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Multimodal Hybrid Powerplant for Unmanned Aerial Systems (UAS) Robotics

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Abstract

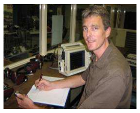
Most UAS propulsion systems currently utilize either Internal Combustion Engines (ICE) or Electric Motor (EM) prime movers. ICE are favoured for aircraft use due to the superior energy density of fuel compared to batteries required for EM, however EM have several significant advantages. A major advantage of EM is that they are inherently self starting have predictable response characteristics and well developed electronic control systems. EMs are thus very easy to adapt to automatic control, whereas ICE have more complex control response and an auxiliary starting motor is required for automated starting.

This paper presents a technique for determining the performance, feasibility and effectiveness of powerplant hybridisation for small UAS. A Hybrid Powerplant offers the possibility of a radical improvement in the autonomy of the aircraft for various tasks without sacrificing payload range or endurance capability. In this work a prototype Aircraft Hybrid Powerplant (AHP) was designed, constructed and tested. It is shown that an additional 35% continuous thrust power can be supplied from the hybrid system with an overall weight penalty of 5%, for a given UAS.

Dynamometer and windtunnel results were obtained to validate theoretical propulsion load curves. Using measured powerplant data and an assumed baseline airframe performance characteristic, theoretical endurance comparisons between hybrid and non-hybrid powerplants were determined. A flight dynamic model for the AHP was developed and validated for the purposes of operational scenario analysis. Through this simulation it is shown that climb rates can be improved by 56% and endurance increased by 13%.

The advantages of implementing a hybrid powerplant have been baselined in terms of payload range and endurance. Having satisfied these parameters, a whole new set of operational possibilities arises which cannot be performed by non-self-starting ICE only powered aircraft. A variety of autonomous robotic aircraft tasks enabled by the hybrid powerplant is discussed.

Keywords: UAS Aircraft Hybrid Propulsion Performance Simulation



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1 Introduction

Worldwide UAS development constitutes a significant aviation business growth segment. Visiongain [1] expects the global UAV market would reach a valuation of nearly $7.2 billion by 2009. A large proportion of emergent small UAS platforms rely on propeller propulsion using powerplants sourced from COTS aeromodelling equipment. Compared to traditional aircraft powerplants, many of these units have significant disadvantages in operational utility and energy efficiency.

Some systems developers have successfully modified COTS aeromodel ICE powerplants to obtain excellent endurance (eg aerosonde), however these units continue to be inflexible for a range of operational requirements (eg. manual starting, no in-flight re-start, fixed pitch propeller design). However it will be shown that even though there is an increased weight penalty, a suitable combination of ICE and EM powerplant configuration (hybridisation), particularly Brushless Direct Current EMs (BLDC) can lead to overall improvements in range, endurance, and payload capacity whilst simultaneously allowing greatly enhanced UAS operational flexibility. The benefits include improved take-off and climb performance, significant onboard electrical power generation, and electric-only stealth operation. In addition, the engine can be restarted remotely at any time, and the propeller may be used as a regenerative turbine as desired on descent.

Harmon et al [2] has investigated high level hybrid control schemes and Santangelo and Taylor [3] have investigated some aspects of engine management in a hybrid UAV powerplant context. There remains much scope for basic system optimisation techniques.

A parallel aircraft hybrid powerplant system is shown in the schematic representation in *Figure 1-1*. All of these components are already found on most operational UAS, eg Aerosonde, ScanEagle. The particular sizing, control system and mechanical design of these items must be determined to suit a desired airframe and mission performance.

A generic AHP propulsion system consists of Battery, EM, Fuel, ICE, Transmission and Propeller. These components must be modelled to characterise their individual performance in order to construct overall system characteristics. The important parameters are: Battery (Energy Density, Power Density, Mass, Charge efficiency), EM (Torque and Power Curves, efficiency), ICE (Torque and Power curves, efficiency), Transmission (Layout, efficiency) and Propeller (Thrust Coefficient, Power Coefficient, efficiency).

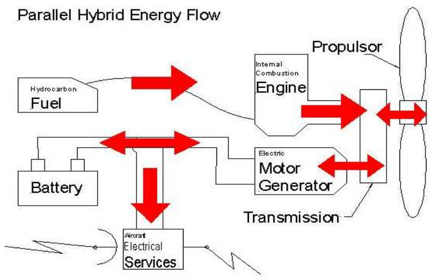

Figure 1-1. Parallel Aircraft Hybrid Powerplant Schematic

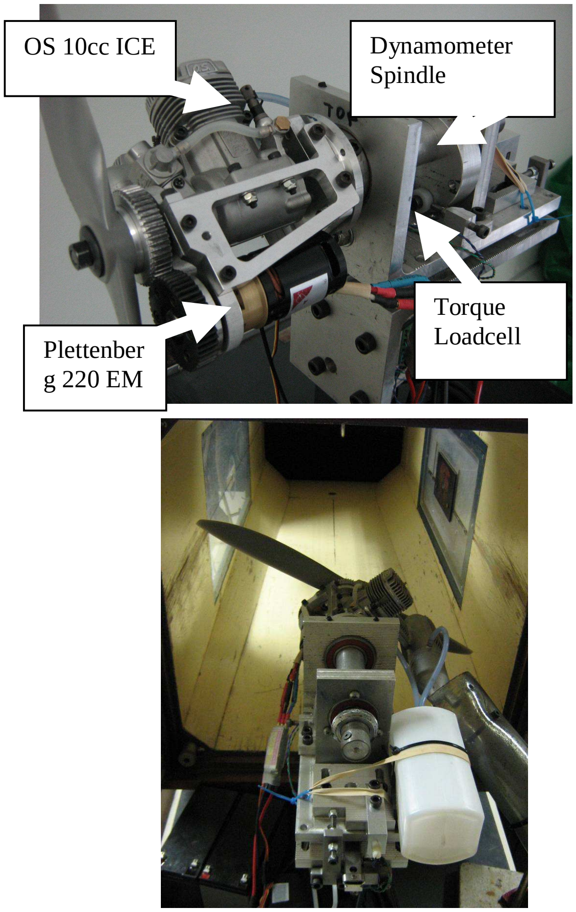

Figure 1-2. AHP on Dynamometer

A key tenet of the expected improvement in propulsive efficiency derives from the change of C_T , Thrust Coefficient, and C_Q, the Coefficient of Torque, with Advance Ratio, J [4]. The following analysis is based on a fixed pitch type propeller which is the most common type in use on small UAS. If a larger propeller can be driven at static and low speed conditions with the aid of EM boost power, at cruise speed, this same propeller may be driven from ICE power alone, or at a speed where some excess ICE power may be diverted to electrical services or storage.

