Modeling and Testing of Control Logic Approaches for Series Hybrid-Electric Powertrain for Unmanned Aerial Systems

Darren Dehesa*, Shyam Menon† and Matthew Monju‡
Louisiana State University, Baton Rouge, LA, 70808

Hybrid-Electric aircraft powertrain modeling for Unmanned Aerial Systems (UAS) is a useful tool for predicting powertrain performance of the UAS aircraft. UAS aircraft utilize small-displacement engines that have poor thermal efficiency and, as a result, could benefit from a hybridized powertrain by reducing fuel consumption. The scope of this work aims to model a hybrid electric powertrain and explore different control strategies that can be validated on a physical system. Utilizing MATLAB Simulink, a powertrain model will be developed that can estimate the component power requirements during mission segments, as well as provide a system model for a comparative study of rule-based control strategies.

I. Introduction

Fig. 1 Siemens series hybrid drive (*Left*); Boeing Insitu ScanEagle UAS (*Right*).

The interest in hybrid aircraft has slowly grown since automobiles began to implement hybrid power technology. The next-generation of aircraft seek to leverage hybrid electric technology to reduce fuel consumption and emissions without affecting the aircraft's performance in terms of payload weight capacity, range, and endurance. Figure 1 shows a photograph of Siemen's DA36 E-Star 2 aircraft, which utilizes a hybrid powertrain implemented in a series configuration. The aircraft was able to complete a one-hour flight at the Paris Air Show in 2013 and claimed a 25% reduction in fuel consumption and emissions. Figure 1 also shows a photograph of the Boeing Insitu ScanEagle, which is a popular UAS platform used by various defense services and could show performance benefits from powertrain hybridization.

However, the challenge of hybridizing an aircraft is weight created by the batteries in the powertrain electrification process. Aircraft design aspects such as payload weight, thrust, and lift are all impacted by this increase in aircraft weight resulting from electrification. Therefore, when introducing a hybrid powertrain configuration into an aircraft, the components must be carefully selected for power, weight, and efficiency to have optimal performance in addition to a robust and efficient energy management control strategy so that the aircraft is able to perform the same or better than a conventional aircraft. The efforts in this paper focus on exploring the effects of hybridizing a group 2 Unmanned Aerial Systems (UAS). The UAS hybrid powertrain goal is reducing fuel consumption, which is a particular concern for UAS in group 2. This class of UAS utilizes small-displacement engines that have low thermal efficiencies of 4-18% and thus high fuel consumption [1]. Due to this low efficiency, this class of aircraft could benefit from a hybrid powertrain where

*Graduate Research Assistant, Mechanical and Industrial Engineering Department, ddehes1@lsu.edu.
†Assistant Professor, Mechanical and Industrial Engineering Department, smenon@lsu.edu.
‡Undergraduate Researcher, Mechanical and Industrial Engineering Department, mmonju2@lsu.edu.

some of the propulsive power can be supplemented by electrical power. Thus, by using a hybrid powertrain, we can operate the engine in its most efficient region, which increases system efficiency overall. However, significant effort is needed in developing powertrain control systems so that each component of the powertrain can operate efficiently and achieve the best performance. Many control methods have been implemented on hybrid power-trains where Enang and Bannister provide a review of the various control methods implemented in the automotive industry for hybrid power-trains [2]. In a study by Gao et al. [3] many control strategies were analyzed for increased fuel economy for a series hybrid powertrain where they determined that an equivalent fuel consumption optimal control method offered the most fuel savings due to the ability of the controller to optimize the power distribution between the engine-generator and battery. Thus to enable more efficient operation of the powertrain, more variables must factor into the control strategy in order to operate in an optimal range. A fuzzy logic control approach proposed in [4] analyzed the ability to reduce fuel consumption for a series hybrid vehicle and noted that fuzzy logic is able to provide optimal performance, in cases where conventional rule based control strategies are non-optimal.

For this study, a comparative study of different rule-based energy management control schemes for hybrid UAS will be conducted. When implementing a hybrid system for this class of UAS, careful consideration of the control strategy must aim to increase the overall powertrain efficiency by minimizing fuel consumption during charging operations given the operation state of the mission. Thus, three rule-based control strategies, which are a baseline, Ideal operating line (IOL), and rule-based fuzzy logic control (FLC), will be analyzed for the control of the hybrid powertrain with each method increasing in complexity respectively to determine the gains in fuel savings between the methods. The performance of the controllers will be evaluated as implemented in the control of a series hybrid powertrain providing propulsive power for a UAS operating on a representative flight profile. The simulations will be carried out using MATLAB Simulink.

