Development of a hybrid-electric propulsive system model for Unmanned Aerial Systems

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Abstract

The growing economic and environmental pressure on aviation applications worldwide demand for innovative concepts to decrease the emission footprint of future aviation vehicles while increasing the performance. Since the beginning of the 21^{st} century the research efforts by various public aeronautical agencies and private companies has significantly increased. In this process hybrid-electric propulsion, distributed propulsion and novel aircraft concepts have emerged as technologies with a high potential to fulfil these requirements.

In the aviation sector these concepts are relatively new and therefore the knowledge towards these technologies needs to be deepened to maximize their performance. The hybrid-electric concept is going to be explored in depth with the development of a numerical simulation model in MATLAB for an Unmanned aerial vehicle propulsion system. The components are modeled with analytical and surrogate modeling techniques. Afterwards a validation of the models with experimental data is performed and models with high accuracy are obtained. The propulsion module is managed by a rule-based controller with five operating modes. Furthermore it is equipped with the Ideal Operating Line energy management strategy to maximize the fuel efficiency of the aircraft. The advantages and disadvantages of the hybrid-system are explored in a surveillance mission analysis with the research aircraft QT1 for various propulsion system configurations.

Keywords: Hybrid-electric propulsion, Unmanned Aerial Systems, Parallel Hybrid System, Ideal Operating Line, Surrogate Model

1. Introduction

Aviation is a fast growing transport sector with an expected passenger increase of 100% in the next 20 years.[1] The environmental and health impact of air travel is a growing public concern. Publications directly relate aviation with approximately 16000 premature deaths yearly and 2-3% of the man-made CO_2 emission.[2][3] Furthermore airlines worldwide have not only to sustain their fleet size, considering necessary replacements, but expand it to satisfy the market's demands. Recent projections of BOEING and AIRBUS predict around 40000 new commercial aircraft sales in this time-frame.[4][5] The NASA updated performance goals for aircraft with a market entrance date around 2025 reflect those developments and the growing economical pressure on airlines. The fuel consumption of aerial vehicle should be reduced by 50% compared to the best of class aircraft of the year 2005 and from 2020 on a carbon-neutral growth achieved.[1] New aircraft concepts employing innovative technologies to increase performance, while decreasing emission are thus necessary.

Researches identified technologies like hybrid-electric propulsion (HEPS), distributed propulsion and novel air-frame configurations as concepts to achieve greener aviation. Furthermore the development towards a more electric aircraft not only demands for powerful energy storage concepts but also leads to new challenges for the thermal management and the electrical system of an aircraft. The implementation in commercial aircraft is the ultimate goal, but as most concepts are still relatively new, extensive studies in stepping stone platforms like Unmanned Aerial Vehicles (UAV) or small scale regional planes are necessary. Therefore a numerical model for a hybrid propulsion system is developed and validated with experimental data to deepen the understanding, map the performance and improve the efficiency of the propulsion system.

The paper is structured as follows: section 2 presents an introduction into HEPS including as-

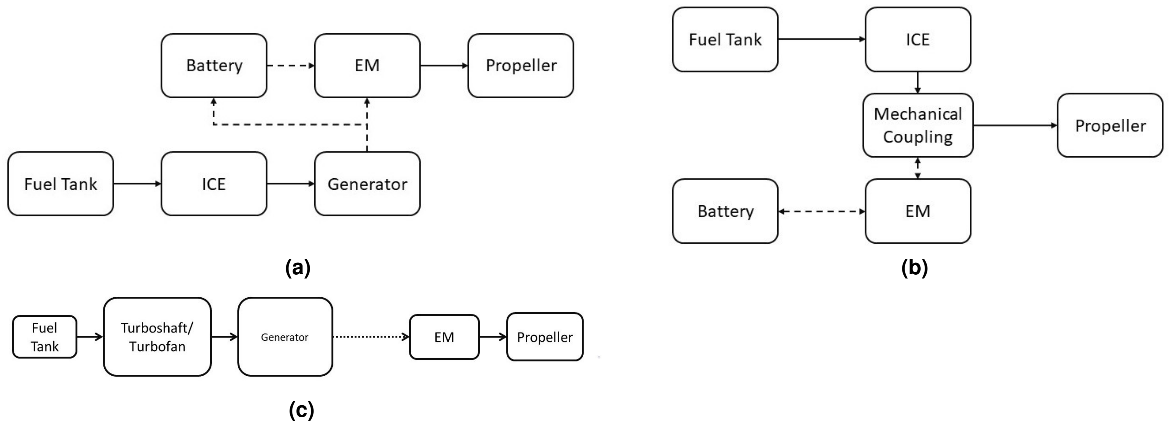

Figure 1: Functional Scheme for: (a) Serial Hybrid System (adapted from [6]), (b) Parallel Hybrid System (adapted from [6]) and (c) Turobelectric Hybrid System (adapted from [7]