Figure 1-3 below illustrates graphically the expected dynamometer trends.

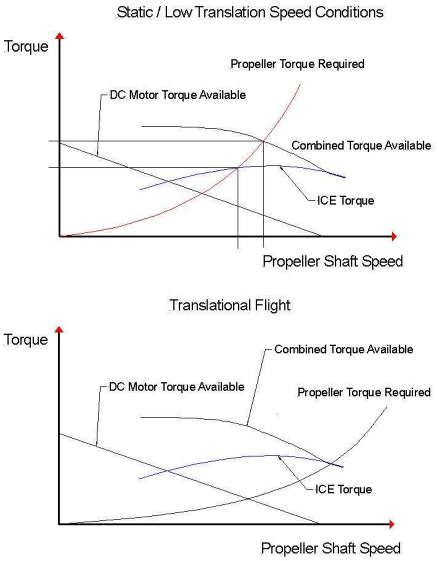

Figure 1-3 Expected Load Curves

1.1 Experimental Results

Figure 1-4 shows the measured static and translational torque curves for the 16”x6” (406mm diameter) propeller, the 10cc 2-stroke ICE, the EM and the combined prime-mover torque available. The 10cc ICE under consideration is designed to drive a 12”x6” (305mm diameter) propeller. It can be seen that for this combination of ICE and 16”x6” (oversize) propeller there is sufficient ICE torque available to supply the propeller torque required up to only 6800 RPM in the static condition. At this RPM the thrust available is low, see *Figure 1-6* (32N) compared to the thrust available when operating the conventional 12”x6” propeller (41N). Also the engine is operating well below its best power output condition, ie significantly to the left side of the torque curve, see *Figure 1-4* “Static Operating Point”. At the 30 m/s cruise condition (8000 RPM), the engine is operating within a good region of power output and BSFC and the thrust is comparable to that which would be obtained from the 12” propeller *Figure 1-5* and *Figure 1-6* show the take-off operating points for the 12” and 16” propeller respectively, note that in static conditions with no electric boost, the larger propeller configuration cannot produce as much thrust as the smaller propeller.

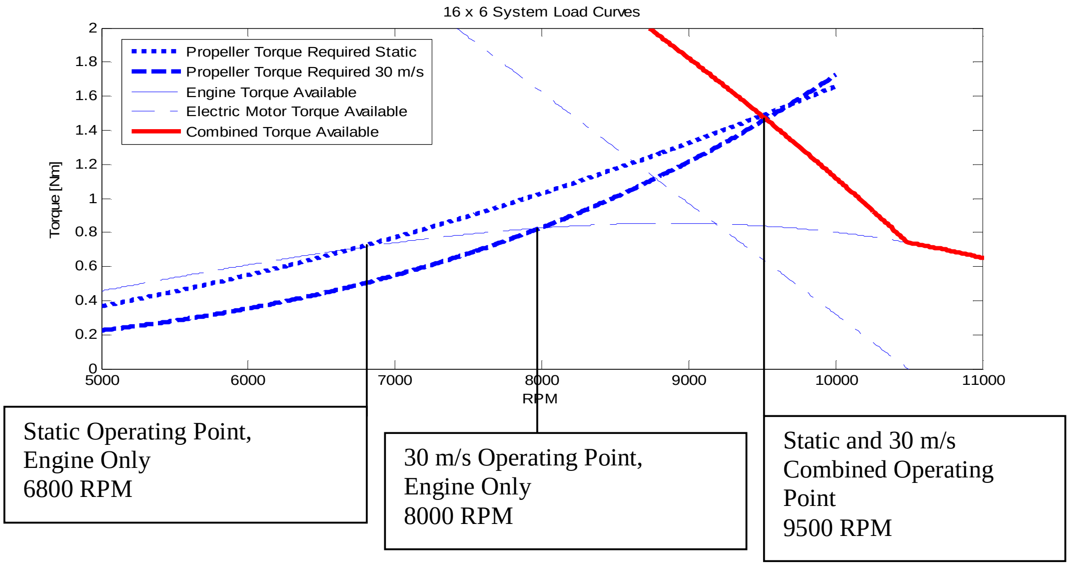

Figure 1-4 Hybrid System Load Curves

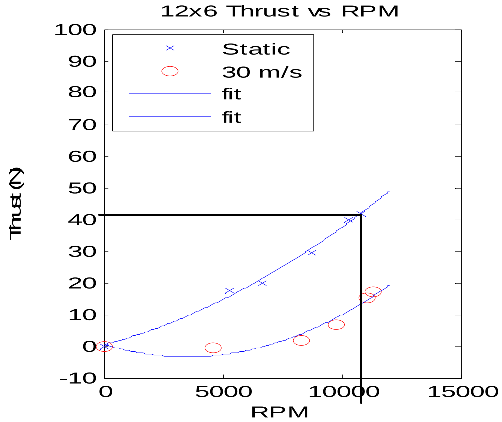

Figure 1-5 Conventional Size Propeller Thrust Curves

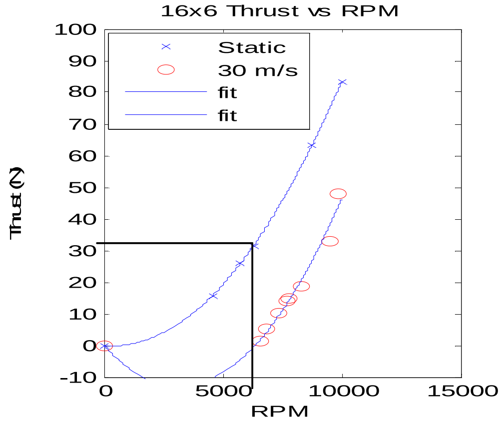

Figure 1-6 Oversize Propeller Performance Curves

Figure 1-6 shows the effect of oversizing the propeller for a given engine and gearing combination under static conditions, however as shown in *Table 1-3* during dynamic conditions at cruise speed, the same combination can develop equivalent thrust.

