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Conceptual design of a high-endurance hybrid electric unmanned aerial vehicle

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Abstract

Small electric unmanned aerial vehicles (UAVs) have the advantages of low visual, heat and acoustic signatures, but have only limited flight endurance. For electric motor/battery powered UAV designs, to increase the flight endurance means an increase in the weight of the onboard battery, which in turn adds to the overall weight of the UAV and hence more power is used, especially during the ascent and possibly loiter stages of the mission. A marked increase in an aircraft's endurance can be achieved with the inclusion of an internal combustion engine in the design, but this will result in high noise levels and possibly, an unwanted heat signature. The objective of this preliminary work is to show the feasibility of combining the two power sources, an internal combustion engine and electric motor to obtain a hybrid-electric UAV which will provide high flight endurance capability together with low visual/heat/acoustic signatures.

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Keywords: Hybrid electric; endurance; UAV.

1. Introduction

Unmanned aerial vehicles can be advantageously used for aerial surveillance [1], with certain missions requiring no detection of the aircraft. A small, low altitude UAV offers advantages in cost, both for the airfame itself, and the

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use of a less sophisticated close-range sensor payload. To use such an aircraft for clandestine surveillance, it is mandatory to keep the acoustic, visual and even the heat signatures as low as possible. An electric propulsion system would be the best choice for this objective, but such a choice strongly limits the endurance and range due to the low specific energy.

An aircraft mission usually consists of several flight phases with different requirements, such as take-off and climb, the cruise flight to and from the surveillance area, loitering (which may include descent and climb) and finally descent and landing. The pacing element in designing a conventional aircraft propulsion system is the sizing of the power plan to the maximum power phase, take-off and climb. During the cruise and surveillance phases, which usually occupy a longer portion of the mission time, the power demand is much lower with the plant running on partial power and perhaps not very efficiently. This is typical for internal combustion engines (ICEs) which have excessive energy losses and unsatisfactory efficiency.

The work here is an investigation into a system, which allows for a combination of different energy converters or storages to optimize efficiency and capabilities in each flight phase, called the hybrid-electric propulsion system. Specifically, for a surveillance mission, the surveillance can be operated using silent electric propulsion only, with the internal combustion engine contributing to a fast or long-enduring cruise phase. Both systems may be operated together to achieve maximum power, so that both power units may be downsized, thereby saving weight, compared to a conventional system. The challenge in designing a hybrid-electric UAV is to outbalance the increased mass resulting from electric propulsion with increased efficiency as much as possible.

There is a growing demand for reliable, low cost UAV systems. This is especially true for mini-UAV systems with wing spans of up to 2 m. UAVs are used for many civilian applications, for example, wildlife surveillance [2], mapping for land registry [3], environmental damage tracking [4], climate change studies [5] and fire surveillance [6]. For military use, they have many uses such as, target and decoy, reconnaissance, and combat. They also come in many forms depending on the task they are designed for such as, lighter-than-air [7], tail-sitter [8], tilt-rotor/tilt-wing [9,10], fixed-wing [11] and quadrotors [12].

An electric UAV has already been designed [13], and, the object of this work is to investigate the feasibility of building on the skills and knowledge already researched and designing a similar UAV, but which will have a low acoustic/visual/heat signature, and high endurance capabilities. Without doubt helicopters are more versatile than fixed-wing and vertical take-off and landing (VSTOL) aircraft, when it is required to switch between several flight modes during a mission. However a helicopter's range and endurance is much less due to low energy conversion efficiency rotors and supersonic speed limitations at rotor tips for high cruise speeds. VSTOL UAVs do not have these restrictions for forward flight, and also, providing the propeller radius is not large, the mechanical designs are usually simple [14]. Of course the efficiency of VSTOL aircraft during hovering is much less than helicopters due to the relatively small effective rotor area. The purely electric UAV is for a flight mission where the cruise time is much greater than the hover time pointing the choice towards a VSTOL aircraft, which can be thought of as a cross between a rotary and fixed-wing UAV.