While the simulations provide a detailed understanding of the potential performance gains obtained through rule-based control strategies, it is necessary to validate these approaches through direct implementation in test configurations. To this end, a hardware-in-the-loop setup is being developed where actual powertrain components including the engine, generator, motor, propeller, and battery are connected together as they would be in the UAS powertrain, while the aircraft and mission profile is simulated and the performance of the controller is determined through direct measurements.

This paper is organized as follows: Section II provides a brief description of the system models used in the series hybrid powertrain simulation and how the controllers analyzed in this study function. Section III describes the hardware-in-loop hybrid powertrain test-bed in development as well as lists the measurements that will be obtained from the completed setup. Section IV describes the three control methods used in the series powertrain model simulation and how they function. Section V presents the preliminary results of the powertrain simulation and compares the baseline, IOL, and FLC control method's ability to operate the powertrain efficiently. Lastly, Section VI provides concluding remarks and details of future work.

II. Methodology

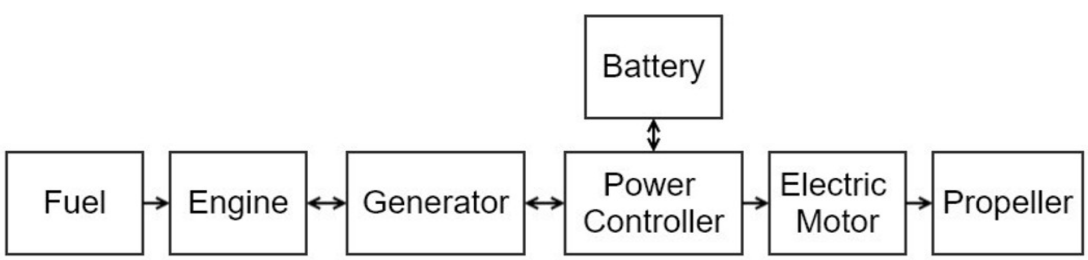


Fig. 2 Series hybrid signal flow path.

The series configuration shown in Fig. 2 is the simplest powertrain type consisting of electric motors (EM), batteries, and an internal combustion (IC) engine with a generator. For this configuration, propulsion is purely derived from electric motor driving the propeller, while the IC engine powers a generator to keep the battery charged at a desired state of charge (SOC). This configuration allows for operating the IC engine at its most efficient operating setting for the desired power demand given that it is not constrained to operate at a certain torque or speed setting.

A system model of the hybrid aircraft powertrain for the series hybrid powertrain configuration was created for

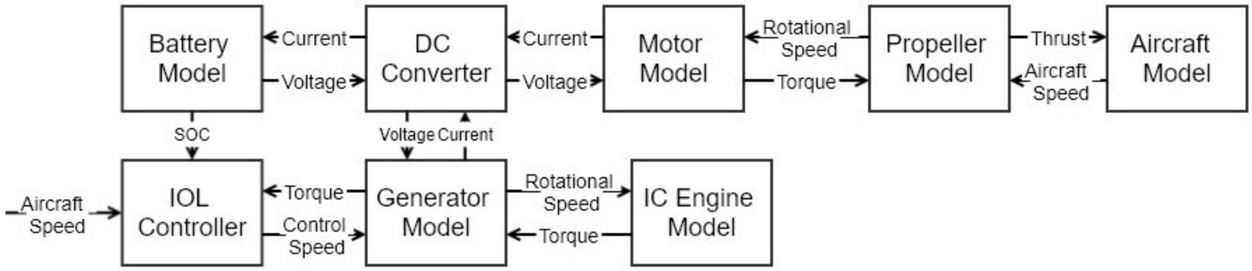


Fig. 3 Series hybrid signal flow path.

simulation as shown in Fig. 3. This system model aims to characterize the power output or input for each essential component model, such as ICE, EM, battery, or generator, as well as the aircraft model, which includes a propeller model. Individual models corresponding to each hardware component are integrated to develop the system model. Component models are generated in Simulink and utilize look up tables or constitutive equations to generate desired outputs to be communicated to the other components in the model. For some of the components like the motor, generator, and battery, the constitutive equations are supported by parameter inputs that were obtained by hardware testing of the individual component. The only external input required for the system model is a flight profile, which specifies the UAS altitude and speed as a function of time. While a simple flight profile is used in this work to gain confidence in implementing the control strategies, more advanced profiles can be tested using the same system model in future studies. Once simulations are completed using the system model, comparisons between the control approaches will be done using performance measures such as the fuel consumption by the IC engine and the ability of the powertrain to maintain the desired SOC during the various stages of the flight profile. The various component models used in the series hybrid powertrain model shown in Fig. 3 are briefly described next. More detailed discussions of the component models have been presented in earlier work [5].