The static and translational operating points for the two different propellers are summarized in Table 1-1 and Table 1-2.

Table 1-1 Conventional size propeller performance summary.

12”X6” Prop	Engine Only Maxima		Full EM Boost Maxima	
Airspeed	RPM	Thrust [N]	RPM	Thrust [N]
Static	10 791	41.6	10388*	31.6*
30 m/s	11 000	16.5	N/A	N/A

*The reduction of thrust encountered upon attempted application of full boost via the Electronic Speed Controller (ESC) is a consequence of the motor speed and gear ratio matching. The electric motor was being run above the maximum speed for which the applied voltage could exceed the back emf, and hence it was operating as a generator.

Table 1-2 Oversize propeller performance summary.

16”X6” Prop	Engine Only Maxima		Full EM Boost Maxima	
Airspeed	RPM	Thrust [N]	RPM	Thrust [N]
Static	6360	31.2	10038	83.6
30 m/s	7860	15.7	9845	47.9

Table 1-2 shows that the application of boost torque from a Plettenberg 220 EM will give significant excess thrust (100% increase) at a shaft speed of around 10,000RPM at static conditions, compared to the non-hybrid equivalent. This would deliver much improved take-off and climb performance. At cruise condition, the propeller torque required curve has shifted to the right. Thus the maximum combined torque available allows higher RPM and thrust for higher flight speed or the generator mode may be employed to take advantage of the excess engine torque available at lower flight speeds requiring less thrust.

On the basis of this analysis, very high thrust output for take-off and climb, significant charging power at low speeds, engine-only operation at moderate speed, and electric-only operation at slower speeds, for a given airframe, is achievable. In addition, the engine can be restarted remotely at any time, and the propeller may be used as a turbine as desired on descent. Furthermore, the fuel flow in cruise can be reduced sufficiently to balance the carriage of the hybridising components. *Table 1-3* details the cruise thrust and fuel flow performance difference between the standard size propeller used on the ICE and the oversize propeller which can be used on the AHP.

Table 1-3Fuel flow summary.

Propeller	Airspeed [m/s]	RPM	Thrust [N]	FuelFlow [l/hr]
12 x 6	30	11000	16.5	1.76
16 x 6	30	7860	15.7	1.28

2 Scenario Modelling

Two modelling techniques have been used to validate the AHP propulsion system performance. Analytical modelling based on representative linearized parameters as well as comprehensive computer simulation. Improvements in the aircraft's range, endurance, and payload have been shown in comparison to existing powerplants.

2.1 Linearized Model

The purpose of this analysis is to compare the range or endurance outcomes of varying powerplant configuration, a full prototype system has yet to be flight tested. Therefore an airframe model must be combined with a powerplant and propulsion model for analytic comparison. The airframe model need only address some very basic parameters, based on representative lift drag ratios and a consequent thrust requirement. The propulsion model is based on the experimentally measured performance, i.e. thrust, and fuel flow at specific flight speeds. Additionally, since a primary constraint in UAV range and endurance arises due to electrical systems energy requirements, the model must incorporate energy supply and usage characteristics.

A real world UAV will operate in a continually changing environment, with variations across most system parameters leading to complex behaviour best analysed in simulation, however for the present purposes a simplified model holding most parameters constant or linearized will yield a clearer view of the powerplant specific effects.

2.1.1 Endurance Equation

The flight time or endurance of the aircraft will be defined according to the magnitude of storage supply and rate of consumption of relevant energy sources. These values were either estimated from real system experience as in the case of the airframe model, or are well known constants such as fuel energy density.

Fundamentally, $Power = \frac{Work}{Time}$

Then,

Endurance =

$$\left(\frac{\text{Energy Storage Density} \cdot \text{Energy Storage Mass} \cdot \text{Conversion Efficiency}}{\text{Power Consumption} \cdot (60)}\right)$$

$$\left[\frac{\text{second} \cdot \text{Joule} \cdot \text{minute} \cdot \text{kilogram}}{\text{Joule} \cdot \text{kilogram} \cdot \text{second}}\right]$$

$$\longrightarrow \quad \left[\frac{\cancel{\text{second}} \cdot \cancel{\text{Joule}} \cdot \text{minute} \cdot \cancel{\text{kilogram}}}{\cancel{\text{Joule}} \cdot \cancel{\text{kilogram}} \cdot \cancel{\text{second}}}\right]$$

$\longrightarrow$ [minutes]

The endurance is limited either by the payload energy availability or the propulsion energy availability, it is assumed that the total payload operating time should equate with the total propulsion operating time.

