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A Power Budget Analysis of an Electrical Uncrewed Air Vehicle (UAV) Flying a Basic Mission Profile

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***Abstract*—The aim of this paper is to determine the feasibility of developing a medium sized Uncrewed Air Vehicle, of 4.4m wingspan, for flight-testing electrical motors, drive units and ancillary equipment. The objectives of this initial study were to select a candidate airframe for the purpose of conducting this initial analysis, to define a mission profile that would enable the safe autonomous flight to be achieved and to estimate the power required for each of the flight phases of the mission and the electrical current consumption. The results were assessed to determine whether such an endeavour could be achieved using existing lithium-ion battery technology and to provide information about the flight endurance that could be expected of such an aircraft. In conducting this study an aircraft weight breakdown analysis has been accomplished and wing geometry and performance characteristics have been established. The outcome of the study indicated that a test UAV could be successfully designed and constructed which would enable practical autonomous flying of basic flight circuits to be conducted at a designated airfield, although it would have limited flight endurance.**

***Keywords*—UAV, aircraft electrical propulsion, UAV mission profile, UAV power consumption**

I. Introduction

Aircraft Electrical Propulsion (AEP) can be considered a relatively new area of research and development when compared to that of electric vehicles (EVs) which can be traced back beyond 120 years [1]. The main reasons for this “technology lag” being ascribed to the “weight problem” of onboard storage and release of electrical energy [2]. Until recently most aircraft electrical load sizing studies have concentrated on secondary/auxiliary power systems and large commercial “more electric” aircraft [3]. For these applications, the primary power sources are the fuel burning, aircraft turbo-jet engines, which drive electrical generators. However, AEP studies consider a wide variety of primary power sources and propulsion system arrangements such as hybrid-electric, fuel cell and primary/ secondary battery cell technologies and concentrated and distributed propulsion architectures [4]-[6].

Mission-profile based comparative studies are a proven way to assess the performance of different system and equipment configurations. For AEP studies, these also allow the all-important achievable flight endurance and range to be assessed [7],[8]. In most cases, such studies can be successfully modelled using laboratory software such as MATLAB. Although such studies are necessary for large commercial aircraft projects, they can be less effective and even unnecessary when considering relatively small and simple Uncrewed Aircraft Vehicle (UAV) applications. Some such laboratory based UAV studies have concluded that a good understanding of system behaviour is required under operational conditions [9]. By implementing computer-aided design and rapid prototyping technologies, it is sometimes more beneficial to manufacture and test tangible test devices under experimental conditions, because many sources of research grants specify Technology Readiness Levels [10] that require prototype equipment manufacture, development and testing to qualify for funding [11].

The design and construction of a flight-test aircraft to facilitate the research and development of zero-emission aircraft propulsion technologies is under consideration at Wrexham University [12],[13]. The Quick Electrical System Test (QuEST) aircraft is intended to enable electrical motors and drive-unit equipment to be developed to UKRI Technology Readiness Levels 6 & 7 [10] and to provide practical UAV operational experience for students. The aim of this paper is to detail the initial analyses carried out to estimate the onboard electrical energy storage requirement for such an Uncrewed Aircraft, and the results of this study were used to judge the feasibility of the project.

II. QuEST Aircraft Configuration

Various fixed wing aircraft architectures were considered during the concept stage of the QuEST UAV project. The underlying design requirements were that the aircraft should be:

- A conventional construction and ability to operate from grass and metalled surfaces.
- A flexible design that could allow for either tractor or pusher power plant installations.
- Be of a proven, robust, and transportable design configuration.
- Simple to construct and light in weight.

A conventionally configured high winged, twin boomed, inverted V-tail aircraft design was selected for the test prototype that closely resembles the AAI RQ-7 Shadow UAV shown in Fig. 1.

A. Autonomous Operation

The aircraft will be designed to be remotely piloted or capable of fully autonomous operation under GNSS control. Open source ArduPilot Mission-Planner software will be used for the autonomous control of the aircraft, and flight testing is intended to take place within the geo-fenced boundaries of a designated airfield. A CubePilot Cube Orange + Autopilot with ADS-B [14] was selected for the Flight Control system hardware and the aircraft also incorporates the following features:

- Tail mounted FPV camera and telemetry.
- Test instrumentation telemetry.
- Ballistic parachute recovery system.

TABLE I. QUEST UAV MASS ESTIMATES

Description	Mass (kg)
Airframe and Ballistic Recovery	15
Landing Gear	3
Powerplant and Propeller/Ducted Fan	12
Batteries/Capacitors/Fuel Cells	15
Aircraft Systems and Wiring	3
Electrical Drive Unit (s)	2
Total (MTOM)	50

B. Aircraft Weight Estimate

The design Maximum Take Off Mass (MTOM) of the QuEST UAV is 50 kg. This figure has been derived from an initial estimate as detailed in Table I. The QuEST aircraft dimensional characteristics are listed in Table II.