2. Current Electric Motor/Battery UAV

2.1. General description

The present design is based on the following requirements: vertical take-off and landing capability; conventional short take-off and landing capability; cruise, loitering and hover capability, low cost of manufacture and maintenance, and have a low noise electrical power unit. A summary of a typical mission is given on Fig. 1. In addition to the flight phase requirements, the UAV is capable of:

- Endurance of at least 30 minutes, which includes cruise plus hovering plus take-off and landing.
- Cruise speed of 20 m/s.
- Payload of up to 0.5 kg. This will usually consist of several 0.2 kg camera placed on a light-weight gimbal.
- Operational radius of 15 km.
- Operational altitude of 10 - 300 m.
- Collapsing for transportation convenience.

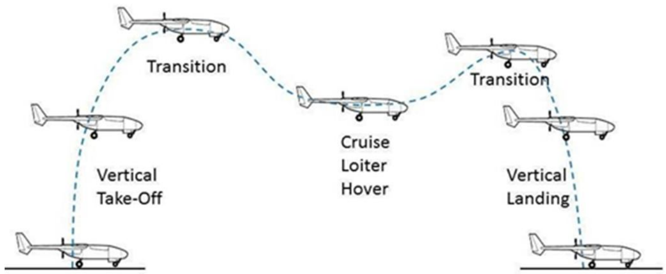

Fig. 1. Typical mission.

For vertical flight mode, there are bi-, tri-, quadro-, hexa-, and octo-copter configuration options. For the current concept it is important that weight is kept to a minimum and hence the number of electric motors should be kept to a minimum. To attain this, and to keep the desired flight maneuverability, a tri-copter arrangement was decided upon. So as to avoid a complex manufacturing process associated with the concept, the choice of a T-frame with a slight modification was made as illustrated on Fig. 2.

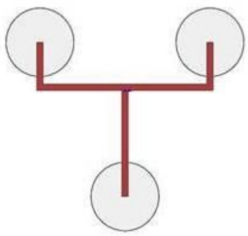

Fig. 2. Selected T-frame configuration.

The airfame and propeller arrangement are summarized on Fig. 3. The UAV has three rotors, two on the main wings to provide thrust for VSTOL and forward flight and one mid-fuselage to provide general stability and yaw. The take-off weight is approximately 6 kg, the wing span is 2 m, the UAV is electrically driven and the propellers have a NACA 4412 cross-section and are 254 mm in diameter.

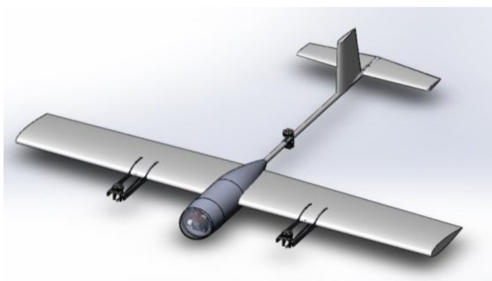

Fig. 3. Final UAV design.

2.2. Propulsion system

An electric propulsion system consists of the battery (energy storage), electric motor and propulsion device (propellers). Some advantages of such a system are that it is easy to operate and is reliable. Also electric motors are renowned for their precise control characteristics and fast response to throttle input. A disadvantage is that this system is limited by the capacity of the batteries.

The maximum thrust required for vertical-take-off (or maneuvering) is estimated to be

$$Required\,Thrust \approx 2 \times Weight \tag{1}$$

For this given design this works out at 22.8 N thrust per propeller at 100% throttle is required.

The electric motor chosen has an out-runner as this was easier to maintain and was quieter and cheaper. The motor also has a low KV rating so as to require low currents and so maximize endurance. The motor is brushless to avoid sparking. When it came to battery selection the three main considerations were, capacity, weight and volume. There are various types of battery on the market as summarized in Table 1.

Table 1. Batteries available.

