Multimodal Hybrid Powerplant for Unmanned Aerial Systems (UAS) Robotics

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Abstract

This paper presents a technique for determining the performance, feasibility and effectiveness of powerplant hybridisation for Uninhabited Aerial Vehicles (UAVs). A Hybrid Powerplant offers the possiblity 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% power can be supplied from the hybrid system with an overall weight penalty of 5%, for a given UAS. A flight dynamic model was developed using the AeroSim™ Blockset in MATLAB® Simulink®. The results have shown that climb rates can be improved by 56% and endurance increased by 13% when using the hybrid powerplant concept. A variety of autonomous robotic aircraft tasks enabled by the hybrid powerplant is discussed.

1 Introduction

Most UAS propulsion systems currently utilize either Internal Combustion Engines (ICE) or Electric Motor (EM) prime movers. ICE are often favoured for aircraft use due to 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.

Starter motors are often omitted due to the extra weight which can compromise aircraft range or endurance, and hence the autonomy of the vehicle becomes limited. However many UAS carry onboard generators to provide electrical flight control and payload services power and an opportunity exists to combine the starting and generating equipment as a starter generator to minimise weight. Figure 1.1 shows the powerplant of a very successful small UAV the Insitu “ScanEagle” [Insitu 2008]. This long endurance UAV powerplant incorporates a high efficiency engine, an electrical generator, and fixed pitch propeller and is representative of its class. Engine starting is by means of externally supplied torque acting on the spinner.

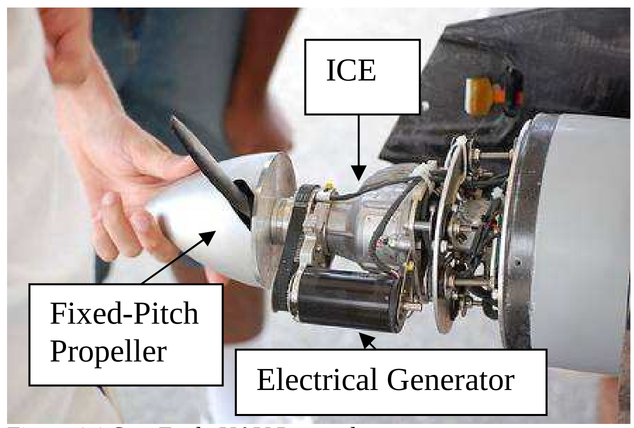

Figure 1.1 ScanEagle UAV Powerplant

If the specification and sizing of the starter generator can lead to a proportion of propulsive power being provided by the starter motor it becomes a Hybrid Powerplant [Miller 2004]. In order to gain industry acceptance, a Hybrid Powerplant should demonstrate overall improvements in aircraft payload, range or endurance capability.

The main components of a parallel aircraft hybrid power plant and there interactions are shown in the schematic Figure 1.2. The arrows indicate the possible theoretical energy flows. The transmission type will determine which flows are viable for a particular installation. The engine and motor may be connected via fixed or variable ratio gears, belts, clutches or a single integrated shaft.

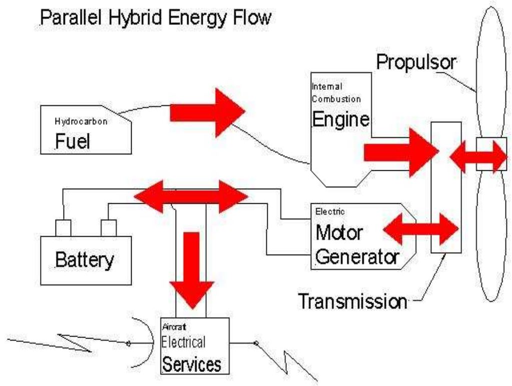

Figure 1.2 Parallel Hybrid Schematic Diagram

It is important to note that all small UAVs of the type in consideration use fixed pitch propellers which inherently limit propulsive efficiency for various flight regimes [Mair et al., 1992]. The opportunity to utilize the properties of a hybrid powerplant in concert with a fixed pitch propeller to increase overall efficiency and offset weight increase is a key driver for this research.

1.1 Experimental Setup

A generic AHP propulsion system consists of Battery, Motor, Fuel, Engine, Transmission and Propeller. These components must be modelled and tested to characterise their individual performance in order to construct overall system characteristics. A prototype AHP was constructed as shown in figure 1.3.