sociated energy storage concepts. Further a brief description and examples of the distributed propulsion technology and novel air-frame configurations are given. In section 3 the simulation models of each propulsion system component is developed. Afterwards the propulsion system model is assembled in section 4 and the operating strategies of the hybrid test bench are validated with the experimental data. The IOL energy management strategy and the propulsion system controller are described in section 5. In Section 6 the performance of different propulsion systems is evaluated with a surveillance mission analysis.

2. Background

The mechanical configuration of the hybrid propulsion system can be classified into the three main categories series, parallel and turboelectric (see figure 1) for small aerial vehicles. In the serial configuration the internal combustion engine (ICE) acts as an auxiliary power unit to charge the batteries via the generator. The rotational speed of the propeller and the ICE are decoupled and therefore it can always be operated at its most efficient point. Only the electric motor (EM) powers the propulsor of the aircraft and needs to be sized according to the maximum required power. This leads to an extra weight penalty in low energy demanding flight segments like cruise. The energy losses along the power flow due to the multiple energy conversion steps effect the efficiency of the powertrain. In the parallel configuration on the other hand the ICE and EM are both directly connected to the propulsor with a clutch. Furthermore the EM can also be used as a generator to recharge the battery. The advantages include downsized power sources and the given redundancy of the propulsion system. Because the rotational speeds of all components are linked it is necessary to integrate a continuous variable transmission (CVT) to guarantee the ICE is operating in its most efficient region. The complexity of the propulsion system and control increases with this concept.[8] Compared to a series configuration the parallel concept is approximately 10% lighter.[6] The turboelectric architecture is the third hybrid-electric concept and is currently under investigation to be implemented in large regional aircraft by the year 2035. In this configuration the propulsion system is completely powered by a turbofan/turbojet which is directly connected to EMs and therefore no energy storage system is necessary.

Energy storage is vital for most hybrid-electric configurations and a challenging aspect as the energy density of typical hydrocarbon fuels is around 13000 Wh/kg.[9] Projects employing fuel cells exist, but rechargeable batteries are favoured in the literature due to operating and aircraft design flexibilities as well as energy output per second.[9][10] Lithium based batteries like Lithium polymer (Li-Po) and Li-Ion (Li-Io) are widespread in automotive and aviation applications with energy densities between 145 and 240 Wh/kg.[9] These energy densities are still two orders of magnitude lower than those of typical hydrocarbon fuels though. The Lithium-Air technology is emerging and presents great potential with a theoretical specific energy density of 11600 Wh/kg. The efficiency value of 14.6% and a energy density of 1700 Wh/kg for the Lithium-Air based battery would represent the average tank-wheel efficiency of the current US car fleet, which is deemed achievable in the future.[11]

Compelling to the HEPS technology is the aerodynamic efficiency of the aircraft, which can be improved with distributed propulsion concepts or novel air-frame configurations. Distributed propulsion defines the beneficial span-wise distribution of propulsive thrust across the aircraft. In the NASA Maxwell X-57 project for example leading edge asynchronous propellers are installed to increase the lift during take-off and landing and therefore the wing area could be significantly reduced.[12]

Because the conventional tube plus wing air-frame concept is close to its performance maximum after years of optimization new design ideas are necessary. Currently the blended wing body and the strut-braced wing concepts are under investigation. These designs present better lift to drag ratios and lighter wings respectively compared to the conventional design.[13][14]

The great potential of the HEPS concept for implementation in an UAV plus available experimental results for validation purposes from a previous researcher favours additional research effort in this technology field.

3. Methodology

The hybrid-electric propulsion module for the simulation consists out of standalone component models for the propeller, the battery, the EM and the ICE.