	Nickel Cadmium	Nickel Metal Hydride	Lithium Ion	Lithium Ion Polymer
Nominal cell voltage [V]	1.2	1.2	3.6	3.7
Specific power [W/kg]	150	250 – 1000	250 – 340	≤ 7500

An electric motor capable of producing the required thrust at 75% throttle was chosen which required 22.2 V. The power of the motor was 324 W again at 75% throttle, with 75% used as a built in safety margin. This required a LiPo battery pack consisting of six cells in series which had the specification of 8000 mAh. The battery pack, which weighed 1.1 kg, was capable of producing flight for 30 minutes.

3. What is planned

This work looks at the feasibility of improving the flight endurance achieved by the current electric UAV shown on Fig. 4 to an improved flight endurance shown on Fig. 5 by the conceptual hybrid-electric UAV.

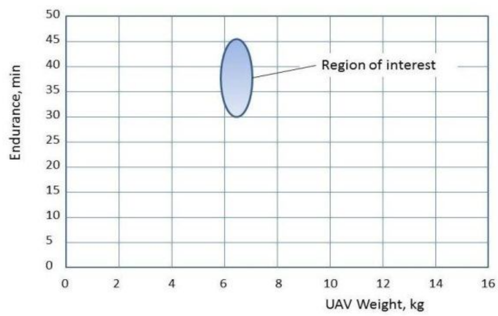

Fig. 4. Region of interest for current electric motor/battery powered UAV.

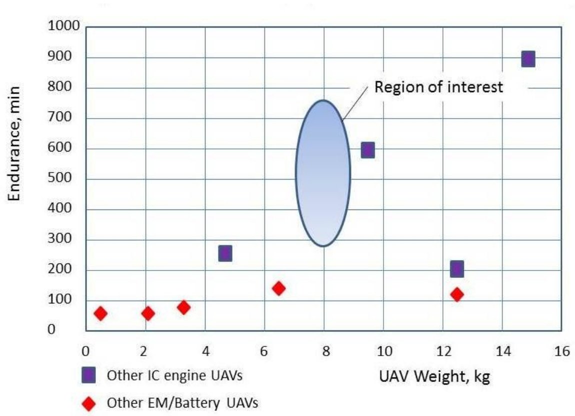

Fig. 5. Region of interest for conceptual hybrid-electric powered UAV.

A comparison of general design parameters between the current EM/Battery and the conceptual HE UAVs is given in Table 2.

Table 2. Comparison between the two UAV designs.

Parameter	Unit	Current EM/Battery	Conceptual Hybrid IC/EM
Span	m	2	2.6
Length	m	1.58	1.8
Weight TO	kg	6	6.6
Weight PL	kg	0.5	0.9
Surface	m^2	0.515	0.832
Power	Watt	300	600
Stall velocity	m/s	10.0	9.5
AR		7	9
Endurance	min	30	240

4. Hybrid IC/Electric design considerations

4.1. Preliminary considerations

To determine what weight combinations of battery, internal combustion engine and gearbox would result in a feasible design the ratio of the hybrid electric UAV to electric UAV total energy available onboard as a function of the ratio of the hybrid electric propulsion (IC engine plus gearbox weight) system to electric UAV battery weight were considered. Knowing the battery and fuel energy densities and by substituting part of the electric UAV battery weight with the hybrid propulsion and fuel weight energy were calculated as shown on Fig. 6.

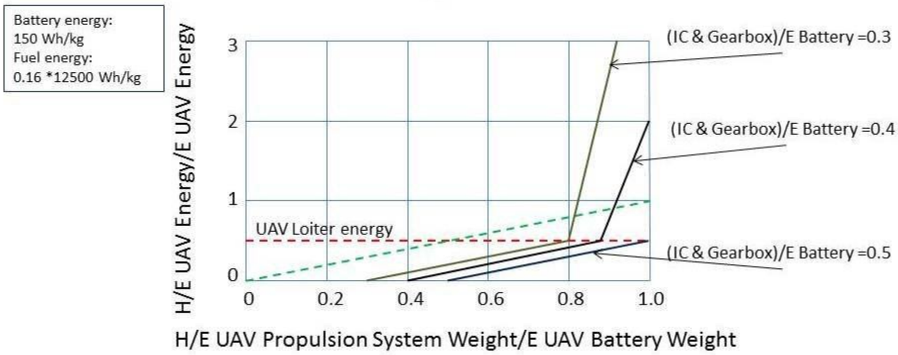

Fig. 6. Propulsion system considerations.