III. TEST FLIGHT PROFILE

The test flight profile (mission) includes ground and flight operations and is considered to take place from the moment that the electrical motor is energised (started) to when it is de-energised (stopped). Twelve flight phases were considered as tabulated in Table III.

A. Test Flying Circuit

The power requirements for the aircraft to fly the basic test circuit shown in Fig. 3 were analysed. The cruise altitude (cross and downwind legs) was selected as 60 m.

B. Power Budget

Each flight phase was analysed to determine the overall aircraft power budget and the on-board electrical energy storage requirement. A power reserve (safety) margin of 50% was also provided within the budget to ensure that the batteries were not discharged below 20% capacity with some room for additional flight time (e.g. headwinds etc.) being accommodated.

IV. PERFORMANCE ANALYSIS

Calculations were carried out for windless, ISA sea level standard conditions. The QuEST aircraft was considered as operating from a hard surface runway having an MTOM of 50kg and a maximum thrust setting of 350 N (100%).

TABLE II. QUEST UAV DIMENSIONAL CHARACTERISTICS

Characteristic	Dimension
Wing section	Clark Y (Fig. 2)
Tail section	NACA 0012
Wingspan	4.4 m
Wing chord	730 mm
Wing Area (plan)	3.2 m^2
Wing Aspect Ratio	6
Optimum Angle of Attack	5°
Optimum Lift Coefficient (C_L)	0.7
Optimum Lift to Drag Ratio (C_L/C_D)	30
Tailplane chord	500 mm
MTOM	50 kg
Thrust (max)	350 N
Motor Power (max)	30 kW
Supply Voltage	400V (DC)
Take-off speed	20 m/s

Fig. 1. AAI RQ-7 Shadow [15].

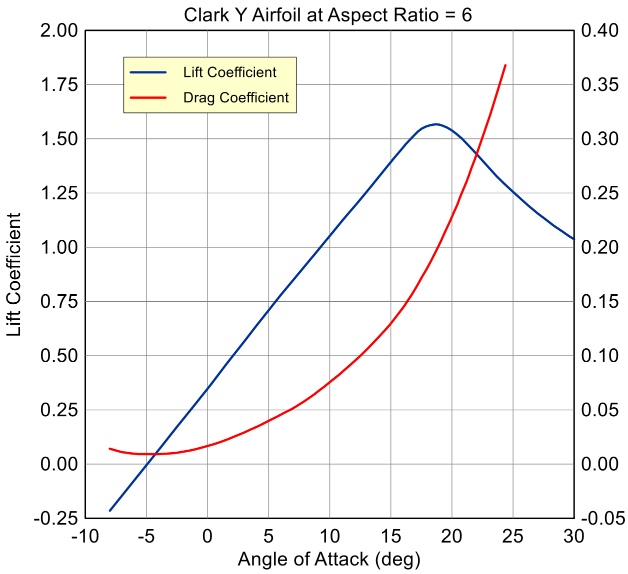

Fig. 2. QuEST UAV wing: lift and drag characteristics [16].

A. Ground Take-off (Flight Phases 1-3)

To calculate the ground take-off phase of flight, it was important to know the UAV's rolling resistance which varies in direct proportion to the UAV's weight, the quality of the take-off strip (e.g. grass or metalled) and the undercarriage characteristics. As a rough guide to rolling

TABLE III. FLIGHT PHASES

Phase Number	Description
1	Start
2	Taxi
3	Take-off run
4	Rotation and climb
5	Level out
6	Cruise
7	Turn Manoeuvres
8	Descent
9	Approach
10	Landing
11	Taxi
12	Stop

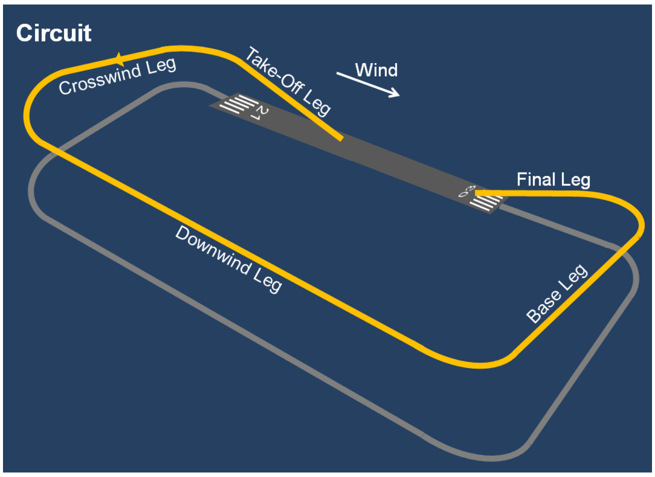

Fig. 3. Basic flight circuit [17].

resistance a minimum of 20% of MTOM can be assumed for grass strips and 5% MTOM for hard surfaces. Therefore, for the QuEST application:

$$R = 0.05 \times W = 0.05 \times 50 \times 9.81 = 24.53\text{N} \quad (1)$$

where R is metalled surface rolling resistance; $W = mg$ is weight force; m is UAV mass (50kg); g is acceleration due to gravity (9.81m/s^2).