- **Electric motor and generator**

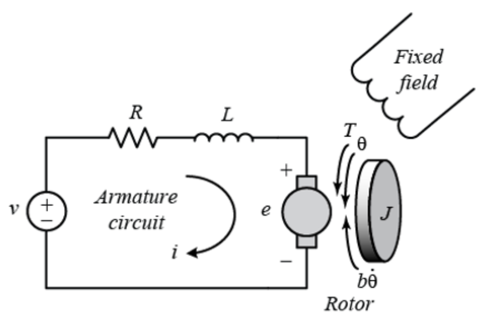


Fig. 4 Electric motor model.

The motor model utilizes a lumped parameter approach characterized by an equivalent circuit model for a permanent magnet DC motor as shown in Fig. 4. The same model is also used in a reverse fashion for the generator since they form identical physical components with simply the direction of power flow reversed. Tests were carried out with a DC motor to parametrize various constants needed to predict motor/generator performance on a test bench.

- **Battery**

  The battery model was developed in a similar manner where charge and discharge data provided by AFRL (Air Force Research Laboratory) was used to parameterize a 2 RC pair equivalent circuit model. The parameters for the RC pairs were calculated for each of the relaxation curves of the cell voltage which corresponds to a particular SOC level. These parameters were calculated utilizing a parameter optimization routine using the least-squares method until an optimal solution was achieved between the test voltage data and equivalent circuit model voltage data which is a function of the optimized RC pair values and its's time constants. These parameters were then populated in the model in the form of a LUT and validated by comparing the model voltage output based upon the same discharge/charge current profile used in the physical cell testing. This optimization process was repeated by modifying initial conditions until the model voltage response agreed with the physical voltage test data.

- **IC engine**

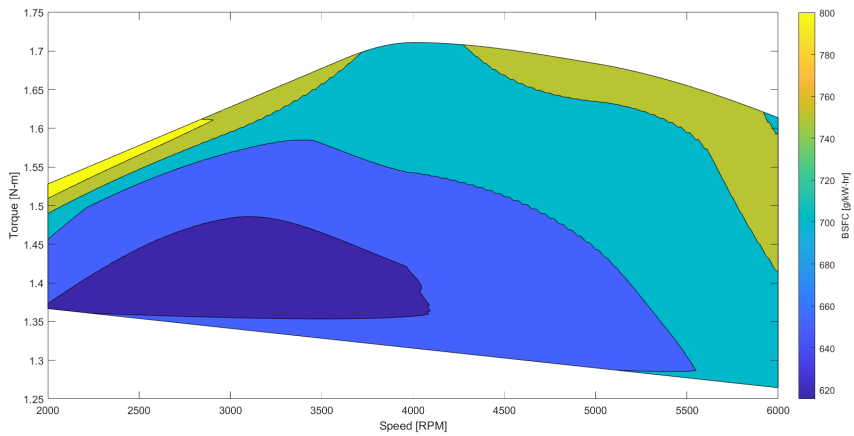


Fig. 5 IC engine BSFC contours.

For the ICE model test data collected by Oregon State University [1] on a single cylinder, gasoline fueled, two-stroke engine (3W-28i) was used to develop lookup tables (LUT) for power, torque, and efficiency (or brake specific fuel consumption, BSFC). Fig. 5 shows iso-contours of BSFC plotted as a function of measured engine torque and speed outputs. The BSFC contours are also used to generate an ideal operating line (IOL), which provides the throttle and speed settings corresponding to engine power demands supplied at the most efficient operating condition.

- **Propeller**
  The propeller model was characterized using test data from the APC hobby aircraft propeller database for an 18x6 propeller [6].

- **UAS**
  The aircraft model was parameterized using properties that are representative of group 2 UAS with the gross take off weight being equal to that of the Boeing Insitu Scan eagle. The lift-drag polar of an AAI Aerosonde UAV was used to characterize the aerodynamic performance for the model.

- **Flight profile**
  A mission profile shown in Fig. 6 was created to simulate system power or energy requirement during flight for a simple flight mission, which includes a takeoff, climbing, cruising and decent segment. This profile is the bases for evaluating the efficacy of the various control schemes' ability to provide efficient operation. The mission profile can be adapted for different simulated missions to show different power levels and performance levels that the powertrain will need to operate at and test the power management schemes.