Assuming that at least half the loiter energy of the E UAV is required for the hybrid-electric UAV, one half of the E UAV battery is replaced by the hybrid-electric UAV propulsion weight and fuel. The lighter the propulsion weight, the more fuel can be put onboard and hence the more total energy is available onboard. As can be seen from Fig. 6, when the propulsion is approximately one-third of the total E UAV battery weight, the total energy onboard is over three times that of the E UAV. However the energy available for the loiter flight phase is only one-half of that of the E UAV.

4.2. Selection of propulsion system configuration

The main choices are either to have configurations in series or in parallel as summarized on Fig7.

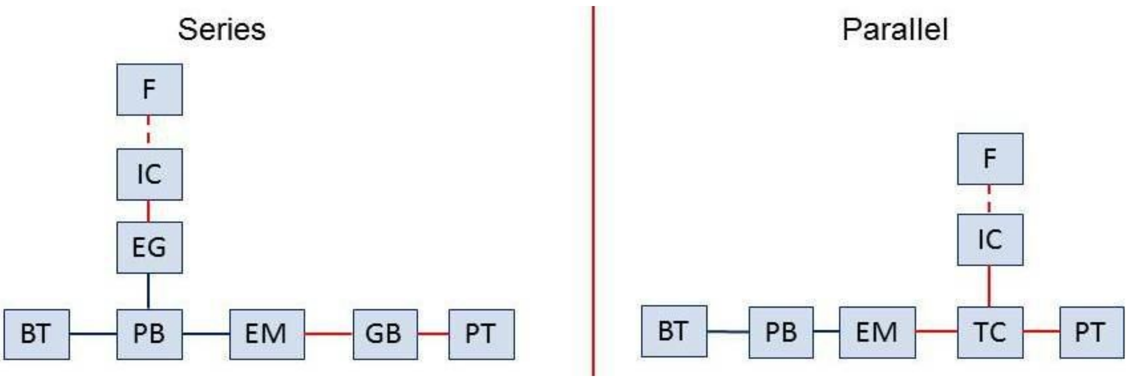

Fig. 7. Series and parallel propulsion system configurations.

where: F – fuel; IC – internal combustion engine; EG – electric generator; BT – battery: PB – power link; EM – electric motor; GB – gearbox; PT – propeller thrust; TC – torque coupler.

Advantages of using a series configuration are that the electric generator can be used as an auxiliary power unit to extend the electric range. This configuration is simple and the engine operates comparatively efficiently. Unfortunately, three electric machines are needed and there are several energy conversion steps. For the parallel configuration, the engine torque can be shifted and the engine size can be downsized. There is only one electric machine needed but unfortunately one or more clutches are needed.

The choice of the hybrid-electric UAV configuration, was made mainly due to weight considerations and is a parallel type as shown on Fig. 8. In this design the gearbox is included in the clutch, with the gearbox allowing the internal combustion engine to produce high power for take-off and landing while seamlessly introducing electric power during the cruise.

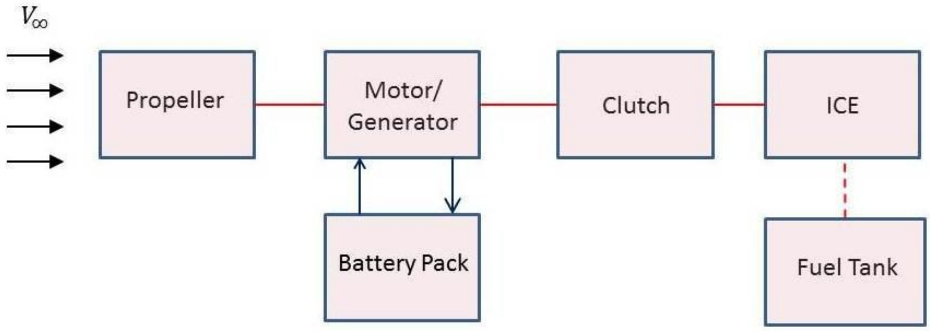

Fig. 8. Parallel hybrid-electric UAV configuration with clutch.