3.1. Propeller

The propeller can not be simulated with the widespread Blade Element Momentum Theory (BEMT) due to the static nature of the test results. The model is based on the propeller specific curve of the thrust coefficient C_T over the rotational speed. The outputs of the model are the power coefficient C_p, the thrust coefficient C_T and the rotational speed of the propeller for the current flight phase. Therefore a rpm vector, based on the operational range of the propeller, is created and the thrust for each step is determined. This loop is repeated until the relative thrust error is smaller than 1% (see figure 2).

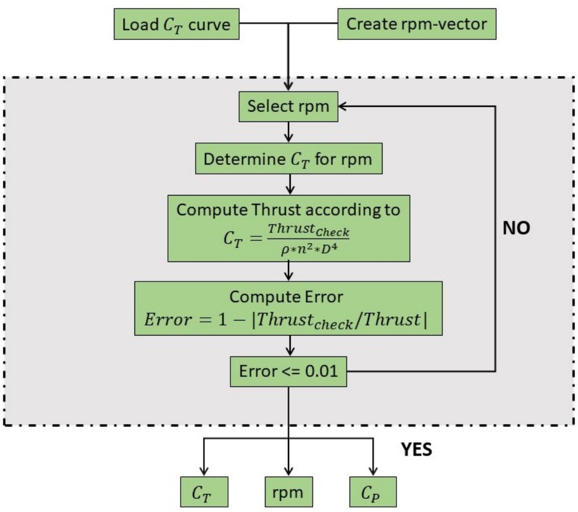

Figure 2: Flowchart for the propeller simulation model

3.2. Battery

The battery model is adopted from a research project performed at the center for aerospace research (CfAR), University of Canada. Because in the UAV market the Li-Po technology is widespread, due to high energy densities, this type is implemented for the battery simulation. The battery curve, governed by the exponential voltage coefficient A, the exponential capacity coefficient β and the polarity voltage K, was fully characterized by 1A discharge experiments performed at CfAR. The charge ($I_n < 0$) and discharge curves ($I_n > 0$) are simulated with the equations 1 and 2 respectively.[15]

$$V(I_t, I_n) = V_0 - \frac{K * Q * I_n}{I_t + 0.1Q} - \frac{K * Q * I_t}{Q - I_t} + A * exp(-\beta * I_t)] \quad (1)$$

$$V(I_t, I_n) = V_0 - \frac{K * Q * I_n}{Q - I_t} - \frac{K * Q * I_t}{Q - I_t} + A * exp(-\beta * I_t)] \quad (2)$$

The maximum capacity is represented by Q, the current during the timestep by I_t, V_0 is the constant voltage and V is the output voltage of the battery.

3.3. Electric Motor

The motor characteristics are simulated with the rpm proportionality constant K_V, the internal resistance R_m and the no load current I_0. The rotational speed of the shaft w_{shaft} is directly connected to the electric motor force voltage U_{emf}. This parameter is defined by the difference between the supplied voltage U_m and the voltage drop across the internal resistance. The losses in the motor are accounted for with the no load current and the internal resistance. In the equations 3 to 5 the governing relations of the motor model are presented.[16]

$$U_{emf} = U_m - I_m * R_m \quad (3)$$

$$w_{shaft} = K_V * U_{emf} \quad (4)$$

The torque output of the motor T_{EM} is a function of the motor input current I_m.

$$T_{EM} = \frac{I_m - I_0}{K_V} \quad (5)$$

In the hybrid test bench the AXI 4130/20 and the respective motor constant are used for the EM model.[17] Furthermore the efficiency map of the EM is modeled depending on the supplied voltage and the requested torque from manufacturer data.[18]

3.4. Internal Combustion Engine

In the hybrid test bench a 2-stroke DA-35 ICE model is installed. The modelling of the thermodynamic processes in an ICE presents significant challenges [19], however the focus of this research project is on the realization of a complete hybrid propulsion model rather than only single components and therefore a different approach is pursued. In engineering applications like finite fluid dynamics scenarios with extensive modeling requirements often arise and therefore Surrogate or Black-box models can be employed. In a dynamometer experiment values for the DA-35 engine characteristics brake specific fuel consumption (BSFC) and power, depending on the throttle and rotational speed setting, were recorded by the manufacturer and presented in [18] by Machado. This data is used as the base for constructing a model, which emulates the physics of the process. Radial basis functions (RBF) and the Kriging regressions are studied for this purpose due to their proven performance. The Kriging method is implemented with the MATLAB toolbox *Dacefit* from the Technical University of Denmark and the RBF simulation is based on a publication by Jekabsons of the Technical University of Riga.[20][21] The data organization and preparation for the surrogate model significantly influences the bias and variance of the simulation results. In the dynnamoter test the recorded test points are low dimensional and uniformly distributed. Therefore a simple random sampling technique is deemed sufficient. The sampled data will be split into test and validation sets with the Hold-Out cross-validation (CV) method.[22] Afterwards the quality of the model is assessed via the prediction sum of squares vector *PRESS*, presented in equation 6. Here p is the number of data points and e the CV error.[23]