III. Hardware-in-the-loop setup

To validate the performance results achieved in the powertrain system simulation, a physical hybrid powertrain test-bed is under construction. Fig. 7 shows a schematic of the experimental setup. The physical system is composed of the same components as those in the simulation model. A brushless DC electric motor (KDE 7215XF-135) is used to power an 18x6 propeller. The motor-propeller combination is mounted on an RC Benchmark series 1580 thrust stand and dynamometer, which uses load cells to measure the torque generated by the motor and the thrust generated by the propeller. The RC Benchmark testing program allows for logging of data such as prop motor torque, power, voltage, current, and speed in addition to propeller thrust generated. An identical brushless DC motor is also used as a

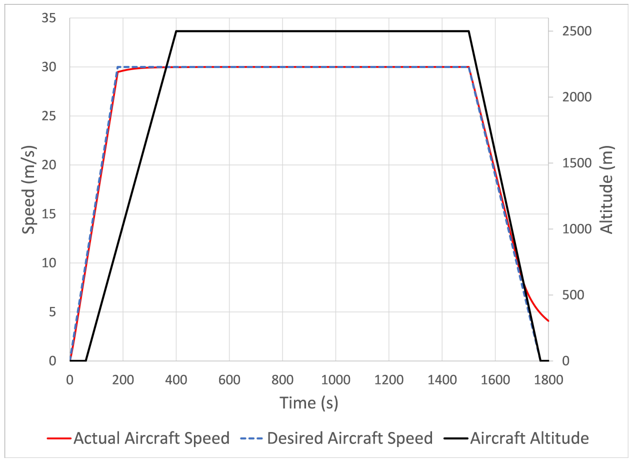


Fig. 6 Mission profile.

generator. Both motors are controlled by electronic speed controllers (ESC's). The ESC for the generator functions as an inverter converting 3 phase AC power into DC power. The generator supplies power to a 6-cell Lithium-ion battery pack through a Roboteq (1040BT) battery management system. The BMS has its own software, which allows the battery cell properties to be monitored and appropriate limits set on charging/discharging currents. The charging operation is triggered by the powertrain control when the SOC falls below the set value. The battery used in this system is a small hobby aircraft 6s 22.2 V, 5 Ah LiPo battery which is connected to a Roboteq 1040BT BMS that manages the battery charging operations by balancing the voltage to each cell in addition to delivering power to the prop motor. This BMS unit also allows for the measurement of the charging and discharging current, battery and load voltage, and the battery SOC. The BMS is also connected to an external load resistance that allows for excess generator power to be handled without affecting the battery performance. The ICE engine used is the 3W-28i, which is a carbureted 2-stroke engine with a displacement of 28cc. The engine throttle is controlled via a small servo motor, and a crank speed signal is connected to the engine to read rotational speed. The engine is connected to the generator motor to form the gen-set, which charges the battery. The powertrain components communicate with the powertrain controller through a computer that interfaces with Simulink through the necessary communication channels from the component to send information feedback to the controller which are then processed by the controller to determine the necessary control actions. The information flow path is shown in Fig. 8.

At present, the components of the experimental setup have been integrated into a series hybrid powertrain layout. However, due to Covid-19 related shutdown of campus research activities, no progress could be made on the experimental setup and as of now, no concrete results are available for presenting in this work.

IV. Control Methods

Three rule-based control strategies will be analyzed for the control of the hybrid powertrain. The first control scheme was a baseline power follower form of control, which controlled the charging operation by maintaining the battery SOC within a 75-95% range based upon the power requested for system operation and charging. This control method served as a baseline because it is the simplest method of control and because it is the least efficient method of controlling the ICE during charging because the engine can possibly operate in an inefficient region while attempting to maintain the battery SOC, thus increasing fuel consumption. The next control strategy implemented was an IOL method adapted from [7] (Fig. 9), which implements a pre-determined operating line where the engine power production is most efficient. Like the baseline control method, the IOL method was tasked with maintaining the SOC within the 75-95% range.