4.3. Trade-off between loiter and cruise energy for a hybrid-electric UAV

With the total weight of the battery, propulsion system and fuel set at say 2 kg, and 0.7 kg set for the propulsion system weight, the trade-off between available loiter and cruise energies can be performed by trading the battery and fuel weight. As shown on Fig. 9, with battery weight set at 1 kg, the hybrid-electric UAV offers one-half the loiter energy, but the cruise energy is extended to 750 Wh compared with the 300 Wh of the electric UAV.

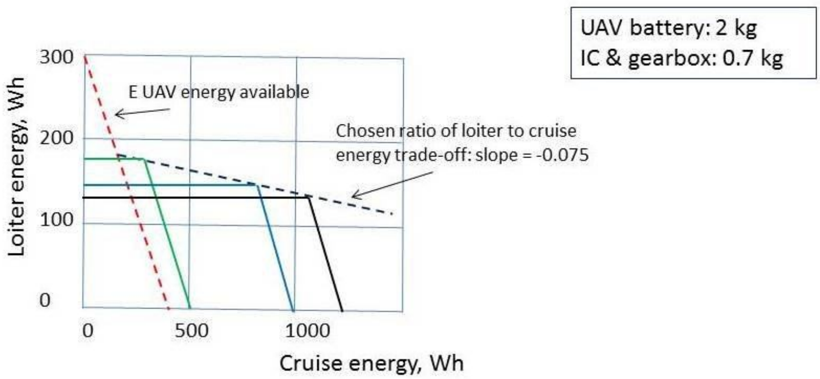

Fig. 9 Trade-off between loiter and cruise energies.

The slope of the trade-off line is equal to $\approx 1/13$ which is determined by the ratio of the fuel energy multiplied by the IC engine efficiency, i.e., $0.16 \times 12500 = 2000$ Wh/kg to the energy density of the battery, 150 Wh/kg. So for every 1 Wh loss of loiter energy, the hybrid-electric UAV gains ≈ 13Wh of cruise energy. The height of the trade-off line depends on the weight of the propulsion system.

4.4. Reducing the visual signature

Of great importance to the design of the hybrid-electric is the reduction of the visual signature need the loitering area, due to the amount of energy this requires. Even if the acoustic signature is reduce by the use of an electric motor and maintaining sufficient distance from the target, the aircraft can still be seen so negating the advantage offered by the quiet electric drive. A literature search [15] revealed that visual signature reduction has been considered in the past with the idea to illuminate the bottom of the aircraft and essentially hiding the aircraft by matching it with the sky. By varying radiating energy of electroluminescent sheets, the visual cross-section of an aircraft can be changed and appropriate illumination can make it disappear. The question is however: how much power does that require?

Fig. 10 shows examples of how illuminating the bottom of the aircraft can reduce the visual signature at different distances.

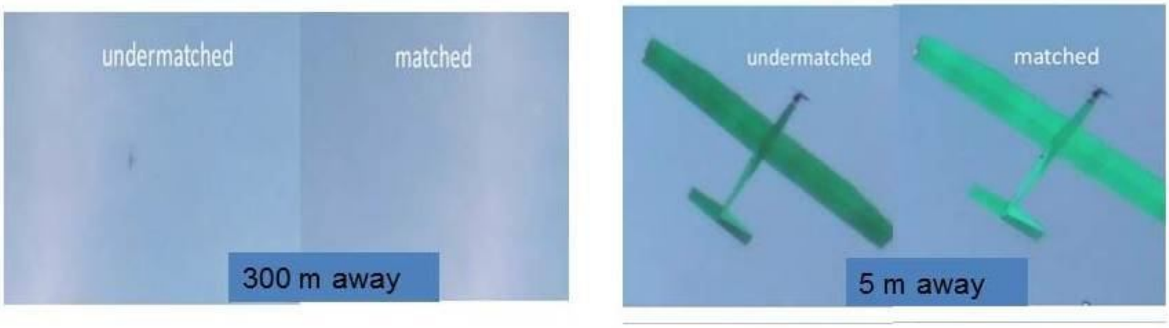

Fig. 10. An example of visual signature analysis.