$$PRESS = \sqrt{\frac{1}{p} * e^T * e} \tag{6}$$

In the evaluation the process is repeated 25 times and the results are averaged to consider the variation due to the random sampling technique.

4. Validation

The operating modes of the propulsion module are validated with experimental data from a parallel hybrid test bench developed by Machado [18] for the implementation in an UAV.

4.1. EM only mode

In the *EM only* or *Stealth* mode the performance parameters for the simulation are the throttle and current prediction. Through a EM throttle sweep from 10% to 100% the validation data was recorded. The trend of the throttle prediction in the simulation model is in agreement with the experiment as one can see from figure 3, however an absolute error of $\approx 10\%$ is noticed in the model. The EM is able to draw more current in the hybrid test bench than in a simple EM-propeller setup and therefore the equivalent circuit model overestimates the throttle setting. Regarding the current the simulation achieves results with large errors ($\approx 40\%$) in low throttle regions. But because these regions do not influence the state of charge (SoC) of the battery significantly and the model has good accuracy in high throttle regions (error lower than 10%) the overall mode quality is deemed satisfying (see figure 3).

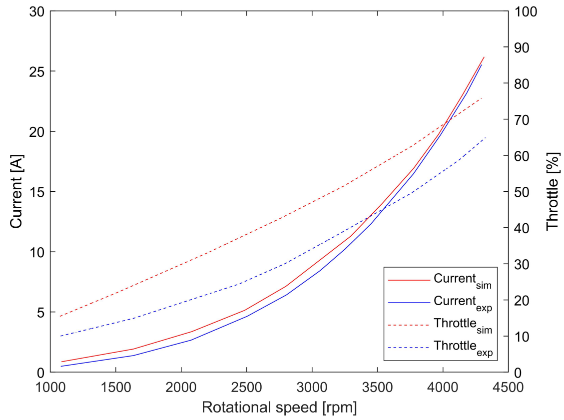

Figure 3: Simulation and experimental results for the EM only mode

4.2. ICE only mode

The Kriging model is implemented in the ICE simulation model as the results are of higher quality compared to the RBF method. The studied parameters for the *ICE only* operating strategy are the throttle and the fuel flow rate, recorded with weight measurements over time, of the engine. In the experiments the ICE values were recorded for throttle settings from 25% to 40%. The simulation trend for the throttle setting matches the experiential values, as observable from figure 4, although the absolute error of $\approx 15\%$ is only present due to a throttle pin adjustment at CfAR (see figure 4), which is not considered in the surrogate model. Because the fuel flow measurement was performed outside, environmental impacts (e.g wind and hot temperatures) can influence the results. While the fuel flow trend is in agreement up to a rotational speed of ≈ 5700 rpm, the simulation does not predict the decrease in inclination for higher operating speeds. This would correlate to a higher relative engine efficiency as the power output increases. However the trend could also correlate to an measurement error, due to an inaccurate fuel flow recording technique (no flow meter), or the environmental impacts. The prediction error varies from $\approx 28\%$ to $\approx 4\%$ for low and high throttle settings, respectively (see figure 4). Considering the complexity of the process and the inaccurate measuring technique the results of the *ICE only* mode are of satisfactory quality.

