Design of Hybrid-Electric Propulsion Systems for Small Unmanned Aerial Vehicles

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Abstract

HYBRID-ELECTRIC propulsion systems were driven into public attention by the development in the automotive industry. There, the combination of internal combustion engines and electric motors is used to reduce fuel consumption. The basic measure to do so is to recover energy during braking, to propel the vehicle electrically at low speeds and to have the internal combustion engine run in its optimum point of operation most of the time and hence downsize it. As cost and weight increase, hybrid-electric systems are not a per se solution to reduce fuel consumption, but need to be designed very carefully. The advantages mentioned cannot be transferred to unmanned aircraft applications one-to-one, as a flight profile is much more static than a driving cycle and hence the aspects of recovering energy and frequent low speed phases have to be discarded. The primary objective of hybrid-electric propulsion systems for unmanned aircraft is not to lower energy consumption. Combustion engines are hybridized to give aircraft the capability to fly more silently. This implies the assumption that electric propulsion systems are more silent than those based on internal combustion systems, which must not be the case for all conditions. Nonetheless hybrid propulsion systems should be as efficient as possible. As another advantage, they may easily be designed to provide complete propulsion redundancy.

One primary field of application of unmanned aerial vehicles (UAV) is surveillance. Depending on the mission task, it may be required to operate secretly. In order to use cheaper low or medium altitude UAV for this task, they have to fly quietly. One of the main sources of noise of non-electric small UAV is the internal combustion engine. Silent battery-electric propulsion systems do not yet provide sufficient specific energy to offer the same flight endurances that can be reached with combustion engines, nor will they in the near future. This makes a UAV a very suitable platform for hybrid-electric propulsion systems, a transition technology, offering high specific energy internal combustion engines for the way to and from the surveillance area and quiet electric propulsion for the clandestine operation[1].

Here we show models for the preliminary design of hybrid-electric propulsion systems and their application in preliminary design. The motivation for the creation of the models is to compare different hybrid systems over a wide range of requirements. In doing so, it is quantified where the advantages of the different systems lie. The models are intended to be used in an automated preliminary aircraft design environment, so they need to be as generic as possible and, for a possibly applied optimization process, require the lowest possible computation time.

Power based models, in which an energy converter's characteristics are determined merely based on its power requirement, are not suitable for the use in an automated process over a wide range of requirements. The reason for this is that the converters' efficiencies almost always depend on state variables. State variables within this document shall be the term for the variables whose product is power. For the mechanical domain this is rotational speed and torque or force and translational speed. Voltage and current are the state variables in the electrical domain and in the chemical domain they are the lower heating value and mass flow[2]. Within a power based design process efficiencies have to be manually estimated and hence inaccuracies might flaw the quality of the results. Existing publications offer solutions for the modeling and optimization of hybrid-electric systems suitable for small unmanned aircraft, but only power based[1]. Battery-electric systems are modeled based on state variables, but the relationships for the electric motor are either discrete[3], i.e. computation time consuming, or derived from a very wide spectrum of commercial models and hence not as accurate as desired for the specific use case[4]. Performance prediction models for small internal combustion engines based on state variables are not readily available. Automotive solutions are either too detailed or not applicable. The models presented in this document enable a design process for hybrid-electric propulsion systems based on state variables and hence increase its accuracy.

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The core work on modeling was done on the internal combustion engine and the electric motor. For the electric motor, a commonly used electric model[3,5] was augmented with a mass prediction model and a model to determine the two main characteristics of brushless direct current motors, internal resistance and no-load current from the engine's diameter, length and specific rotational speed. The extensive amendment of a model previously published by the author[6] has a much wider design space and allows extrapolation. Both new models were derived from a database of COTS electric motors below 4 kW shaft power. For the internal combustion engine, models to determine mass and efficiency were created. While the mass prediction model is derived from a database of small COTS engines below 420 cm³ displacement volume, a scaling approach was developed to compute the efficiency. The scaling process uses a suitable baseline efficiency map, which is formulated in mean-value variables and normalized. The prerequisites are that the wide open throttle curve's behavior is similar over the whole design space and that efficiencies for a given pair of the mean-value variables are equal over the design space. The first prerequisite was validated with published data. The second one cannot be validated due to the lack of efficiency data for small engines, but is also used in automotive engineering. The performance prediction of small internal combustion engines is generally complicated by the lack of validation data. The reason for this is the engines' use in niche markets such as gardening, sports, motor scooters, aeromodeling or as generators, where customers do not require detailed consumption data.

Propulsion systems powered by an internal combustion engine, a battery-electric and a hybrid-electric systems are compared for the thrust, velocity and endurance ranges relevant for small unmanned aerial vehicles. To evaluate the results, the propulsion system mass is compared. An exemplary plot is given in Figure 1 below, showing the behavior of the mass of a hybrid-electric propulsion system for flight times from 1 hour to 24 hours and velocities from 20 m/s to 50 m/s at a thrust requirement of 20 N.

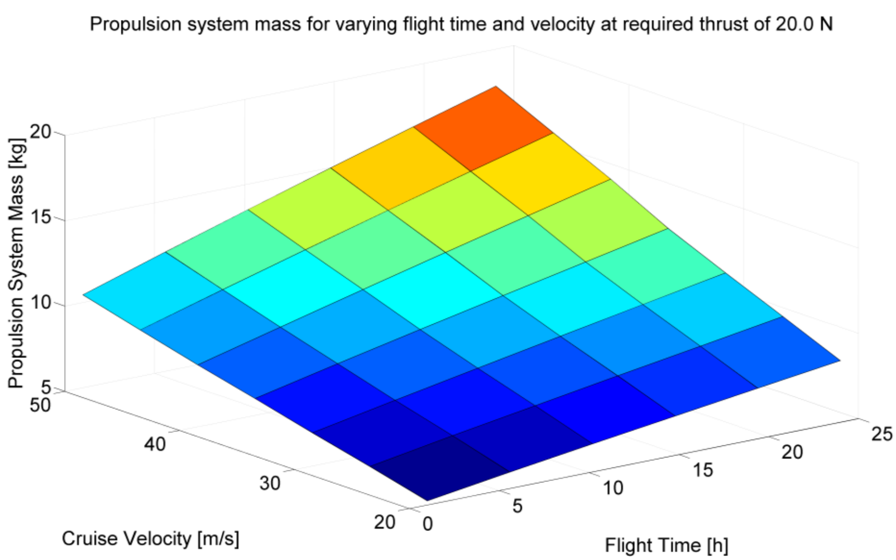

Figure 1: Behavior of hybrid-electric propulsion system mass for flight times from 1 hour to 24 hours and velocities from 20 m/s to 50 m/s at a thrust requirement of 20 N

For one single set of requirements, the effect of selected parameter variations, as the silent electric flight time fraction and the degree of hybridization are presented. Further cases show the mass penalty of complete propulsion redundancy within the hybrid-electric system and a system designed for minimum fossil fuel consumption.

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