

Hybrid-Electric, Heavy-Fuel Propulsion System for Small Unmanned Aircraft

Kyle Merical, Troy Beechner, and Paul Yelvington
Mainstream Engineering Corp.

ABSTRACT

A series hybrid-electric propulsion system has been designed for small rapid-response unmanned aircraft systems (UAS) with the goals of improving endurance, providing flexible and responsive electric propulsion, and enabling heavy fuel usage. The series hybrid architecture used a motor-driven propeller powered by a battery bank, which was recharged by an engine-driven generator, similar to other range-extended electric vehicles. The engine design focused on a custom, two-stroke, lean-burn, compression-ignition (CI), heavy-fuel engine, which was coupled with an integrated starter alternator (ISA) to provide electrical power. The heavy-fuel CI engine was designed for high power density, improved fuel efficiency, and compatibility with heavy fuels (e.g., diesel, JP-5, JP-8). Commercially available gasoline spark-ignition engines and heavy-fuel spark-ignition engines were also considered in the trade study. The series hybrid configuration allowed the engine to be mechanically decoupled from propeller, so that the engine could be operated at the load/speed condition for peak fuel-conversion efficiency. An energy-dense rechargeable battery pack was used to store energy and allow the UAS to operate with the engine shut off, which provided an engine-off operating mode. The ISA allowed re-starting the engine in flight without the need for a separate starter motor.

Simulation-based design tools were developed, and trade studies were performed for the various system components. The series hybrid UAS outfitted with the custom diesel engine demonstrated endurance improvements, due to additional benefits netted from the improved engine efficiency. Development of the hybrid propulsion system is ongoing, with current efforts focused on reducing system mass, packaging, and gearing up for a future hardware demonstration.

CITATION: Merical, K., Beechner, T., and Yelvington, P., "Hybrid-Electric, Heavy-Fuel Propulsion System for Small Unmanned Aircraft," *SAE Int. J. Aerosp.* 7(1):2014, doi:10.4271/2014-01-2222.

INTRODUCTION

The goal of this ongoing research program is to develop a small hybrid-electric rapid-response UAS that is capable of cruising for extended periods and performing "fast dash" maneuvers. Additionally, the UAS is being designed for heavy fuels (primarily JP-5/8 jet fuels) rather than gasoline or other fuels, to simplify the supply chain for military operations. Commercial applications are also anticipated, for example, to support oil exploration or marine wildlife observation.

Hybrid propulsion systems exploit the best attributes of multiple types of power sources to more efficiently propel a vehicle. Common hybrid power sources include internal combustion engines (ICEs), electric motors, hydraulic pumps, and flywheels. Hybrid electric vehicles (HEVs) that combine energy dense internal combustion engines and highly efficient electric machines are among the most common hybrids. The HEV offers more utility than a pure electric vehicle (EV) because the energy dense hydrocarbon fuel aboard the HEV allows for an extended range and can be quickly refueled. The HEV also improves upon a conventional propulsion system because a

highly efficient electric machine can be used to complement the ICE and reduce the time the ICE spends at inefficient operating conditions, thus conserving fuel.

The design of a series hybrid electric propulsion system for a small UAS is presented. The propulsion system uses a two-stroke, compression-ignition, heavy-fuel engine connected to an ISA, to generate electrical power. The generated power is then used to either recharge a lithium-ion battery pack, or directly power a brushless DC (BLDC) motor that is connected to the pusher propeller. This type of propulsion system allows the engine operation to be decoupled from the propeller, thus allowing the engine to function as a generator, running at its most efficient condition. The hybrid architecture also allows the UAS to be operated with the engine turned off.

A true compression-ignition two-stroke heavy-fuel engine was designed for the subject application using one-dimensional engine cycle simulation software (Ricardo WAVE). This custom engine was designed to replace the modified light aircraft engines that are currently used in small UASs (nominally 30-60

lb [14-27 kg] gross take-off weight, GTOW). The power density of the two-stroke cycle is ideal for aviation. Direct fuel injection is used to prevent short circuiting of fuel out the exhaust of the engine, as this leads to excessive fuel consumption with carbureted two-stroke engines. The compression-ignition (i.e., diesel) cycle also increases thermal efficiency and allows for practical use of heavy fuels, such as JP-8, thus adhering to the single fuel forward concept of the U.S. military. A high efficiency ISA was used to both start the engine, as well as generate electricity, after the engine is firing. Combining the starter and alternator into a single component reduces space, weight, and parts count.

