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# EVALUATION OF ENERGY EFFICIENT PROPULSION TECHNOLOGIES FOR UNMANNED AERIAL VEHICLES

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***Abstract***— The transition to cleaner, more efficient and longer-endurance aircraft is at the forefront of current research and development in air transportation systems. The focus of this research is to experimentally evaluate Hybrid Propulsion and Energy Harvesting Systems in Unmanned Aerial Vehicles (UAV). Hybrid systems offer several potential benefits over more conventional gasoline and electric systems including lower environmental impacts, reduced fuel consumption, longer endurance, redundancy and distributed propulsion. Additional energy efficiency can be achieved by harvesting some of the thermal energy of the exhaust gases. By using the Seebeck effect, the temperature gradient between ambient air and the exhaust can be used to generate electric power, making it possible to eliminate costly mechanical systems such as alternators and reduce fuel consumption.

The development and experimental evaluation of a hybrid-propulsion UAV was carried out at the University of Victoria Center for Aerospace Research (UVIC-CfAR) in the framework of the Green Aviation Research & Development Network (GARDN) grant. The work involved the development of a framework to evaluate UAV hybrid propulsion efficiency, as well as to predict the amount of power harvestable from thermoelectric generators (TEG). The hybrid propulsion framework was used to investigate the trade-offs between different hybrid architectures against conventional electric and internal combustion propulsion systems. The energy harvesting module was designed to evaluate the trade-off between energy harvested, implementation costs and weight.

In order to validate the computational results, experimental testing was performed. First, an apparatus was designed to collect performance data of a triple-TEG system connected to a 4-stroke Saito internal combustion engine. Thermal performance of the system was evaluated at eleven different test points, and a number of variables were modified to simulate real flight profiles. Next, another apparatus was designed to characterize the performance of a parallel hybrid-electric propulsion system in a UAV. This apparatus allows for different mission profiles that closely match the flight test data from other propulsion types.

***Keywords: hybrid propulsion, series and parallel architecture; energy harvesting; thermoelectric generators***

## I. INTRODUCTION

Conventional aircraft are powered by fossil fuels used in different types of internal combustion engines, which produce a substantial amount of pollutants in the form of carbon dioxide. With new regulations and increase of public interest there has been an effort to transition to green transportation. Hybrid-electric propulsion and energy harvesting technologies are potential solutions to mitigate some of the issues identified. There is substantial pressure on the industry to maximize the efficiency of propulsion systems and minimize environmental impact. Gasoline internal combustion engines and electric motors are the two main architectures for UAVs, but each system has disadvantages.

Internal combustion engines tend to have higher endurance than electric systems, but this comes at the cost of high vibration and noise pollution, as well as high levels of emissions. Typically, gasoline engines are oversized for cruise in order to satisfy climb requirements. Electric propulsion systems have the benefit of lower noise, vibration and emissions and can supply a high torque across their operating range. However, the power density of battery packs is much lower than that of hydrocarbons, and the additional weight means that electric propulsion systems suffer from low endurance. A hybrid propulsion system that offers the benefits from both gasoline and electric configurations could prove to be a viable candidate for UAVs. The potential advantages of a hybrid propulsion system include the reduction in fuel burn and emissions, lower acoustic signature when operating in electric-only mode, lower-vibration operations, and the possibility of novel configurations through distributed propulsion. The efficiency of the overall system could be increased even further if some energy harvesting techniques are applied to the exhaust gas using thermoelectric generators. A hybrid propulsion system could also include some intangible benefits such as redundancy in the case of engine failure.

The two types of hybrid-electric configurations used in this project are series and parallel, as shown in Fig. 1. In a series configuration, the combustion engine and electric motor are not mechanically coupled. Instead, the combustion engine generates power using a separate generator which can be used to drive the electric motor or charge the battery packs. In a parallel

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configuration, the combustion engine and electric motor are connected using some sort of mechanical coupling, and together drive the propeller. In a parallel configuration, a clutch is required to disconnect either the electric motor or combustion engine to operate in isolated modes.