The last control method that will be explored is a fuzzy logic rule-based control (FLC) which uses multi-valued logic. The fuzzy logic controller as shown in Fig. 10 makes use of linguistic representation of the control inputs which is converted into a numerical representation with membership functions in the fuzzification and defuzzification process [2]. The advantage of using the fuzzy controller is the increased degrees of freedom of control meaning more variables in the system such as the SOC, generator power, and engine efficiency can now be optimized to operate within their most efficient region. This degree of control enables the powertrain system to operate at its optimal efficiency which

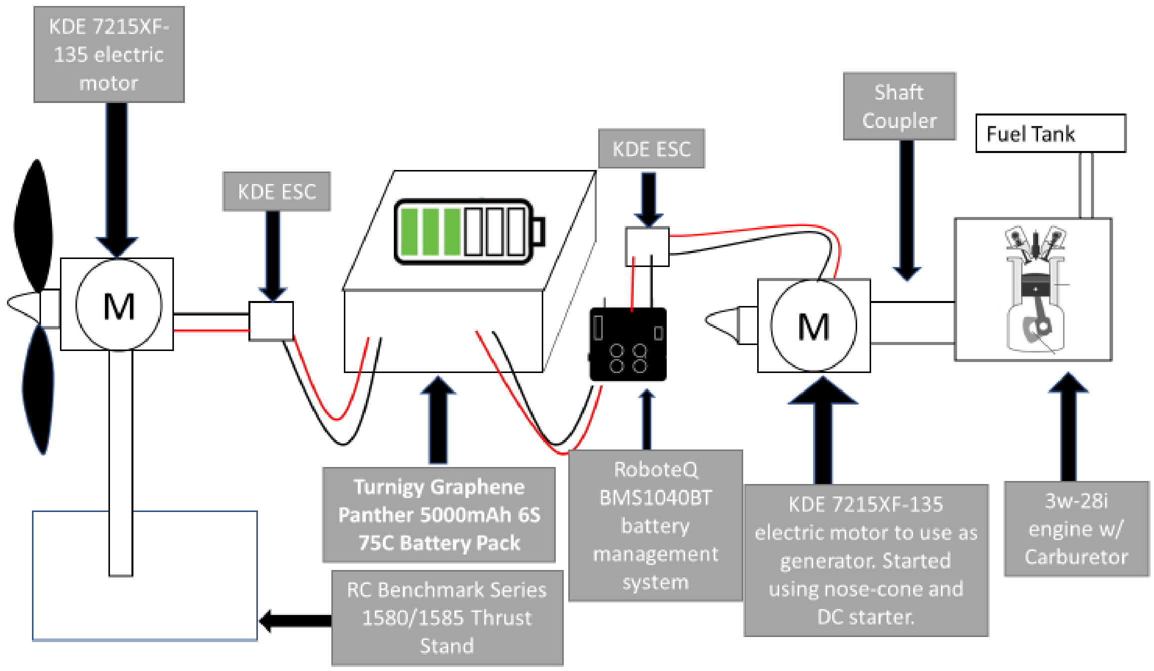


Fig. 7 Series hybrid powertrain testbed diagram.

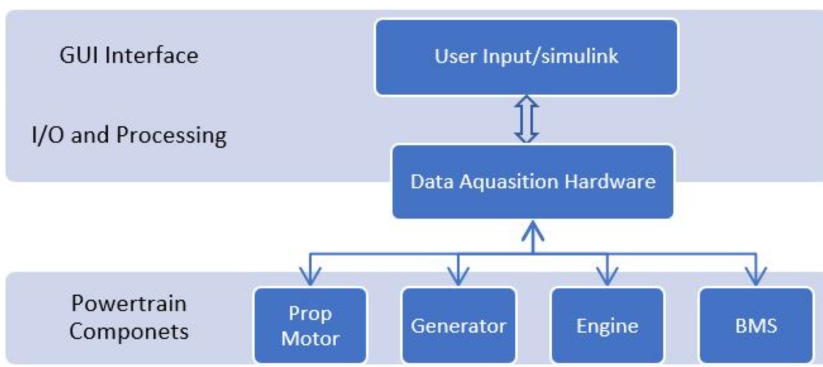


Fig. 8 Hardware communication flow path.

results in reduces fuel consumption and increased range. The controller functions by utilizing two FLC's where one determines the generator demand to maintain the SOC within a nominal range and the second manages the engine operation to minimize generator power error while minimizing the engine fuel consumption. The control method was adapted from [4] where a power scaling factor (k) is used to determine the amount of generator power that should be supplied based upon a reference power value. The reference power is determined based upon the maximum power output of the generator which is 1000 W. The scaled generator power is then compared to the current generator power to produce an effort signal that is used in the engine operating point FLC. The engine operating point FLC then uses fuel consumption and engine speed data to determine the proper throttle setting to minimize fuel consumption. The FLC also requires a set of membership functions and rules to determine the relationship between the input variables to the output variable to produce the required performance. these membership function Fig.11 define the range of operation for the system and their classification within the rule-set (Table. 1 and Table. 2). Three different rules exist for each FLC controller where the first controller (FLC1) responsible for determining generator power demand uses the SOC, ΔSOC, and the change in power available (ΔPa) to determine the scaling factor for generator power production. The second