BACKGROUND

Three potential HEV architectures are shown in Figure 1. Parallel HEVs use an ICE and electric motor simultaneously connected to a drivetrain to deliver power to the propeller. Most of the previous design studies of hybrid aircraft have considered this configuration. The portion of the required propeller power that comes from the ICE versus the electric motor is varied at different operating points to maximize efficiency. The series HEV architecture uses the ICE solely to generate electricity, which is then used to power the electric drive motor that is directly connected to the propeller.

The more complex power-split hybrid is a type of parallel hybrid architecture that uses a planetary gear set to split power among an ICE, generator/motor, and electric drive motor. This architecture allows for the most efficient use of all devices but requires additional hardware and more advanced control. There are currently no prototype hybrid UASs that use the power split architecture.

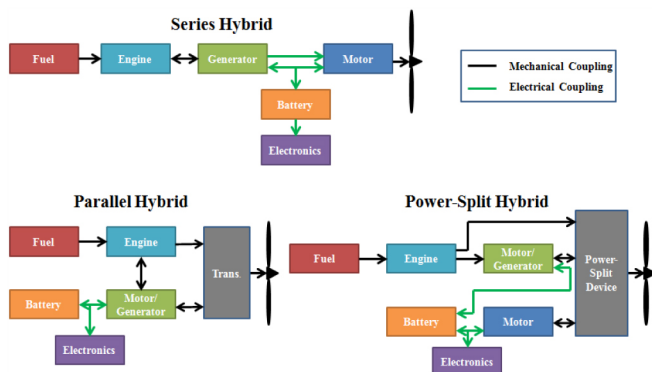


Figure 1. Series, parallel, and power-split HEV configurations, adapted from Hung and Gonzalez [1].

The relatively low specific energy of battery packs has traditionally prevented HEVs from being used in aviation. However, various hybrid UAS propulsion architectures and applications have been simulated [1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20]; although, to our knowledge, none of these have yet been flown. The design of a

30 lb UAS using a parallel hybrid-electric propulsion system was detailed in Harmon, Frank, and Chattot [2]. This vehicle used a downsized four-stroke spark-ignition (SI) ICE and electric motor coupled to the propeller via a belt and pulley system. A one-way bearing on the ICE pulley allowed the vehicle to operate in electric-only mode, but a separate starter was required to restart the engine. Simulations predicted that energy consumption was reduced by 54% for a one hour mission and 22% for a three hour mission when compared to the baseline UAS. However, the low power density of this aircraft limited its predicted top speed to 75 mi/h (120 ki/h). This design was refined and bench tested by Hiserote and Harmon [3] and Greiser et al. [4]. The complete propulsion system was retrofitted into a small aircraft and underwent taxi tests by Ausserer and Harmon [5]. Flight tests were pending as of 2012.

Design of a parallel hybrid propulsion system for the AAI Aerosonde UAS was presented by Hung and Gonzalez [1]. This propulsion system consisted of a small four-stroke spark-ignition engine and electric motor connected to a continuously variable transmission (CVT). A rule-based ideal operating line strategy was used to achieve a predicted 6.5% reduction in fuel consumption during a nominal mission, compared to a vehicle with conventional propulsion system.

The series hybrid architecture has already been used in the Diamond Aircraft DA36 E-Star manned aircraft, as well as automobiles such as the Chevrolet Volt. The current Diamond Aircraft DA36 E-Star 2 is powered by a propeller attached to a 65 kW electric motor. Electrical power is supplied by a 30 kW Austro AE50R rotary engine and generator, yielding a 25% reduction in fuel consumption over a conventional aircraft.

Many different types of control have been used to minimize energy consumption of HEV powertrains. Simple rule-based control is viable but potentially difficult to implement because, as more scenarios are considered, the number of necessary rules becomes cumbersome. Fuzzy logic controllers still use rule-based control but use continuous output values between 0 and 1 (instead of a discrete output of 0 or 1). Fuzzy logic control is robust but can be complicated for systems with many input variables. Neural network controllers use optimization algorithms to assign relative importance between controller inputs. The selected controller response is the most optimal solution at that time. The equivalent consumption minimization strategy (ECMS) minimizes a cost function describing the equivalent fuel consumption of a parallel HEV.

Rule-based control was chosen for this effort because the control of a series hybrid vehicle is much simpler than control of a parallel or power-split hybrid. In a series hybrid, the engine is either turned on or off to generate electrical power. There is no power split between the engine and electric motor to determine, so complex control methods are not necessary.

ENERGY ANALYSIS AND COMPONENT SIZING

Initial steady-state calculations were performed to estimate the power requirements for cruise and dash conditions, which provided initial constraints on the engine size, and battery pack capacity.