From calculations associated with the visibility the following can be deduced.

- At 45° latitude and with $k = 35$ W/m^2 the UAV will be invisible all year long.
- At 30° latitude and with $k = 35$ W/m^2 the UAV will be invisible all autumn and winter.
- At 20° latitude and with $k = 35$ W/m^2 the UAV will be visible in the spring and summer for just under 3 hours a day around solar noon.

The loiter power required with $k = 35$ W/m^2 was calculated as ≈ 85 W with an optimal wing area (S) ≈ 0.8m^2. The cruise power required at 25 m/s was estimated to be 250 W again with a wing area of 0.8 m^2.

4.5. Conceptual design

The conceptual design process is described on Fig. 11. Loiter power is calculated as the sum of two terms: power to overcome the drag force and power to illuminate the bottom of the aircraft. The wing area is chosen to minimize the loiter power, and with the wing area chosen the cruise power as a function of cruise speed can be calculated. There are two main constraint equations which must be satisfied for both loiter and the cruise phases, i.e., the endurance speed has at all times to be greater than the stall speed by some safety margin. Once loiter and cruise powers are determined, the electric motor and internal combustion engine and gearbox can be selected. The safe acoustic signature operating distance is determined via the noise dissipation equation shown.

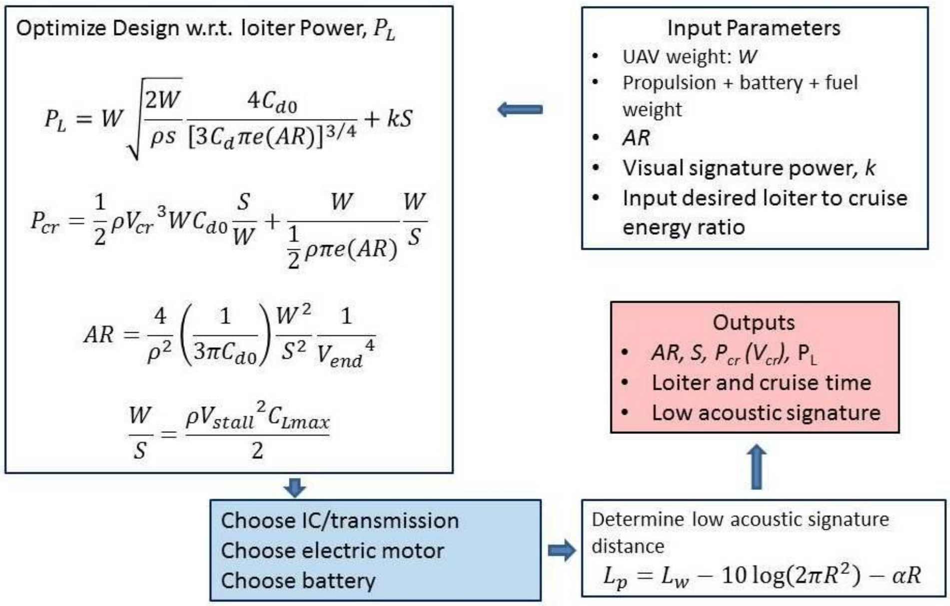

Fig. 11. Preliminary design flow diagram.

The required IC engine and EM powers are calculated assuming 80% efficiency for the propeller and the gearbox transmission. A 450 W IC engine was chosen weighing 0.2 kg, and a 150 W EM weighing 0.16 kg was selected. It can be shown that the efficiency of the IC engine was only 16%. The following equations where used in the calculations.