2.1.2 Case 1: Singular ICE operation with no onboard generator.

As determined from generic studies, and experimental outcomes for 12x6 propeller, the following quantities will be used;

Battery Energy Density = 0.50 MJ/kg

Battery Conversion Efficiency = 100%

Fuel Energy Density = 14.9 MJ/kg

Engine Efficiency = 8.7%

Engine Power Required for Propulsion = 710 Watts

Electrical Power Required for Payload = 50 Watts

W_{fuel} = mass of fuel, W_{bat} = mass of battery for payload power, W_{proIC} = mass of propulsion system, W_{Pay} = mass of payload

Endurance =

$$\left(\frac{\text{Energy Storage Density} \cdot \text{Energy Storage Mass} \cdot \text{Conversion Efficiency}}{\text{Power Consumption} \cdot (60)}\right)$$

$$\text{Endurance}_{\text{Payload}} = \left(\frac{\left(0.50\times10^{6}\right)\cdot\left(W_{bat}\right)\cdot(1)}{(50)\cdot(60)}\right)$$

$$\longrightarrow \quad \text{Endurance}_{\text{Payload}} = W_{bat} \times (166) \text{ [minutes]}$$

$$\text{Endurance}_{\text{Propulsion}} = \left(\frac{\left(14.9\times10^{6}\right)\cdot\left(W_{fuel}\right)\cdot(0.087)}{(710)\cdot(60)}\right)$$

$$\longrightarrow \text{Endurance}_{\text{Propulsion}} = W_{Fuel} \times (30.4) \text{ [minutes]}$$

Hence;

$$\text{Endurance}_{\text{Payload}} - W_{bat} \times (166) = 0$$

$$\text{Endurance}_{\text{Propulsion}} - W_{Fuel} \times (30.4) = 0$$

$$\text{Endurance}_{\text{Payload}} - \text{Endurance}_{\text{Propulsion}} = 0$$

$W_{fuel} + W_{bat} + W_{proIC} + W_{Pay} = 6$

$W_{proIC} - W_{fuel} = 0.7$

Solving for Endurance as a function of W_{pay}

$$\text{Endurance} = \frac{\left(5.3 - W_{Pay}\right)}{\left(\frac{1}{30.4} + \frac{1}{166}\right)} \quad \text{[minutes]}$$

For W_{pay} incremented by 1 kg and constant 50W power requirement the resulting Endurances are shown below in *Table 2-1*.

Table 2-1 Case 1 Endurance Summary

Payload [kg]	1	2	3	4
Maximum Endurance [minutes]	110	85	59	33

2.1.3 Case 2: Singular ICE operation with onboard generator.

In this case the quantity of battery mass for payload power will be variable to explore the resulting effects on endurance. At some point, for heavy payloads and relatively short flights, carrying the generator and associated equipment may be less effective than carrying sufficient battery.

The assumption that generator power will be available rests on the assumption that sufficient engine power above that required for generating the thrust at this condition is satisfied. Conceptually it is possible to retain the propeller RPM and thrust while operating the engine at the higher power, using gearing. A further assumption regarding the efficiency or SFC of the engine at the higher output must be made. It has been found already that the SFC remains fairly constant for this engine through the range considered, with a slight increase toward the higher end. For a conservative estimate, the original 12 x 6 efficiency (8.7%) will be assumed.

The following quantities will be used;

Battery Energy Density = 0.50 MJ/kg

Battery Conversion Efficiency = 100%

Fuel Energy Density = 14.9 MJ/kg

Engine Efficiency = 8.7%

Engine Power Required for Propulsion = 710 Watts

Electrical Power Required for Payload = 50 Watts

$W_{fuelPropulsion}$ = mass of fuel for propulsion only, $W_{fuelPayloadPower}$ = mass of fuel for payload power generation, W_{bat} = mass of battery for payload power, $W_{proICgen}$ = mass of propulsion system including generator and power conditioner (rectifier etc), W_{Pay} = mass of payload.

$$\text{Endurance} = \left(\frac{\text{Energy Storage Density}\cdot\text{Energy Storage Mass}\cdot\text{Conversion Efficiency}}{\text{Power Consumption}\cdot(60)}\right)$$

Noting that the Payload Power will be provided by a combination of the battery and the generator, the resultant operating time will be the sum of the times provided by each source. Thus;

$$\text{Endurance}_{\text{Payload}} = \left(\frac{\left(0.50\times10^{6}\right)\cdot\left(\text{W}_{\text{bat}}\right)\cdot(1)}{(50)\cdot(60)}\right) + \left(\frac{\left(14.9\times10^{6}\right)\cdot\left(\text{W}_{\text{fuelPayloadPower}}\right)\cdot(0.087)\cdot(0.50)}{(50)\cdot(60)}\right)$$

$$\longrightarrow \text{Endurance}_{\text{Payload}} = \left(\text{W}_{\text{bat}}\times(166)\right) + \text{W}_{\text{fuelPayloadPower}}\times(216)\ \text{[minutes]}$$

$$\text{Endurance}_{\text{Propulsion}} = \left(\frac{\left(14.9\times10^{6}\right)\cdot\left(\text{W}_{\text{fuelPropulsion}}\right)\cdot(0.087)}{(710)\cdot(60)}\right)$$

$$\longrightarrow \text{Endurance}_{\text{Propulsion}} = \text{W}_{\text{fuelPropulsion}}\times(30.4)\ \text{[minutes]}$$

$$\text{W}_{\text{fuel}} = \text{W}_{\text{fuelPropulsion}} + \text{W}_{\text{fuelPayloadPower}}$$

Let p = proportion of payload energy mass as battery mass

$$\text{Let } R_{pp} = \frac{W_{bat}}{W_{fuelPayloadPower}} = \left(\frac{p}{1-p}\right)$$

$$\text{Endurance}_{\text{Payload}} = \left(\text{W}_{\text{bat}}\times(166)\right) + \text{W}_{\text{fuelPayloadPower}}\times(216)$$

$$\text{Endurance}_{\text{Propulsion}} = \text{W}_{\text{fuelPropulsion}}\times(30.4)$$

$$\text{Endurance}_{\text{Payload}} - \text{Endurance}_{\text{Propulsion}} = 0$$

$$\text{W}_{\text{fuelPayloadPower}} + \text{W}_{\text{bat}} + \text{W}_{\text{proICgen}} + \text{W}_{\text{Pay}} = 6$$

$$\text{W}_{\text{proICgen}} - \text{W}_{\text{fuelPropulsion}} = 1.015$$

$$\text{W}_{\text{fuel}} = \text{W}_{\text{fuelPropulsion}} + \text{W}_{\text{fuelPayloadPower}}$$

Solve for Endurance as a function of W_{pay} and R_{pp}

$$\text{Endurance} = \frac{\left(4.985 - \text{W}_{\text{pay}}\right)}{\left(\frac{1}{216}+\frac{1}{30.4}\right) - \frac{p\left(\frac{166}{216}-1\right)}{\left(\left(166\times p\right) + 216(1-p)\right)}}\ \text{[minutes]}$$

Figure 2-1 shows the flight time plotted for all values of payload and generator utilization factor.