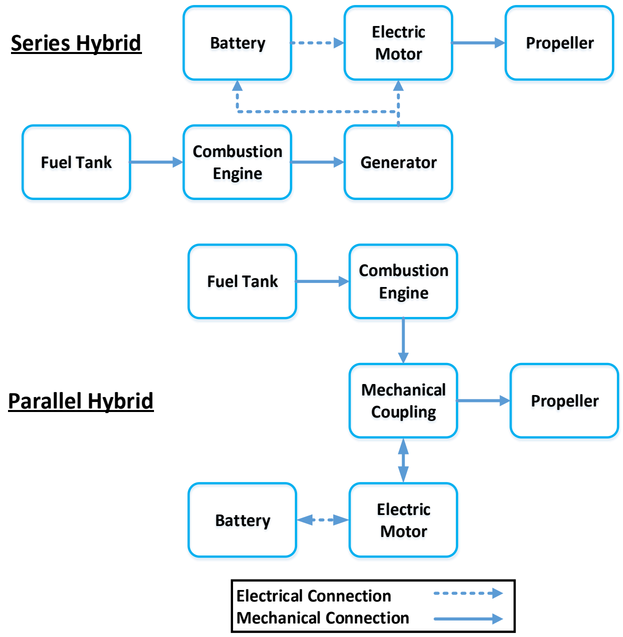


**Figure 1. Series and Parallel hybrid-electric configurations.**

One of the first major hybrid-electric propulsion UAV projects began in 2010 with the Air Force Institute of Technology's 'Project Condor'[1], [2]. This design involved conceptual design work, simulation, and control strategy development by several groups and predicted efficiencies of 94% [3]–[5]. The University of Colorado has shown success with their project HELIOS which also made use of a parallel hybrid architecture in their UAV [6]. Further, parallel hybrid research by Glassock, Hung, Gonzalez and Walker at Queensland University have suggested that an increase of power of 35% can be achieved with only a 5% weight penalty for a UAV [7].

In a study conducted by Harmon, Frank and Joshi [4] it was estimated that a parallel configuration on a small UAV would be approximately 8% lighter than a series configuration. This estimate is due to the large electric motor and generator requirement of the series configuration. Although series hybrid configurations suffer substantial energy-conversion losses, they are simpler to control and offer features that are suitable for intelligence, surveillance and reconnaissance (ISR) missions such as distributed propulsion or electric-only operation. These features are possible for a series configuration because the internal combustion engine is decoupled from the electric motor that provides the propulsion.

Energy harvesting is the practice of generating energy from ambient energy sources, such as solar, vibrational, acoustic or thermal energy. Many applications for energy harvesting can be found in aviation, from structural health monitoring (SHM) systems requiring in-situ power production to electric-based systems harvesting energy to increase endurance. Research into energy harvesting at UVIC CfAR has focused on recovering thermal energy to provide auxiliary power to an aircraft's electrical systems.

Thermoelectric generators utilize the Seebeck effect to convert thermal energy to electrical power when subjected to a temperature gradient. TEG efficiency depends on both the materials used and the temperature difference between the two sides of the module, as TEGs commonly operate at approximately 20% Carnot efficiency [8]. Commercial units have up to 12% conversion efficiency, with a 5% efficiency being common.

As mentioned previously, reciprocating internal combustion engines are a popular choice for UAV propulsion due to the fuel high energy density; however, this comes with a tradeoff of low thermal efficiency. Only 30-45% of the fuel energy is utilized to produce mechanical power, and this figure is even lower for small-scale engines [9]. The remaining energy is lost to the environment, with 40% of the total energy lost as exhaust gas kinetic and thermal energy [10]. Exhaust temperatures commonly reach as high as 800 degrees Celsius. Therefore, the high temperature of the exhaust relative to the environment makes the exhaust system a potential candidate for thermoelectric energy harvesting.

Thus far, thermoelectric energy harvesting research has largely been concentrated in the automotive sector. Generally, TEGs are placed on a specially designed exhaust pipe and are cooled with engine coolant; systems using heat pipes have been explored but are limited to low-temperature applications [8]. As weight is a secondary concern in the industry compared to aviation, a number of high-power energy recovery systems have thus been created and tested by companies such as BMW, Ford and Honda. Research has indicated that thermoelectric systems are capable of meeting the electrical requirements of vehicles, with experimental systems exceeding 700W power generation during bench testing [10]. An increase in fuel efficiency of up to 10% has been claimed, [11] though real-world efficiency gains were closer to 3% [9].