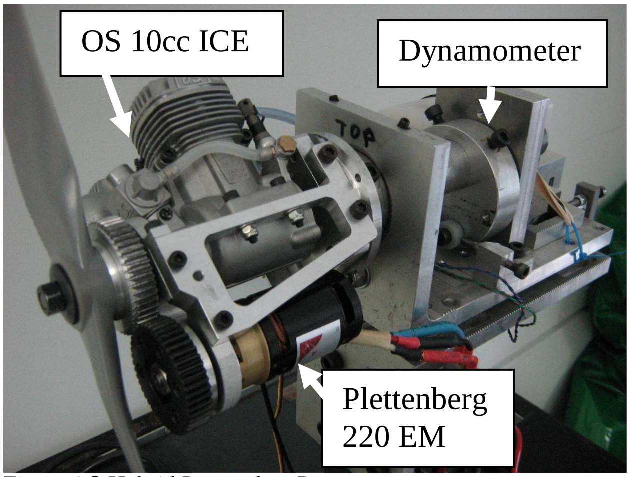

Figure 1.3 Hybrid Powerplant Prototype

Dynamometer results were obtained to validate the theoretical load curves in Figure 1.4 and Figure 1.5. The two figures show the very low speed take-off (static) condition and the higher speed (translational) cruise condition respectively. The "combined torque available" is simply the algebraic sum of the individual ICE and EM torque available at each shaft speed condition. In practice there will usually be some innefficiency due to the transmission system, but this is considered negligible.

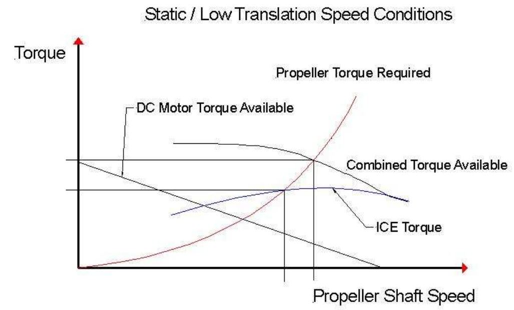

Figure 1.4 Hybrid Powerplant Theoretical Load Curves Static (take-off condition)

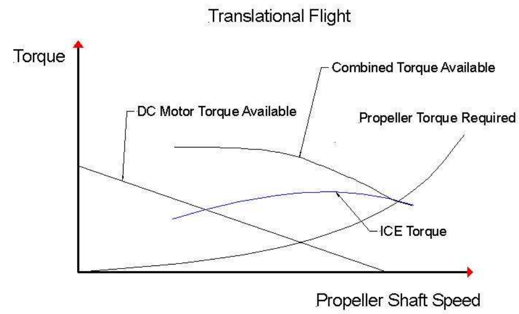

Figure 1.5 Hybrid Powerplant Theoretical Load Curves Translational (cruise speed)

It is expected that the propeller torque required for any particular operating RPM will reduce as forward translational speed is increased . A propeller may be sized for cruise condition efficiency but be unsuitable for takeoff and climb performance. Many current small UAVs require significant external infrastructure such as launch catapults [Aerosonde 2008] or well prepared runways to ensure successful takeoffs with cruise configured propulsion.

Figure 1.6 Aerosonde Launch Mechanism

The hybrid powerplant incorporates significant variation in available torque magnitude and duty time, which can be modeled and engineered for particular outcomes. The increased torque available translates into increased thrust and therefore aircraft performance capability irrespective of the propeller selection. Thus an aircraft with cruise configuration propeller can be capable of the take-off and climb performance it would get from a take-off optimised propeller.

1.2 Experimental Results

The prototype powerplant was measured using a dynamometer and windtunnel to yield the load curves shown in Figure 1.7.

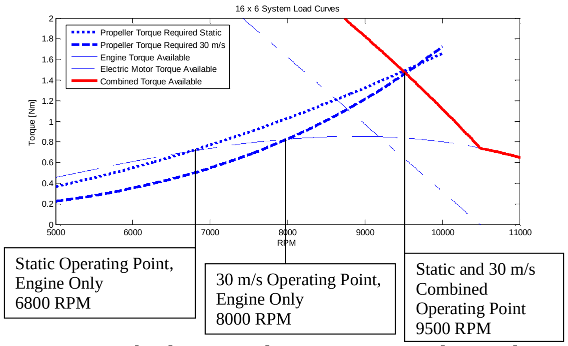

Figure 1.7 Hybrid Powerplant Experimental Results Load Curves

The load curves indicate system operating points and what component changes would be required to alter them. Thrust and fuel flow measurements at these operating points allow efficiency calculations. The performance data tabulated in Figure 1.1 is a baseline reference for a 12”x6” propeller which is the standard size for the given engine. Figure 1.2 shows the corresponding performance as plotted in Figure 1.7.