IC engine power:

$$P_{ICE} = \frac{P_{cr}}{\eta_{trans}\eta_{prop}} = \frac{250}{0.8 \times\cup 0.8} \approx 390\text{ W} \tag{2}$$

EM power:

$$P_{EM} = \frac{P_L}{\eta_{tran}\eta_{prop}} = \frac{85}{0.8 \times 0.8} \approx 132\text{ W} \tag{3}$$

These calculations led to the selections shown in Table 3.

Table 3. Selections for IC, transmission and EM.

IC selection	0.2 kg, η = 16%, 450 W
EM selection	0.16 kg, 150 W
GB weight	$\beta \times IC_{weight}$ $(1 \le \beta \le 2.5)$ kg
Battery & Fuel weight	$\left(2 - IC_{weight}(1+\beta)\right)$ kg
Battery stored energy	150 Wh/kg

The conceptual design has results in a hybrid-electric UAV with the specifications listed in Tables 4 and 5, and illustrated on Fig. 12. The design of the gearbox is of a conservative design with a weight of twice that of the internal combustion engine. The wing aspect ratio is taken as 9 and the battery weight options are left for the moment at 1.2, 1.1 and 1.0 kg. Obviously the less the battery rate, the more fuel can be taken onboard.

Table 4. Conceptual Design Specifications for the Hybrid-Electric UAV.

Parameter	Unit	Value
UAV weight	kg	6.6
IC weight/power	kg/Watts	0.2/450
GB weight (β = 2)	kg	0.4
EM weight/power	kg/Watts	0.16/150
Wing surface area (S)	m^2	0.81
AR		9
PL weight	kg	0.5

Table 5. Hybrid-electric UAV battery weight.

Design	Unit	Value
(1)	kg	1.2
(2)	kg	1.1
(3)	kg	1.0

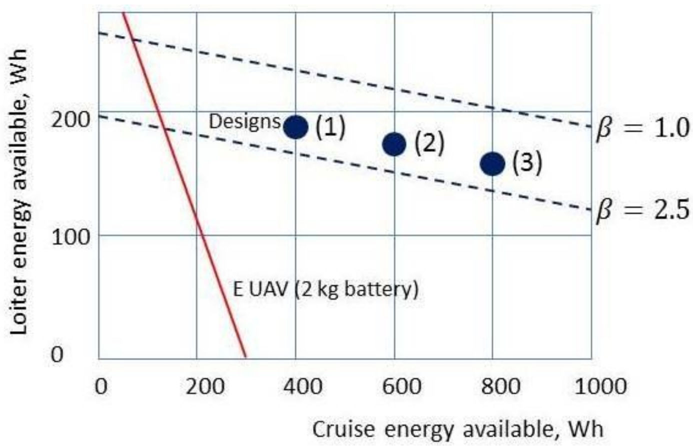

Fig. 12 Hybrid-electric UAV cruise vs. loiter power trade-off.

The conceptual design specified, which most likely is not the most optimum, demonstrates that an extended cruise endurance hybrid-electric UAV is feasible. This cruise extension does come as a result of a trade-off with the electric (quiet) part of the mission. For every 1 Wh loss of electric power there is a gain of approximately 13 Wh of cruise energy. The design uses existing components, for example, the electric motor, battery and IC engine specifications. Further attention will be needed in the choice of gearbox. Included in the design are estimates of power needed to illuminate the bottom of the aircraft to render it invisible to the eye against the sky.

5. Conclusions

The conceptual design of the hybrid-electric UAV demonstrates that an extended cruise endurance hybrid-electric UAV is feasible. The cruise endurance extension, however, comes at the expense of reducing the electric energy onboard: for every 1 Wh loss of electric energy for loiter, 13 Wh of cruise energy is gained. This means that the loiter endurance is reduced. The visual signature can be reduced by illuminating the hybrid-electric UAV's bottom surface with a model developed to estimate the illuminating power level. The acoustic signature can be reduced by maintaining a minimum distance to target which for this concept HE UAV would be about 300-400 m. Many of the components mentioned in this paper are commercially available.

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