In contrast, thermoelectric energy harvesting for UAV applications has only received limited attention. Fleming, Ng and Ghamaty investigated thermoelectric power systems for micro air vehicle applications, [12] and Langley, Taylor, Wagner and Morris conducted theoretical modelling, design and optimization, and subsequent flight testing of a thermoelectric power system [13]. As system weight is of much higher concern in aerospace, thermoelectric energy harvesting is largely prevented from employing the liquid-cooled heat exchangers prevalent in automotive research; ambient air becomes a much more feasible option for cooling. Previous research on the subject has largely been limited to low-temperature, small-gradient applications [14].

## II. HYBRID PROPULSION SYSTEM

The purpose of the framework is to compare conventional electric and gasoline UAV propulsion systems against various hybrid-electric and energy efficient systems. As new hybrid UAV projects emerge, it is difficult to quantify their performance against other designs as there is a wide range of designs and applications. This framework was developed using MathWorks MATLAB and includes all of the aircraft dynamics independent of the propulsion module so that propulsion systems can be used interchangeably. Once the models are validated with real flight test data, this framework can be used to compare theoretical systems or prototype systems still in development. Since all of the aircraft components are modelled parametrically, the design space can be thoroughly explored and optimized through various component sweeps and trade studies. The results from this exercise can be used to observe tradeoffs and impacts between different propulsion architectures and will drive design decisions for future UAVs.

The series and parallel hybrid architectures were evaluated for several mission profiles. These missions provide a variety of different operating points that UAVs are typically used for, rather than steady-state comparison between propulsion systems. These profiles include a high-speed Interception Mission, a maximum-endurance Communications Relay Mission, a terrain following Pipeline Inspection Mission, and finally a flight path optimization mission for LIDAR Data Collection. These missions are depicted in Fig. 2.

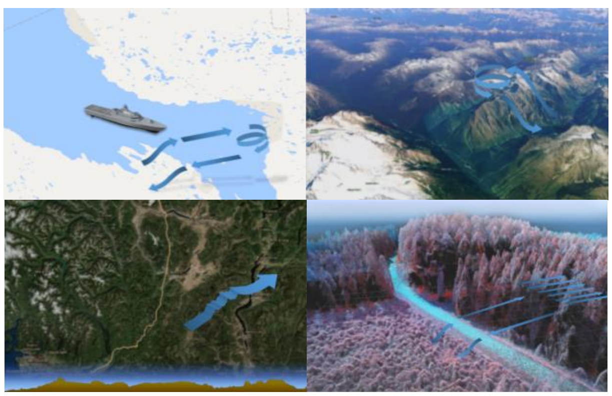

**Figure 2. Interceptor Mission (top left), Communications Relay Mission (top right), Pipeline Inspection Mission (bottom left), and LIDAR Data Collection (bottom right) profiles.**

Several of the individual components of the aircraft, such as the propeller, lithium polymer (LiPo) batteries, electric motors and the internal combustion engines were modelled from existing architectures and combined in the framework. The propeller model includes a parametric model to morph measured geometry for a range of sizes. For the LiPo batteries, an equivalent circuit was used to model both the discharge and charge characteristics of a battery in order to accurately estimate the voltage drop. This model was used in combination with experimental data of voltage curves collected by discharging a LiPo battery at different rates. A thrust test stand was developed to determine the performance of these LiPo batteries with several electric motors. This thrust test stand allowed for any combination of batteries, electronic speed controller and motor to be tested together to collect experimental data, and included safety cut-offs for thermal, voltage or current thresholds. In order to validate these models, component-level bench tests were conducted.

Fig. 3 depicts the results of an example exercise using the framework. Here, the coefficient of lift parameter was swept from 0.55 to 0.90 to observe the trade-offs of fuel burn between the gasoline configuration, and both series and parallel hybrid configurations for a sample aircraft. As can be seen, the series hybrid architecture will burn less fuel than the gasoline-only configuration at higher $C_L$ values, and the parallel hybrid is the most efficient with the lowest fuel burn for the full $C_L$ range. The ability to observe these trends and analyze the tradeoffs between different propulsion systems attests to the power and novelty of this framework.