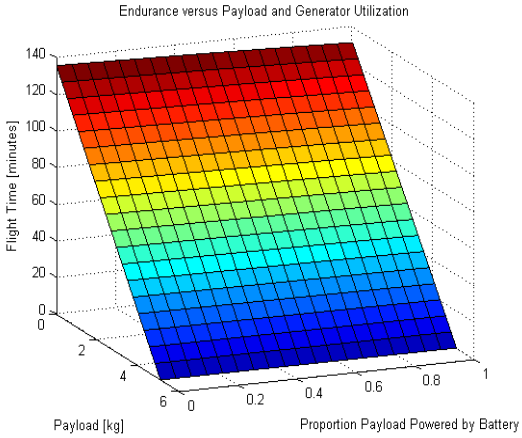

Figure 2-1 Case 2 Endurance, Payload and Generator Utilization

Given that a generator is fitted, it is always better for endurance to use it for all values of payload mass. There may be situations where carrying some proportion of payload energy as battery is required, such that the payload remains operational with the engine shutdown. The figure above shows the cost to endurance of this trade-off.

In this case, the change in endurance is slight due to the inefficiency of the engine, the low energy density of the methanol fuel, and the high energy density of the assumed battery type.

Table 2-2 Case 2 Endurance Summary

	Payload [kg]	1	2	3	4
Maximum Endurance [minutes]	Generator Only (p=0)	106	80	52	26
	Battery Only (p=1)	102	76	51	25

In comparison to Case 1, the endurance has decreased. A consequence of the low engine efficiency, fuel energy density and moderate payload power consumption in this example is that carrying the extra generator weight is not as beneficial as carrying that weight in extra fuel and battery. Referring to *Table 2-2*, it is clear that the aircraft could fly slightly longer at all payloads, if no generator were fitted.

For comparison, a plot showing the value of utilizing a generator with better values for engine efficiency (22%), and petrol fuel (40 MJ/kg) and higher payload power consumption (100W) on the same airframe and payload is shown in *Figure 2-2* below. These engine and fuel parameters are consistent with commercial operational UAVs such as Aerosonde and ScanEagle, the following plot exemplifies why generators are present on these aircraft.

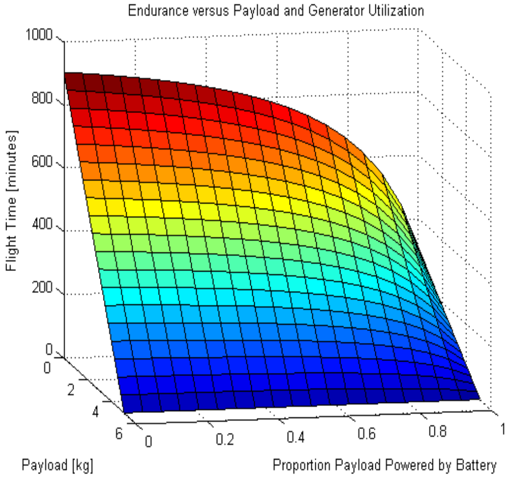

Figure 2-2 Endurance, Payload and Generator Utilization for Case 2 High Efficiency

A marked improvement in endurance is seen for all values of payload when utilizing the generator to power the payload, rather than batteries, when high efficiency engine and fuel is used as summarized in *Table 2-3*.

Table 2-3 Case 2 High Efficiency Fuel and Engine with Generator Endurance

	Payload [kg]	1	2	3	4
Maximum Endurance [minutes]	Generator Only (p=0)	719	539	359	178
	Battery Only (p=1)	236	177	117	58

2.1.4 Case 3: Hybrid

As for Case 2, the requirement for the engine to produce more power to service both propulsion and electrical generation is assumed to be feasible by suitably gearing to a higher point on the power curve. The Propulsion power required from the engine is based on the thrust required, airspeed and propeller efficiency. For the baseline airframe, these factors do not change. In full hybrid mode then, this engine will be required to operate at significantly higher RPM to generate the 100W extra power required for the assumed payload requirement after 50% power-conditioning efficiency. It has been shown that at the higher RPM this engine will be slightly more efficient, however as a conservative estimate, the lower efficiency (8.3%) will be assumed.

The following quantities will be used. Note that the engine efficiency and propulsion power required are altered to reflect the measured experimental outcomes of changing the propeller;

Battery Energy Density = 0.50 MJ/kg

Battery Conversion Efficiency = 100%

Fuel Energy Density = 14.9 MJ/kg

Engine Efficiency = 8.3%

Engine Power Required for Propulsion = 510 Watts

Electrical Power Required for Payload = 50 Watts

$W_{fuelPropulsion}$ = mass of fuel for propulsion only, $W_{fuelPayloadPower}$ = mass of fuel for payload power generation, W_{bat} = mass of battery for payload power, W_{hybrid} = mass of propulsion system including starter/generator and power conditioner (ESC), W_{Pay} = mass of payload

Endurance =

$$\left(\frac{\text{EnergyStorageDensity}\cdot\text{EnergyStorageMass}\cdot\text{ConversionEfficiency}}{\text{PowerConsumption}\cdot(60)}\right)$$

Again, the Payload Power will be provided by a combination of the battery and the generator;

$\text{Endurance}_{\text{Payload}}$ =

$$\left(\frac{\left(0.50\times10^{6}\right)\cdot\left(W_{bat}\right)\cdot(1)}{(50)\cdot(60)}\right)$$

+

$$\left(\frac{\left(14.9\times10^{6}\right)\cdot\left(W_{fuelPayloadPower}\right)\cdot(0.083)\cdot(0.50)}{(50)\cdot(60)}\right)$$

$$\longrightarrow \text{Endurance}_{\text{Payload}} = \left(W_{bat}\times(166)\right) + W_{fuelPayloadPower}\times(206) \quad \text{[minutes]}$$