As the QuEST UAV can produce 350N of thrust (T), there is $T - R = 350 - 24.53 = 325.5$N of thrust to accelerate it to lift-off speed. For a first estimate disregarding air resistance until lift-off, the acceleration can be calculated using the formula: *Force* = *Mass* × *Acceleration*. Therefore,

$$\frac{dV}{dt} = \frac{T-R}{m} = \frac{350-24.53}{50} = 6.51\text{m/s}^2 \quad (2)$$

where dV/dt is speed acceleration.

$$t_{TO} = \frac{V - V_0}{\frac{dV}{dt}} = \frac{20-0}{6.51} = 3.07\text{s} \quad (3)$$

where t_{TO} is take-off time; V is take-off speed (20m/s).

$$d_{TO} = \frac{1}{2}\frac{dV}{dt}t_{TO}^2 = 0.5 \times 6.51 \times 3.07^2 = 30.7\text{m} \quad (4)$$

where d_{TO} is take-off distance.

Energy used during take-off is

$$E_{TO} = Pt_{TO} = 30 \times 10^3 \times \frac{3.07}{3600} = 25.58\text{Wh} \quad (5)$$

where E_{TO} is take-off energy; P is motor power (30kW).

Hence, required current capacity from electrical energy source is 25.58Wh/400V = 0.0639Ah (63.9mAh).

B. Climb (Flight Phase 4)

The vertical component of the velocity is the rate of climb (ascent) of the aircraft (Fig. 3).

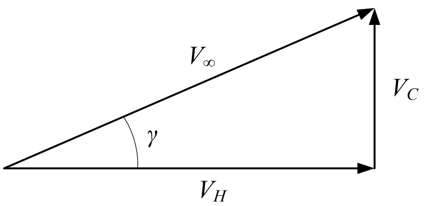

Fig. 3. Velocity components.

$$V_C = V_\infty \sin\gamma \quad (6)$$

where V_C is climb speed; V_∞ is UAV airspeed; γ is climbing angle.

In a constant speed climb the thrust produced by the aircraft must be greater than the drag and overcome the rearward component of the weight.

$$\sin\gamma = \frac{T-D}{W} \quad (7)$$

$$\cos\gamma = \frac{L}{W} \quad (8)$$

where T is thrust force, D is drag force; W is weight force, L is lift force.

An estimate of the optimum lift coefficient (C_L = 0.7) and the lift to drag ratio (C_L/C_D = 30) of the QuEST UAV was determined using NASA Open VSP software [18].

The lift generated at take-off was calculated:

$$L = \frac{1}{2}\rho V^2 S C_L = \quad (9)$$
$$= 0.5 \times 1.225 \times 20^2 \times 3.2 \times 0.7 = 548.8\text{N}$$

where ρ is air density; S is wing area (3.4m^2). And the drag generated was calculated:

$$D = L\frac{C_D}{C_L} = \frac{548.8}{30} = 18.3\text{N} \quad (10)$$

The climb angle was then determined using (7)

$$\sin\gamma = \frac{T-D}{W} = \frac{350-18.3}{50 \times 9.81} = 0.676 \quad (12)$$

$$\gamma = \sin^{-1}(0.676) = 42.5° \quad (13)$$

The climb velocity was then calculated using (6)

$$V_C = 20 \times 0.676 = 13.52\text{m/s}^2 \quad (14)$$

The time to top the climb was calculated as:

$$t_{TC} = \frac{h}{V_C} = \frac{60}{13.52} = 4.44\text{s} \quad (15)$$

where t_{TC} is time to top of climb; h is change in altitude.

Energy used during climbing (E_{TC}) is

$$E_{TC} = Pt_{TC} = 30 \times 10^3 \times \frac{4.44}{3600} = 37\text{Wh} \quad (16)$$

Hence, required current capacity from electrical energy source is 37Wh/400V = 0.0925Ah (92.5mAh).

The horizontal (ground) distance covered during the climb phase could then be calculated from the product of the horizontal velocity and the climb duration of 4.44 seconds.

$$V_H = V_\infty \cos\gamma = 20.14 \times \cos 42.5° = 14.85\text{m/s} \quad (17)$$

where V_H is horizontal velocity (Fig. 3). Hence, ground distance covered is $V_H \times t_{TC}$ = 14.85 × 4.44 = 66m.