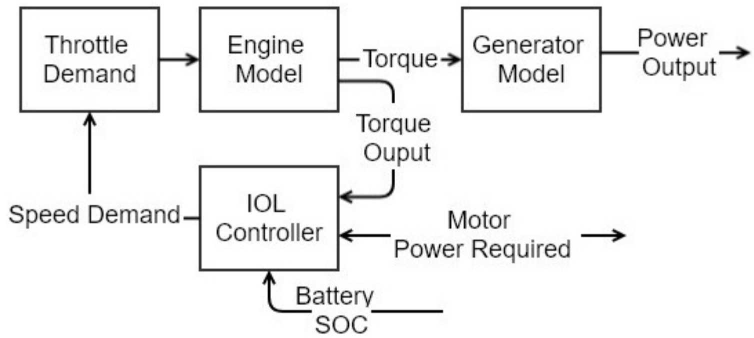


Fig. 9 IOL control scheme layout.

controller (FLC2) utilizes the engine speed, instantaneous BSFC, and the generator power error (ΔPg) to determine the amount of throttle that should be requested to produce the desired amount of generator power at the lowest BSFC value. The membership functions were defined to provide the finer control over the charging operation and the engine efficiency. Therefore in the first fuzzy logic controller (FLC1) besides the SOC range and the ΔSOC was defined to determine if the system is in a state where a high power demand is being requested which drains the battery quickly The (ΔPa) variable is used to determine if the proper amount of power is being generated by the generator to satisfy the system power demand. The second fuzzy logic controller (FLC2) is used to maintain the engine speed and efficiency while achieving the desired generator power requested from (FLC1). The throttle command is then produced by engine operation point FLC which regulates the engine operation based upon the specified in Table.2. The rules that one defines have a large effect on the performance of the system therefor it is crucial that the controller rules are validated to provide the proper performance in different operating scenarios. Thus one must define more detailed mission profiles to simulate the various conditions that can occur in flight. the mission profile used in the simulation was chosen to validate initial controller performance and more detailed profiles will be analyzed.

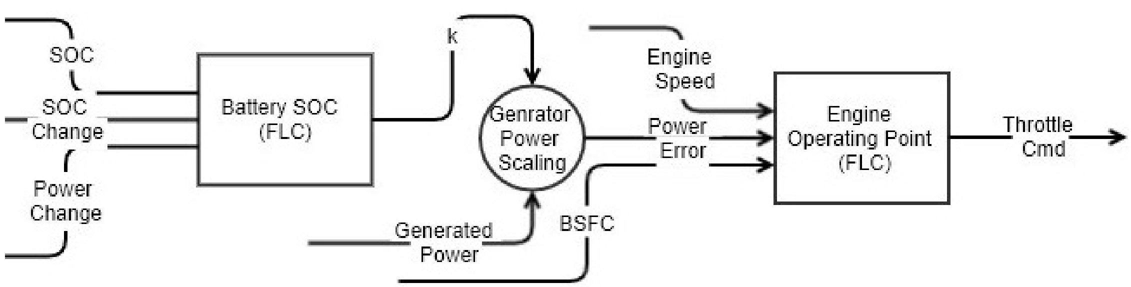
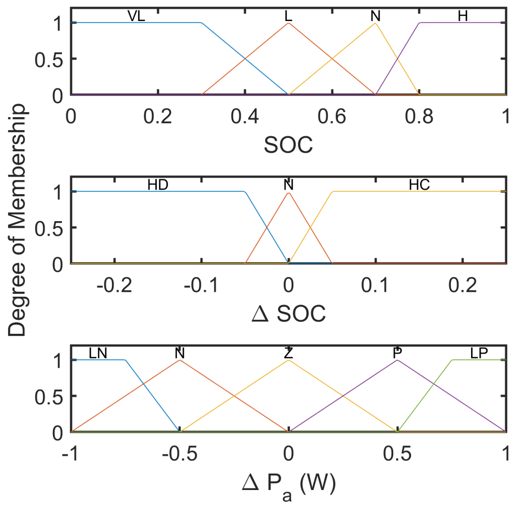


Fig. 10 Fuzzy logic control diagram.