$\text{Endurance}_{\text{Propulsion}}$ =

$$\left(\frac{\left(14.9\times10^{6}\right)\cdot\left(W_{fuelPropulsion}\right)\cdot(0.083)}{(545)\cdot(60)}\right)$$

$$\longrightarrow \text{Endurance}_{\text{Propulsion}} = W_{fuelPropulsion}\times(378) \quad \text{[minutes]}$$

$W_{fuel} = W_{fuelPropulsion} + W_{fuelPayload}$

$$\text{Let } R_{pp} = \frac{W_{bat}}{W_{fuelPayloadPower}} = \left(\frac{p}{1-p}\right)$$

$$\text{Endurance}_{\text{Payload}} = \left(W_{bat}\times(166)\right) + W_{fuelPayloadPower}\times(206)$$

$$\text{Endurance}_{\text{Propulsion}} = W_{fuelPropulsion}\times(37.8)$$

$$\text{FlightTime}_{\text{Payload}} - \text{FlightTime}_{\text{Propulsion}} = 0$$

$W_{fuelPayloadPower} + W_{bat} + W_{hybrid} + W_{Pay} = 6$

$W_{hybrid} - W_{fuelPropulsion} = 1.130$

$W_{fuel} = W_{fuelPropulsion} + W_{fuelPayloadPower}$

Solve for Endurance as a function of W_{pay} and R_{pp}

Endurance =

$$\frac{\left(4.87 - W_{pay}\right)}{\left(\frac{1}{206}+\frac{1}{37.8}\right) - \frac{p\left(\frac{166}{206}-1\right)}{\left(\left(166\times p\right)+206(1-p)\right)}}$$

[minutes]

Figure 2-3 below plots the endurance according to Case 3 parameters.

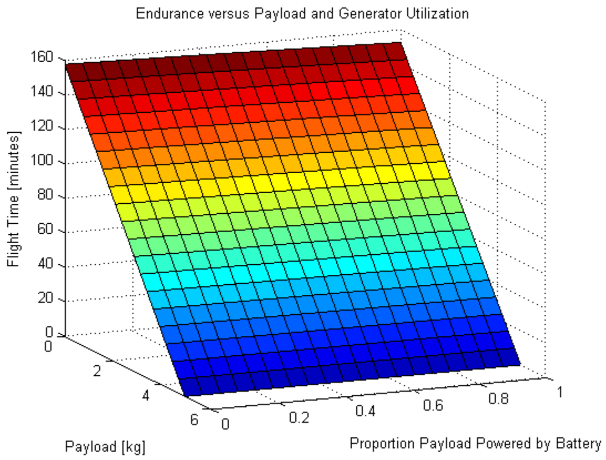

Figure 2-3 Case 3 Hybrid Endurance, Payload and Generator Utilization

Table 2-4 summarizes that the hybrid powerplant equipped aircraft has increased endurance at all payloads and payload power battery usage compared to the generator only equipped aircraft. The extra mass of the electrical boost motor and subsequent loss of fuel mass capacity is more than offset by the improved overall propulsive efficiency at the design conditions.

Table 2-4 Case 3, Hybrid Endurance

	Payload [kg]	1	2	3	4
Maximum Endurance [minutes]	Generator Only (p=0)	124	92	60	29
	Battery Only (p=1)	119	88	58	27

2.2 Summary

The following table summarizes the theoretical endurance of the given airframe model utilizing the three powerplant options.

Table 2-5 Powerplant Specific Endurance Comparison

Payload [kg]	1	2	3	4
Maximum Endurance No Generator/Hybrid [minutes]	110	85	59	33
Maximum Endurance Generator Only [minutes]	106	80	52	26
Maximum Endurance Hybrid [minutes]	124	92	60	29

The improvements of Case 3 hybrid endurance over the Case 1 and 2 powerplants are due to the increased propeller efficiency. It is clear that the Case 1 and 2 powerplant configurations could be fitted with a Case 3 propeller to yield the same cruise performance, however it must be emphasized that the main conditional assumptions are that the aircraft must be capable of independent takeoff performance and use a fixed pitch propeller. If fitted with the larger propeller, both Case 1 and 2 powerplants would suffer a 25% decrease in static thrust compared to the original propeller, see *Figure 1-6.* Neither Case 1 nor Case 2 powerplants can deliver the static and low-speed thrust which the Case 3 hybrid powerplant is capable of. Under these conditions the hybrid powerplant appears to be superior for all but the highest payload mass and shortest duration missions.

The difference is modest due to the poor efficiency of the given engine and fuel energy density, but even under these conditions the aircraft has extremely improved utility and effectiveness in addition to improved endurance.

Using measured powerplant data and an assumed baseline airframe performance characteristic, the theoretical endurance comparison between powerplants as shown in *Table 2-5* was be determined. Apart from airframe energy use parameters, the key assumption in this comparison is an equivalent onboard systems electrical power requirement. Thus, a trade-off between carriage of battery and carriage of generator and fuel was arranged. The difference in “Generator Only” and “Hybrid” endurance which implies extra propulsion system weight is accounted for by the improved cruise thrust per fuelflow ratio which was observed using the oversized propeller.

Modelling of overall energy requirements for a representative UAV (uninhabited aerial vehicle) indicate that an overall improvement in endurance is possible for most mission scenarios. Maximum payload mass implies minimum fuel carriage, systems electrical energy requirement, and endurance, hence it is better to carry a battery for the systems electrical supply and replace the generator mass with propulsion fuel in this case. At some intermediate payload, Hybrid propulsion maximises endurance.

3 Increased Autonomy Scenarios

The advantages of implementing a hybrid powerplant have been base-lined in terms of payload range and endurance. Having satisfied these parameters, a whole new set of operational possibilities arises which cannot be performed by non-self-starting ICE only powered aircraft.

Compared to an all electric battery powered aircraft the hybrid powered aircraft will have significantly greater overall energy density owing to the carriage of hydrocarbon fuel. The energy may be expended in propulsion, payload or communications processes.