C. Level out, Cruise and Manoeuvres (Flight Phases 5,6 and 7)

The cruise velocity was used to determine the energy consumption during these flight phases and was confirmed using the general aerodynamic formula for level flight as follows:

$$V_{MC} = \sqrt{\frac{W}{0.5\rho S C_L}} = \sqrt{\frac{50 \times 9.81}{0.5 \times 1.225 \times 3.2 \times 0.7}} = 18.9\text{m/s} \quad (18)$$

where V_{MC} is min. cruise velocity.

TABLE IV. FLIGHT PHASE AND REQUIRED ELECTRICAL CURRENT CAPACITY

Flight Phases	**Flight Duration (s)**	**Current Capacity (mAh)**
1-3	3.07	63.9
4	4.44	92.5
5-7	63.3	1319
8-12	19.4	202
Totals:	90.21 (1.504 minutes)	1677.4
	50% Reserve Allowance	838.7
	Total capacity requirement	2516

The ground distances covered to complete the level flight sections of the top of climb, crosswind, base, and downwind legs was estimated to be 196m, 250m, 500m, 250m respectively which totaled 1196m. The time taken to complete these flight phases was calculated using the minimum required cruise velocity.

Time for level flight phases is

$$t_{FP} = \frac{d_T}{V_{MC}} = \frac{1196}{18.9} = 63.3\text{s} \tag{19}$$

where t_{FP} is time for the level flight phase; d_T is total distance (1196m).

Energy used during flight phases is

$$E_{FP} = Pt_{FP} = 30\times10^3\times\frac{63.3}{3600} = 527.5\text{Wh} \tag{20}$$

Hence, required current capacity from electrical energy source is 257.5Wh/400V = 1.319Ah (1319mAh).

D. Descent, Approach, Landing, Taxi and Stop (Flight Phases 8,9,10,11 and 12)

For this initial power estimate, these flight phases were analysed together and considered to take place at a 50% engine thrust setting. The ground distance covered involved a descent over 66m and a landing rollout and taxi over 303m, totalling 369m.

Time for descent and landing is

$$t_{DG} = \frac{d_{GR}}{V_{MC}} = \frac{369}{18.9} = 19.4\text{s} \tag{21}$$

where t_{DG} is time for descent and landing; d_{DG} ground distance (descent and landing rollout).

Energy used during descent and landing is

$$E_{DG} = \frac{1}{2}Pt_{DG} = \frac{1}{2}\times30\times10^3\times\frac{19.4}{3600} = 81\text{Wh} \tag{22}$$

Hence, required current capacity from electrical energy source is 81Wh/400V = 0.202Ah (202mAh).

E. Required Capacity

Table IV shows the results of the above calculations and the adjustment to allow for the 50% reserve battery capacity.

V. DISCUSSION

The calculations indicate that a minimum battery capacity of 2516 mAh would be required to enable this test circuit to be successfully flown. The electrical current drawn to power the aircraft throughout the flight phases can be considered low (75 A maximum) because the DC supply voltage for the QuEST UAV is relatively high (400V) when compared with similar aircraft that usually use 48 VDC supplies.

A possible solution to power the aircraft would be with a lithium-ion battery pack. A series assembly of eighteen six-cell (6S) lithium-ion batteries could be used for such an application and would provide a nominal voltage of 400 VDC. One such 6S battery unit [19] would have a capacity of 3500 mAh, a nominal voltage of 22.2V and a unit weight of 472g. In this case, the total mass of batteries required would therefore be under 8.5kg. This is a significant reduction to the 15kg stated in Table II. Suggesting that much greater capacity battery units could be used to enable longer flight durations. Or alternatively, improved aircraft performance could be gained from the weight reduction.

VI. CONCLUSION

The results of this initial study indicate that a QuEST UAV could successfully be designed and constructed to enable practical autonomous flying, of basic flight circuits, at a designated airfield. However, the design, construction, and operation of such a 50kg MTOM UAV will require conformity to the national airworthiness requirements. It is therefore recommended that further studies to determine the airworthiness requirements and aircraft performance are conducted to determine the route to certification and the optimum airframe configuration. Additionally, the proposed arrangement of eighteen, 6S lithium-ion batteries connected in series would amount to 108 cells. It is considered important to ensure that a satisfactory battery management and monitoring system and suitable telemetry provision is incorporated into the UAV design to provide balanced charging and discharging and avoid thermal runaway problems. The nominal supply voltage assumed for this study was 400 VDC which resulted in a current draw of 75 amps at the maximum power setting. Many Lithium-ion batteries have C-numbers (discharge ratings) of 50C or greater and can easily accommodate such a current discharge. Therefore it is recommended that similar studies are also conducted for 300, 200, 100 and 50 VDC nominal supply voltages.

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