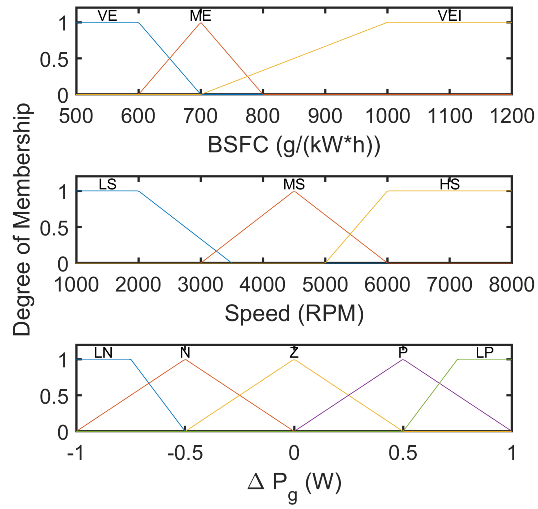
Table 1 FLC1 rules

	Very low SOC				
(ΔSOC)/(ΔPa)	LP	P	Z	N	LN
HD	-	-	-	LP	LP
N	-	MP	MP	-	-
HC	-	-	-	-	-
	Low SOC				
(ΔSOC)/(ΔPa)	LP	P	Z	N	LN
HD	-	-	-	-	MP
N	-	SP	SP	MP	-
HC	SP	-	SP	-	-
	Nominal SOC				
(ΔSOC)/(ΔPa)	LP	P	Z	N	LN
HD	-	-	-	SP	SP
N	-	SN	-	Z	-
HC	MN	-	SN	Z	-
	High SOC				
(ΔSOC)/(ΔPa)	LP	P	Z	N	LN
HD	Z	Z	Z	Z	SP
N	Z	Z	Z	Z	Z
HC	Z	Z	Z	Z	Z

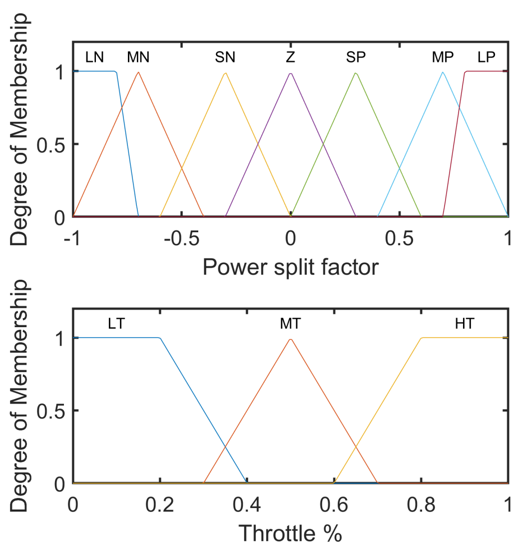
HD-Low speed, N-Moderate speed, Hc-High speed
LP-Large positive, P-Positive, Z-Zero, N-Negative, LN-Large negative
LN-Large negative, MN-Moderate negative, SN-High negative, Z-Zero, SP-Small positive, MP-Moderate positive, LP-Large positive



(a) FLC1 input membership functions.



(b) FLC2 input membership functions.



(c) Output membership functions.

Fig. 11 Fuzzy logic membership functions.

V. Preliminary Results

The results of the simulation for the baseline and IOL control scheme were conducted using the same mission profile shown in Fig. 6, where profile simulates an aircraft performing a cruising mission. The mission simulates the aircraft taking off then climbing at 30 m/s to an altitude of 2500 m where it cruises at 30 m/s. The aircraft then transitions in to its decent phase and lands. The baseline controller and IOL controller were tasked with maintaining a SOC within the bounds of 95-75% by controlling the engine throttle. The results below (Fig. 12) show simulation data for the engine torque, engine speed and the generator current. The results show that the IOL method when compared to the baseline controller maintains the engine at a higher torque and lower speed than the baseline controller. In addition, the IOL controller manages to produce more generator current because of the higher torque production. These results show that the IOL controller manages to hold the engine in a more efficient region as shown in Fig. 5.