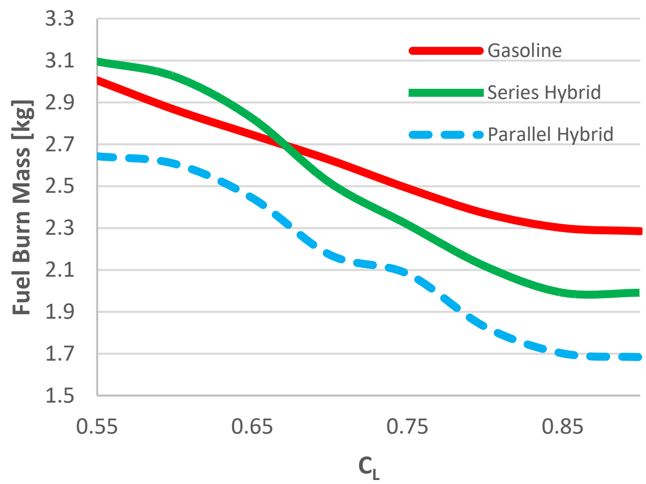


**Figure 3. Framework design study example: Pipeline Inspection Mission $C_L$ versus Fuel Consumption.**

In future work, all of the components will be combined for system-level bench tests for both series and parallel hybrid architectures. The system-level bench tests will provide the opportunity to observe the performance of the propulsion system in a controlled environment and provide repeatable results. As with the component level testing, the results from the hybrid bench tests will be updated back into the framework to increase the accuracy of the theoretical models and lead to the design and integration into an airframe.

## III. THERMOELECTRIC ENERGY HARVESTING

To validate the theoretical model of an exhaust energy harvester, a test apparatus was designed and built. The energy harvester was designed to use the exhaust flow from a commercial-grade 50cm$^3$ 4-stroke Saito FG36 gas engine to provide heat to 3 Marlow Industries 30mm x 30mm TG12-4 thermoelectric generators. The cooling was provided by forced air. An Advanced Thermal Solutions ATS-EXL68-300-R0 heat sink was modified to provide two 15cm-long profiles, and the TEG modules were fixed between them using Arctic Silver Ceramique 2 thermal paste to maximize thermal contact. The heat sinks were enclosed in aluminum shrouds and the two sides were clamped together. To simulate external airflow, an electric ducted fan unit was integrated to simulate an aircraft speed of up to approximately 200 km/hr at ground level. The cold air flow and the exhaust flow were counter-current to each other. The system was connected to the engine exhaust using a corrugated metal hose. Removable fiberglass insulation was also installed to control heat loss from the apparatus.