12” x 6” Prop	Engine Only Maxima		Full Boost Maxima	
Airspeed	RPM	Thrust [N]	RPM	Thrust [N]
Static	10 791	41.6	10 388*	31.6*
30 m/s	11 000	16.5	N/A	N/A

Table 1.1 Standard Size Propeller Experimental Results

*The reduction of thrust encountered upon attempted application of full boost via the ESC is an interesting 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.

A 16” x 6” propeller represents a significant overload for this engine, particularly at static or low forward flight speeds. However with EM boost power, the engine can perform in its optimum speed range and the total take-off power and thrust is significantly increased.

16” x 6” Prop	Engine Only Maxima		Full 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 Oversize Propeller Experimental Results

At 30 m/s translational cruise condition, the 16” x6” propeller non-boosted thrust is seen to be very close to the 12” x 6” propeller case, however the fuel flow rate was reduced by 27%.

Using measured powerplant data and an assumed baseline airframe performance characteristic, the theoretical endurance comparison between powerplants as shown in Table 1.3 was be determined. Apart from airframe energy use parameters, the key assumption in this comparison is an equivalent onboard systems electrical power requirement of 50 Watts. 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.

The Energy Density and Power Density of EM versus ICE powerplants is a major consideration. The type of ICE used in this study is a 2-stroke Methanol burning type. The methanol based fuel is a relatively low-grade hydrocarbon fuel in terms energy density at approximately 15 MJ/kg and measurements of the test engine indicate an overall thermal efficiency of around 8%. The battery used for analysis is a Lithium Polymer type which is at the high end of readily available technology but has an energy density of approximately 0.6 MJ/kg. The Brushless Direct Current Motor (BLDC) and Electronic Speed Controller (ESC) used in the testing have a published combined efficiency of around 85%, but the analysis assumes that only the engine delivers power for propulsion. The battery energy delivery to the payload and systems was assumed to be 100% efficient. Little data was available concerning these components in a charge mode situation so a conservative estimate of 50% was used.

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

Table 1.3 Analytical Performance Comparison

All relevent UAVs require a certain amount of electrical energy to service the aircraft avionics and control requirements. Furthermore, many UAV payloads are themselves dependent on electrical energy for their function. According to this analysis, it is possible to carry more payload for longer distances when utilizing a hybrid powerplant than when using a non-hybrid ICE and battery storage.

2. Increased Autonomy Scenarios

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 possibilties 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.

2.1 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 relaunching 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 [Hurt 1960]. Particular configurations could be capable of expending all fuel, yet be capable of returning solely by EM propulsion.

Goods Delivery and Pickup

Where a UAV is used for goods delivery or pickup, it is clearly advantageous for safety to be able 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.

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.

Sit and Stare

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

2.2 Inflight Restart

A major cause of UAV loss in long range operations is due to propulsion failure [Fitzgerald et al., 2005] . As for human piloted aircraft, fuel system control and reliabilty 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 innappropriate forced landing and allow recovery of the UAV.

2.3 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.

2.4 Dash/Intercept

The nature of EM primemovers allows for extreme overloads for short durations [Yedamale 2003] . 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 manouvres 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. Figure 2.1 shows the improved climb rate result from a simulation in MATLAB® Simulink® simulation environment combined with the AeroSim Aerosonde™ Airframe Blockset. Plettenberg HP220/25 motor power with constant 18V input, was applyed in parallel with the Aerosonde™ engine.

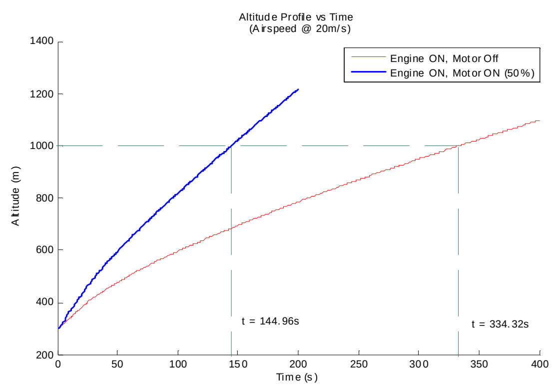

Figure 2.1 Simulated AHP Boosted versus Non-boosted Climb Performance

2.5 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.