Table 2 FLC2 rules

	Low BSFC				
Speed/(ΔPg)	LP	P	Z	N	LN
LS	HT	LT	MT	LT	LT
MS	HT	MT	MT	LT	LT
HS	HT	MT	LT	LT	LT
	Moderate BSFC				
Speed/(ΔPg)	LP	P	Z	N	LN
LS	HT	MT	MT	MT	LT
MS	HT	MT	MT	MT	LT
HS	HT	LT	LT	LT	LT
	High BSFC				
Speed/(ΔPg)	LP	P	Z	N	LN
LS	HT	MT	MT	MT	LT
MS	HT	LT	MT	MT	LT
HS	HT	LT	LT	LT	LT

LS-Low speed, MS-Moderate speed, HS-High speed
LP-Large positive, P-Positive, Z-Zero, N-Negative, LN-Large negative
LT-Large throttle, MT-Moderate throttle, HT-High throttle

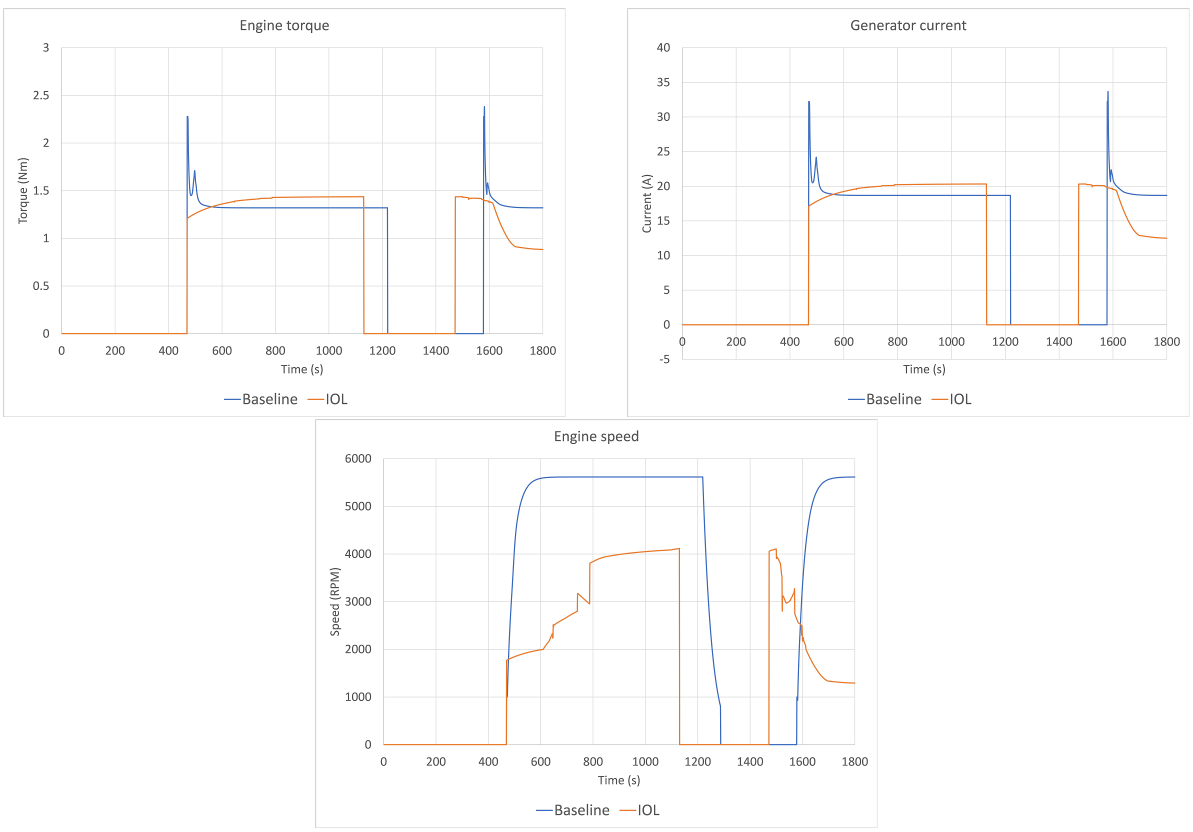


Fig. 12 Simulation result comparison

VI. Conclusion

The results of this analysis showed that the IOL controller was able to keep the engine in an optimal fuel consumption range; however, the engine map used contains low fidelity data which can cause error. This low fidelity data for the BSFC creates error associated with the look-up table method used to implement the data in the model. With improved data for the BSFC map, this error can be reduced because the data better represents the engine's performance. Also, a more sophisticated form of deterministic control logic approach can possibly offer better performance in terms of engine efficiency. Thus, the more sophisticated fuzzy rule-based control schemes will be implemented to increase the performance of the system further. The work in this analysis on series hybrid powertrain modeling and control later will be implemented on physical hardware in a HIL setup to test the performance of the controller in addition to the accuracy of the component models. The ultimate goal of this work is to determine if the hybridization of small aircraft is a feasible and logical means to decrease fuel consumption in small UAS and achieve increased range and endurance performance.

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