Power Requirements

Aerodynamic power requirements were calculated for the hybrid UAS during steady level flight, at varying vehicle speeds, assuming a typical fixed-wing airframe and fixed-pitch propeller. It was assumed that the hybrid UAS had a GTOW of 55.8 lb (25.3 kg), including fuel and payload, for all cases considered. An appropriately sized commercial propeller was selected to match the thrust requirements and motor speed for the hybrid UAS.

A notional drag polar and propeller efficiency curves were used to estimate the aerodynamic power. The aerodynamic power divided by the energy conversion efficiencies of the propeller, drive motor, and motor-drive power electronics, yielded the electrical power requirement of the drivetrain.

Battery Pack Sizing

The battery pack was the sole energy source for the vehicle during engine-off mode, so this requirement helped determine the appropriate size for the battery pack. The goal was to specify a battery pack using commercially available battery cells that would allow the UAS to remain in engine-off mode while at the target cruise speed for one hour.

We estimated that 596 W are consumed by the electric drivetrain during cruise, so 596 Wh of battery capacity are required for the UAS to cruise in silent mode for one hour. The desired pack voltage was 60 V, in order to minimize power transmission losses and negate the need to boost the voltage supplied to the electric drive motor.

A commercial Panasonic lithium-ion cell was selected as the building block for the battery pack because of its high energy density (243 Wh/kg). This cell nominally provides 3.6 V and has 3.35 Ah of capacity. To closely match the target 60 V pack voltage, a string of 16 cells in series was used. The energy requirement of 596 Wh was divided by the pack voltage of 57.6 V to yield a total pack capacity requirement of 10.3 Ah. To nearly match this target, three parallel strings were required giving a total capacity of 10.05 Ah.

Initial Engine Sizing

Engine power demands determined the ideal size of the next-generation, purpose-built diesel two-stroke UAS engine. To offset the additional weight of the hybrid propulsion system and achieve the target top speed, the propulsion system must supply 1884 W of electrical power to the motor. The engine must therefore supply 1432 W of shaft power (considering a

95% energy conversion efficiency for the ISA and 97% efficiency for power conditioning) to the ISA while the batteries are simultaneously discharged at a 2C rate. Assuming that the engine achieves a brake thermal efficiency of 20% at 4500 RPM and an air-fuel-ratio (AFR) of 25, an engine displacing 40 cm³ is required. Below approximately 55 mi/h (88.5 km/h), the electrical power requirement can be met with the batteries alone based on the prescribed 2C maximum discharge rate.

To explore the difference in performance when using compression ignition engines of differing sizes, engines displacing 28 cm³, 54 cm³, and 80 cm³ were also modeled. All four diesel engines were modeled in Ricardo WAVE, along with a commercially available, 28 cm³, two-stroke, gasoline spark-ignition engine and a heavy-fuel variant of the same spark-ignition engine. The WAVE models were exercised over the load and speed range of each engine, while also varying altitude. The data was imported into MATLAB and a script determined the engine operating point with the best brake-specific fuel consumption (BSFC), as well as the operating point with the highest peak power. Table 1 summarizes the predicted performance of each engine in both generator mode and peak power mode.

The masses of the commercial engines were provided by the manufacturer. A trade study was carried out to estimate the mass of each custom-designed engine. Figure 2 shows a scatter plot of engine mass as a function of engine displacement for various commercial small engines. Due to limited availability, data was only accessible for three two-stroke, heavy-fuel, single-cylinder engines. Of these three engines, one was a true compression-ignition (CI) engine (Cosworth), while the other two were spark-ignition (SI) engines. Figure 2 shows that gasoline two-stroke engines are lighter than heavy-fuel engines of the same displacement because of their relative simplicity. Using heavy fuels requires more complex fuel delivery systems as well as fuel heating elements. However, the higher efficiency of the two-stroke CI engine can offset the weight penalty in a UAS application. The additional weight can be minimized by using a downsized CI engine or by carrying less fuel, as less is required for the same flight duration.

Table 1. Predicted Performance of Modeled Engines

Engine Description			Generator Mode Performance		Peak Power Mode Performance	
Displaced Volume [cm ³]	Fuel	Eng. Type	Brake Power [kW]	Brake Th. Efficiency [%]	Brake Power [kW]	Brake Th. Efficiency [%]
28	Gas.	SI	0.86	14.0	2.25	9.4
28	HF	SI	0.71	13.1	2.15	8.7
28	HF	CI	0.66	27.3	0.94	25.7
40	HF	CI	0.98	28.4	1.46	26.4
54	HF	CI	0.82	28.3	2.02	26.9
80	HF	CI	0.99	28.7	2.70	28.5

HF = heavy fuel, CI = compression ignition, SI = spark ignition; brake power in peak-power mode at 8500 RPM for SI engines, 4500 RPM for CI engines