The aircraft propeller can be used as a windmill, either inflight 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 2.2 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.

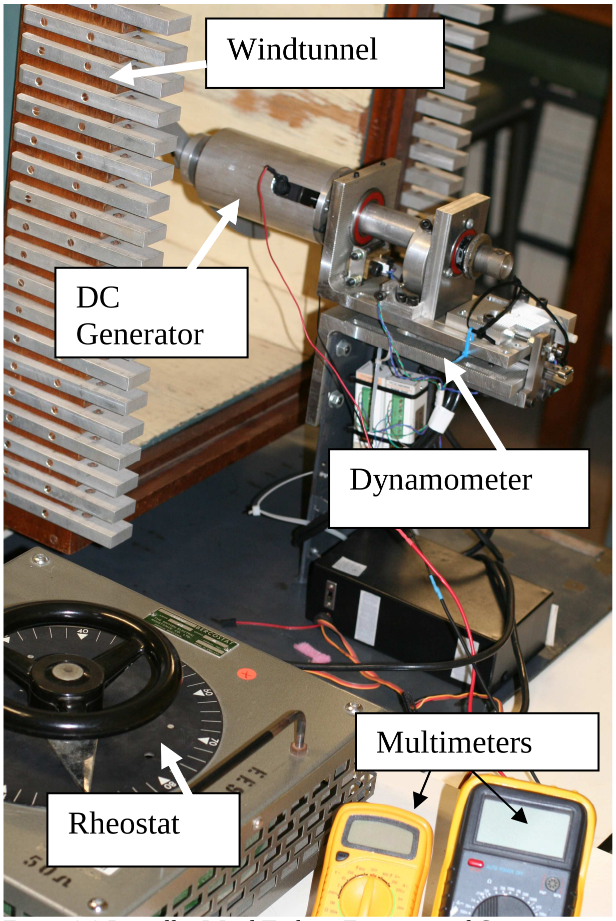

Figure 2.2 Propeller Wind Turbine Experimental Setup

Although using a propeller in this way is relatively innefficient, around 5% of the available airflow energy can be harnessed. Figure 2.3 shows turbine power generated by the 16' x 6' propeller at various velocities.

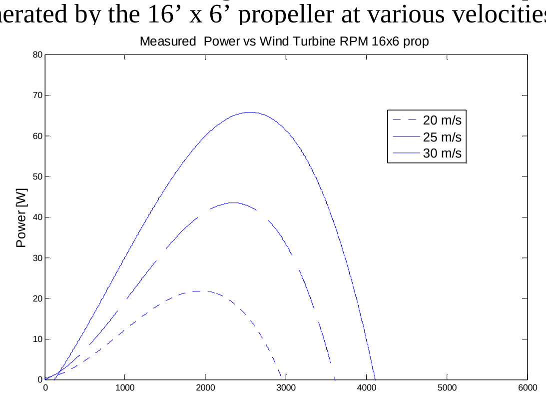

Figure 2.3 Propeller Turbine Power

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 [Zhao et al., 2004]. However when ground based, available wind energy can be used at no cost. Figure 2.4 shows the measured turbine drag at various velocities.

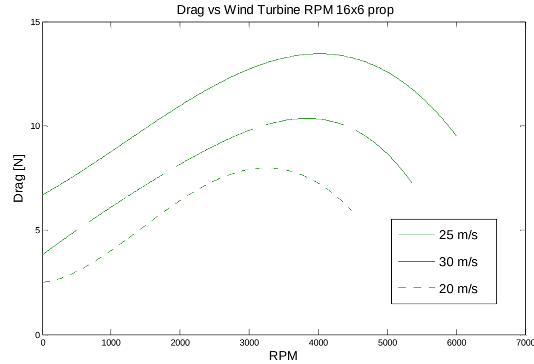

Figure 2.4 Propeller Turbine Drag

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.

3 Conclusion

A prototype Aircraft Hybrid Powerplant specifically suited for small Uninhabited Aerial Vehicles was designed and tested. The performance results indicate that the parallel hybrid scheme can provide significant operational and autonomous mission flexibility benefits while simultaneously increasing basic aircraft range and endurance outcomes.

Increased levels of autonomy in aerial robotics is intrinsically tied to the autonomy of the platform power and propulsion systems. Combining the benefits of electric drives and the associated highly developed electronic and computer control systems with the fundamental energy and power storage benefits of liquid fuelled internal conbustion engines can generate significantly improved UAV capability.

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