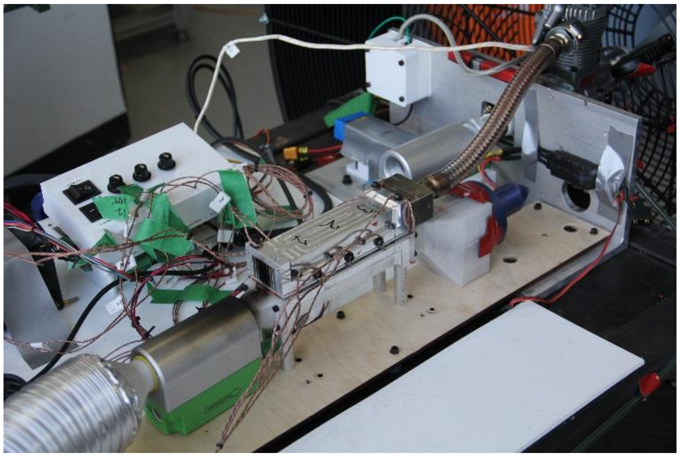

**Figure 4. Energy Harvesting Apparatus Setup.**

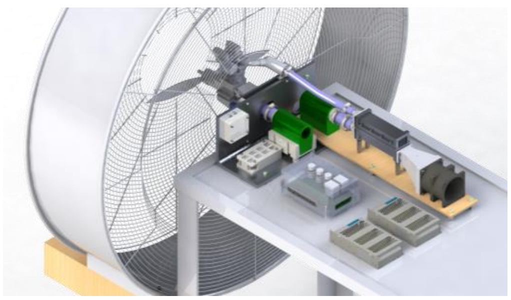

**Figure 5. Energy Harvesting Apparatus.**

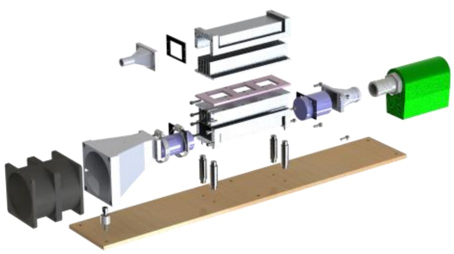

**Figure 6. TEG module exploded view.**

The system was instrumented to record 5 design variables (engine throttle control, cold air flow rate control, and resistive load control for each of the 3 TEGs). The temperature gradient across each TEG was measured using two Digilent K-type thermocouples, and the exhaust temperature was recorded at both the exhaust manifold and the entrance to the heat exchanger. Ambient air flow temperature was tracked at the inlet and the outlet of the heat exchanger, and ambient air flow rate was measured at the heat exchanger inlet using an E+E Elektronik EE741 flow meter. For the engine control, air flow was tracked at the carburetor inlet and fuel mass was tracked using a load cell. Data collection and system control was accomplished using LabVIEW software.

An energy harvesting module for the MATLAB framework was developed to predict thermoelectric power generation based on the operational state of the aircraft. Engine parameters were used as inputs to predict exhaust temperature, and the aircraft's speed is used to determine the cold air flow. Load resistance was set to optimize power production throughout the mission, simulating the overall power generation. This power was directly applied to a battery module in the framework, and can be used to recharge the flight packs or supply power to a payload. Due to the relatively low operating temperature range, the energy harvesting module makes the assumption that the TEG material properties are temperature independent.

Extensive component and system-level testing was performed. The performance of TEG modules was quantified experimentally as shown in Fig. 7. TEG power generation was changed by sweeping load resistance at constant airspeed and engine power. The ability to control load resistance ensures optimal power generation at any flight profile. The relationship between engine power, flight speed, and TEG temperatures was defined empirically and used to refine the energy harvesting module.

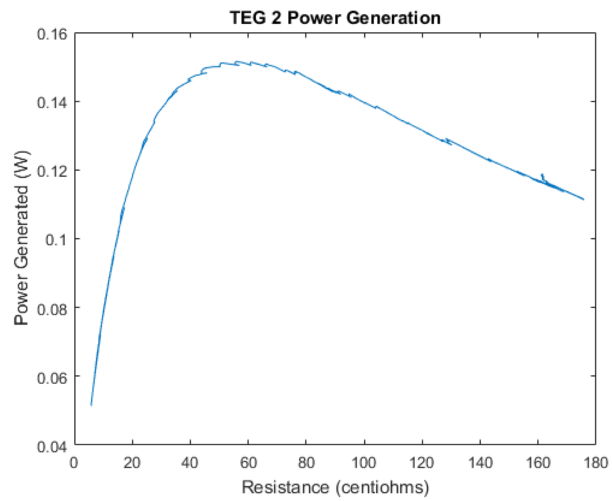


**Figure 7. TEG power generation for a given resistance.**

## IV. CONCLUSION/RECOMMENDATIONS

A hybrid propulsion system framework has been implemented and evaluated for multiple mission scenarios. This framework allows the user to define component information and sizing, aircraft parameters, and complex mission profiles. From this setup, design trade-offs between UAV propulsion systems were identified and quantified to drive engineering design decisions. Specific experiments can be conducted to observe very precise and slight changes to the overall performance of an aircraft. As hybrid-electric aircraft increase in popularity, the aeronautical industry will benefit from such an analysis tool to optimize designs. As new and more efficient propulsion technologies are created, this framework will allow users to benchmark new designs.

Using the framework, mission profiles were designed to simulate realistic missions such as Interceptor, Communications Relay, Pipeline Inspection and LIDAR Data Collection. Since UAVs are used in a variety of applications, it is a useful exercise to test the designs across multiple mission profiles to determine the optimal design. Together with the energy harvesting module, design decisions can be made on the trade-offs between different component sizes and optimized.

Future work will include the construction of more detailed and complex mission profiles to further test the performance of aircraft. The ability to test the designs in real-world missions will not only allow for realistic performance estimates, but also open the opportunity in future work to tune the model using actual flight test results. Furthermore, experimental data from the component bench testing and the energy harvesting apparatus will be used to validate the framework and produce more accurate results.

This project clearly demonstrates the need and novelty of the hybrid propulsion design tool to compare the performance of UAV propulsion types, and proves that hybrid UAVs are viable candidates for a variety of missions. Green aviation will likely be achieved by hybrid technology, and the framework provides valuable insight into engineering design decisions. Results from this project will be used to optimize the hybrid propulsion system for UAVs.

## ACKNOWLEDGMENT

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