled the full retention of control over the roll, pitch, and yaw axes. At the same time, the thrust-to-weight ratio of 1.3 was sufficient to keep it airborne in the deep wing-stall regime. From **Figure 3**, the V_{mp} and V_{md} of the Extra 260 were 40 km·h^{-1} and 55 km·h^{-1}, respectively, and the ratio of V_{mp}/V_{md} was in good agreement with the theoretical value of $3^{-1/4}$ neglecting compressibility drag.

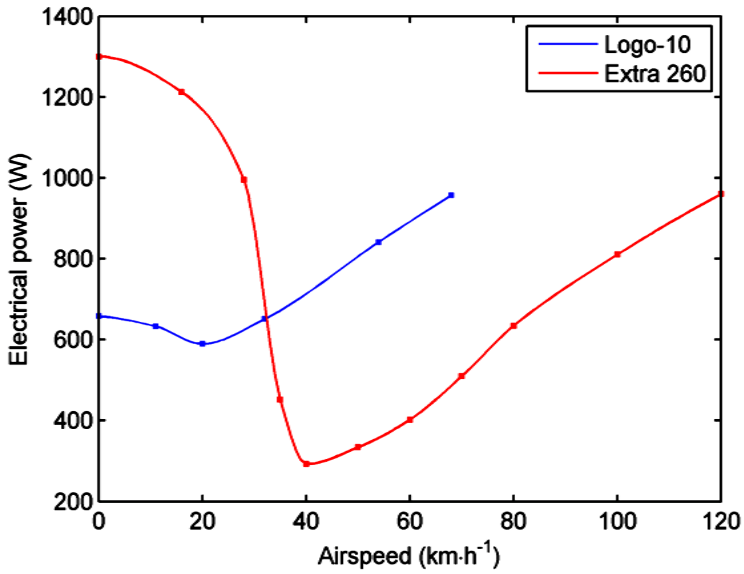

Figure 3. Power requirement for the UAV rotorcraft (Logo-10) and the 3D fixed-wing aerobatic aircraft (Extra 260). The ratio of V_{mp}/V_{md} for the Extra 260 is 72.7%. Flying weights of both aircraft were 4.5 kg.

Results in **Figure 3** supported the well-known fact that fixed-wing aircraft can cruise much more efficiently compared with rotorcrafts of similar flying weight and their ability to cover greater distance at higher speed. The Extra 260 achieved a V_h (maximum speed in level flight with maximum continuous power) of 120 km·h^{-1} with a corresponding power of 960 W. As mentioned, a common disadvantage associated with fixed-wing aircraft is the need of runways for taking off and landing. However, **Figure 3** provided the quantitative evidence that breaks the stigma and validated that 3D fixed-wing aerobatic aircraft can indeed hover and perform VTOL without involving complex movable mechanical components. Mitigation of complex mechanism would result in greater reliability required for mission success and increased operational safety. As the Extra 260's power requirements in the slow flight deep stall phase were about 3 times more than those at V_{mp} or V_{md}, it is recommended that VTOL, hovering and "harrier" maneuvers should only be performed when necessary to conserve onboard energy storage for optimum endurance.

The Logo-10 was able to hover more efficiently than the Extra 260 (658 W vs. 1300 W) mainly because its main rotor was significantly larger than the propeller of the Extra 260. As the Logo-10 made the transition to forward flights, there was a slight drop in the power requirement, reaching a minimum around 20 km·h^{-1} because of the translational lift effect. However, at 35 km·h^{-1} and above, its power requirement was significantly higher than that of the Extra 260. While the highest airspeed data collected for the Logo-10 was 78 km·h^{-1}, it was nevertheless sufficient to provide general comparison of flight power requirement between fixed-wing and rotary-wing aircraft. **Figure 4(a)** and **Figure 4(b)** are the optical images captured by the rearward facing camera attached onto the landing gear of the Extra 260 during the cruising and VTOL phase, respectively. Snapshot in **Figure 4(b)** shows the edge of the flying field with some vegetation and an asphalt road. Mature manufacturing techniques, simple and robust airframes of these 3D aerobatic platforms will help encourage the growth of cost-effective multi-agent fixed-wing UAVs with smart cooperative behaviors which undoubtedly will find important applications such as in large-scale search and rescue operation and rapid mapping of a hilly region in the aftermath of a massive landslide.

4. Conclusion

This work provided quantitative validation that commercially available unlimited aerobatic RC airplanes can serve as basis for VTOL-capable fixed-wing UAVs with simple airframe and avoid complex mechanical components associated with reconfigurable wings. This attribute will translate into low manufacturing cost, ease of maintenance and significantly higher rate of mission success. Experimental results based on a commercially available 25% scale Extra 260 indicated that the concept is indeed viable and such platform has significantly broader trimmable flight envelope compared with the more conventional fixed-wing aircraft with smaller control surfaces. It has demonstrated ability to perform impressive post wing-stall maneuvers such as high-angle slow flight ("harrier") and hovering. Low cost and reliability aspects of such agile platform can help expedite the realization of large-scale multi-agent fixed-wing UAV systems with emergent collective behaviors.

(a) (b)

Figure 4. Image taken by the Extra 260's rearward facing camera during (a) cruising and (b) VTOL.

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