3.1 Remote Operations

Self-starting allows a UAV to fly to, and land at a remote destination which may have no infrastructure or human support, with the option of shutting down the propulsion system and re-launching for further destinations or return and recovery. There are several advantages to shutting down the propulsion system, including reduced fuel consumption, reduced damage risk to aircraft and surrounds, and reduced noise. The UAV may remain on station for long periods of time with the powerplant shutdown, and be capable of generating power for battery replenishment as required. Generally, the availability of significant boost power, even for very short duration, can greatly improve take-off performance and success rate [5]. Particular configurations could be capable of expending all fuel, yet be capable of returning solely by EM propulsion.

3.1.1 Goods Delivery and Pickup

Where a UAV is used for goods delivery or pickup, it is clearly advantageous for safety to be able to shutdown the propulsion system. An operator may unload and reload the cargo bay without undue risk of injury, and need not be concerned about time restriction due to fuel use. Also the ground operator need not have special training or equipment and so the geographic operational flexibility of the system is maximised.

3.1.2 Remote Power, Processing and Communications

The hybrid powered UAV is a mobile electrical generating station complete with computer power and communications systems. The aircraft can navigate to a remote area, land, and become a resource for people in that area.

3.1.3 Sit and Stare

Having a UAV deployed in a remote location with reliable power supply and re-launch capability enables information to be gathered, processed, stored or relayed. Multiple locations can be visited without operator intervention.

3.2 In-flight Restart

A major cause of UAV loss in long range operations is due to propulsion failure [6]. As for human piloted aircraft, fuel system control and reliability as well as significant changes in enroute ambient conditions requiring fuel mixture control or anti-icing measures can cause temporary failures. The system may be capable of operation again after some remedial actions or simply passage of time, however with no self-start, there is little possibility of recovery even with a viable powerplant.

The hybrid system also naturally allows redundancy. The transmission may be configured to allow EM torque only to supply to the propeller and hence, a critical failure in the ICE or fuel system will not cause complete thrust loss. Partial thrust, or full thrust for some time may prevent an inappropriate forced landing and allow recovery of the UAV.

3.3 Stealth

Military UAVs are often used for surveillance where the lowest possible noise signature is required. The hybrid powerplant can allow EM operation or gliding flight with subsequent ICE restart. Non-military uses for low noise signature aircraft include environmental monitoring and overflight of residential areas. An airbourne camera platform for example, may require significant ICE power for launch, hover or climb, but be capable of loitering on station with minimal EM power.

3.4 Dash/Intercept

The nature of EM prime-movers allows for extreme overloads for short durations [7]. The EM may provide several times its rated continuous power for take-off, but this can also be utilized to momentarily increase flight speed, climb rate or climb angle. Such manoeuvres will drain the battery, however given the necessarily short duty time, the battery state of charge can be recovered during normal cruise. This performance capability of the vehicle can maximize the chances of successful intercept or egress from targets and threats.

A simulation in MATLAB® Simulink® simulation environment combined with the AeroSim Aerosonde™ Airframe Blockset. Plettenberg HP220/25 motor power with constant 18V input, was applied in parallel with the Aerosonde™ engine. The block diagram for this model is shown in *Figure 3-1*.

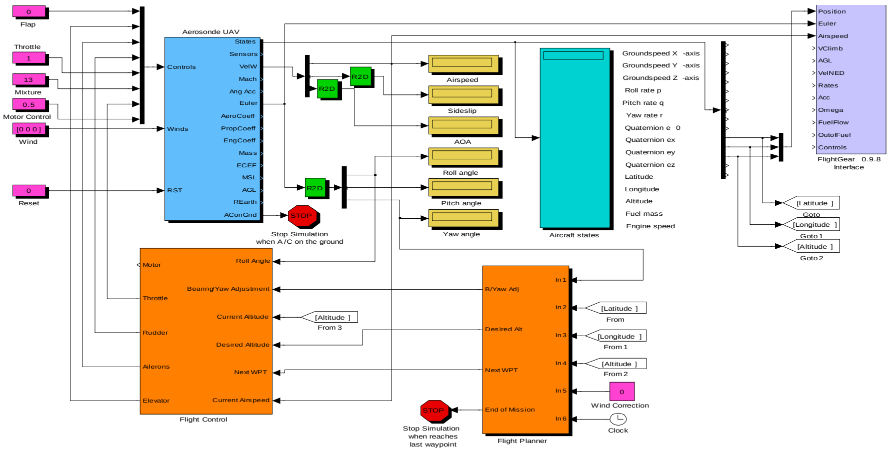

Figure 3-1 The Simulation Model

As a preliminary performance comparison of the AHP and ICE, the simulation model was set up to determine the rate of climb and time required to reach a designated altitude, given the different powerplants used. For each case, the aircraft travels with a constant heading at a fixed airspeed of 20m/s, climbing from an altitude of 300m, with a maximum power setting, up to 1000m. The results of the simulations are shown in the following section.

3.4.1 Simulation Results

Data generated from the execution of the simulation model given the above-mentioned scenario were formulated into the following graph. *Figure 3-2* shows the aircraft altitude with respect to time for the ICE only and AHP.

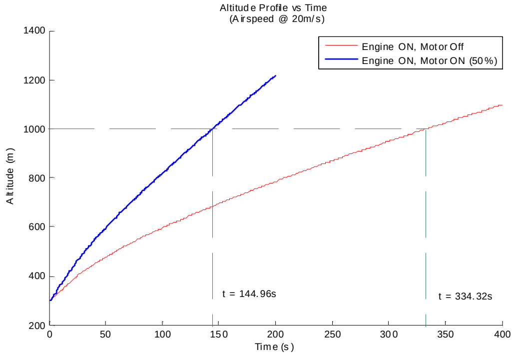

Figure 3-2 Simulated AHP Boosted versus Non-boosted Climb Performance

It is evident from the *Figure 3-2* that the climb rate for the AHP-powered Aerosonde™ is significantly greater than that of the ICE-powered version. The time required for the AHP to reach the designated altitude of 1000m (144.96s) is less than half that of the ICE (334.32s), an improvement of 56%.

The electrical energy used for the climb amounts to 26.3Wh. Assuming an overall EM system efficiency of 80%, the battery weight required to store this energy would typically be around 0.5kg for a NiMH battery with practical energy density of 70Wh/kg. The aircraft type in simulation had an all up weight of 14kg.

3.4.2 Discussion

The result of this basic simulation concurs with one of the major reasons for using an AHP propulsion system onboard an UAV. As expected the extra power provided by the electric motor was able to significantly increase the aircraft's climb rate and thus reduce the time required to reach a given altitude. Thus far, the simulation model block setup provides a reasonable output, on given parameters. However, this simulation was carried out with the assumption that the required voltage and current can be supplied continuously and has yet to take the battery component of the AHP system into consideration. The inclusion of the battery and associated components will constitute the next stage in the development of the simulation model, then further development will enable extended scenarios.

3.5 Windmill/Solar/Mains Recharge

The onboard supply of hydrocarbon fuel is naturally limited, however a hybrid powered UAV may utilize off-board energy resources in a variety of ways. Solar panels are viable and already in use for electric powered UAVs. [8]

The aircraft propeller can be used as a windmill, either in-flight or on the ground to provide energy to the electrical generator and battery. A windtunnel study on the efficiency and viability of this process was conducted. *Figure 3-3* shows the propeller mounted to a DC generator in a windtunnel.

The turbine RPM was controlled with a variable resistor across the generator terminals. Measurements of voltage and current were taken for various speeds, while simultaneous measurements of torque and drag were taken from the dynamometer.

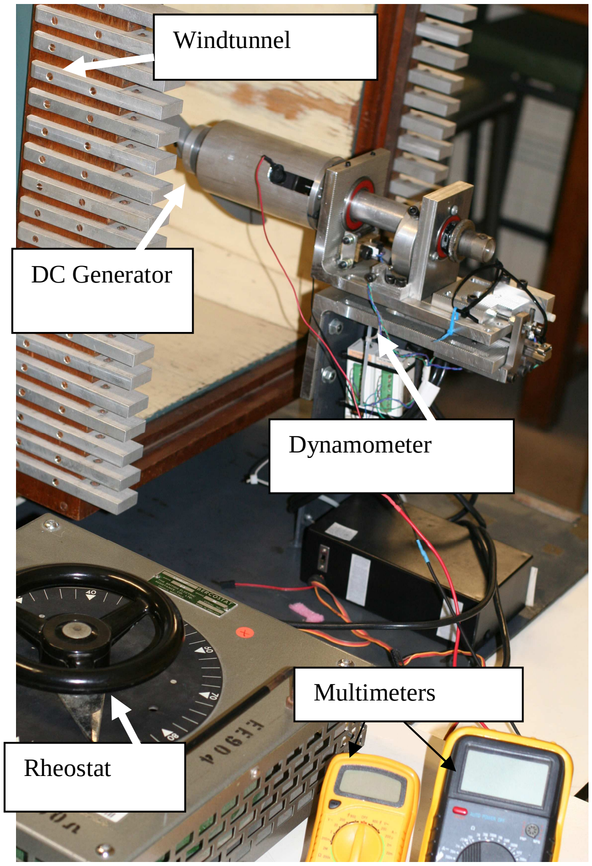

Figure 3-3 Propeller Wind Turbine Experimental Setup

Although using a propeller in this way is relatively inefficient, around 5% of the available airflow energy can be harnessed. *Figure 3-4* shows turbine power generated by the 16’ x 6’ propeller at various velocities.

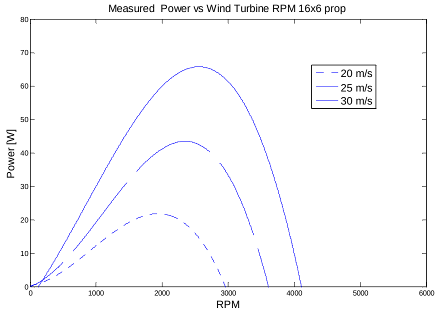

Figure 3-4 Propeller Turbine Power

This useful energy recuperation comes at the expense of considerable drag, which restricts the viability for airbourne application to cases where significant excess altitude or environmental updraughts are present [9]. However when ground based, available wind energy can be used at no cost. *Figure 3-5* shows the measured turbine drag at various velocities.

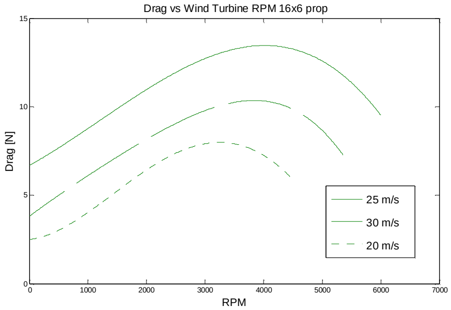

Figure 3-5 Propeller Turbine Drag

If the UAV is landed near mains supply, a suitable connection can be made for recharging. This process could be achieved manually by minimally trained personnel using standard household connectors, or autonomously using specifically engineered devices.

4 Conclusions and Recommendations

The foundation for analysis, development and verification of an improved UAS propulsion system has been laid. A combination of empirically measured data, classical and modern analytical processes can be used to predict performance outcomes and guide system design.

Improved propulsion energy management, storage and delivery systems for UAS can yield a variety of beneficial outcomes. The sizing and matching of prime-movers such as EMs and ICEs with propellers to suit specific operational requirements can be simplified by utilizing load curve techniques. Larger diameter fixed pitch propellers with higher propulsive efficiency can be used across a higher range of aircraft speed, than possible with normally aspirated ICE only powerplant.

Future work will refine propeller, engine and airframe empirical analysis with better experimental apparatus. Also the computer simulation systems for all these items will be enhanced and integrated. Improvements to the accuracy and precision of both these forms of analysis can then be made by reference to the resulting real world aircraft performance.

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