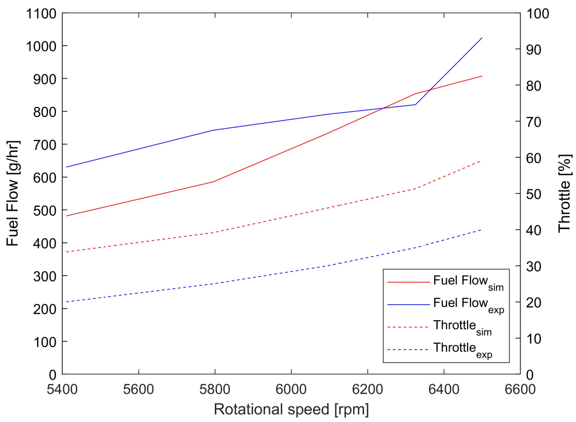

Figure 4: Simulation results for the *ICE only* operating strategy

4.3. Hybrid modes

The hybrid modes *Dash* and *Regenerative Brake* are the two most complex operating strategies, due to the interactions between the different power sources. In the experiment the ICE throttle was kept at an constant level of 40%, while the EM throttle was swept from 0% to 60% and from 0% to -60% for the *Dash* and *Regenerative Brake* mode, respectively. The measurements did not record any values for the fuel flow rate of the ICE and therefore mainly the behaviour of the EM is validated in these modes. The post processing of the experimental data showed a significant variation in torque ICE output over the rotational speed. This behaviour could only be modeled partly with the surrogate model (see figure 5) and therefore is going to influence the accuracy of the results.

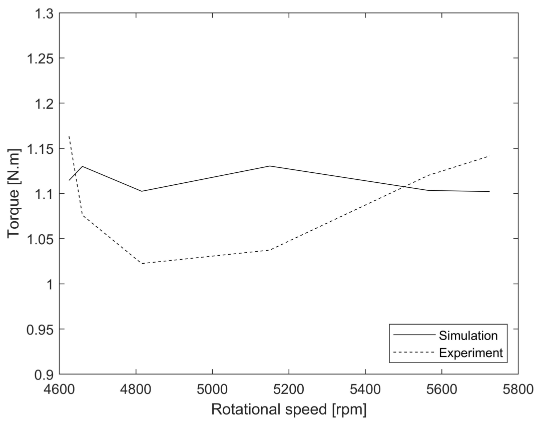

Figure 5: Variation of the ICE torque output at 40% constant throttle over the rotational speed for the *Dash* mode

The performance analysis parameters for both modes are the current and throttle settings of the EM. In the *Regenerative Brake* mode the analysis is extended to include the battery voltage as well. The throttle setting of the EM is determined in the hybrid modes by the definition presented by Greisner in [24]. In the *Dash* operating mode the EM is ineffective for low throttle settings and therefore draws more current from the battery than in the *EMonly* mode (see figure 6). This behaviour results in an exponential throttle increase in this region. The simulation overpredicts the throttle relation until a value of $\approx 30\%$ for the EM is reached. Afterwards both trends show a fairly linear behaviour up to a rotational speed of ≈ 5600 rpm, a further throttle increase only achieves insignificant changes in operational speed. This phenomena could be attributed to a malfunction of the electronic speed controller and is hard to model.

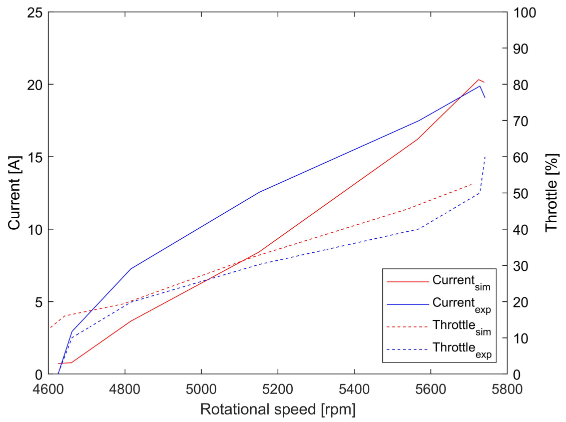

Figure 6: Motor current and throttle simulation results for the *Dash* mode

The current prediction fails to model the exponential current trend for low EM throttle settings as noticeable in figure 6. This results in relatively big prediction errors $\approx 40-50\%$ in these regions. As the EM is operated at higher throttle settings the errors drops to acceptable values of +5% to -5%. Similar to section 4.1 the inaccurate regions do not significantly influence the SoC of the battery and therefore accuracy of the model is good.
The output torque variation for the *Dash* mode (see figure 5) is intensified with the *Regenerative Brake* operating strategy further as stated in [18]. This behaviour is problematic for the validation of the experimental results and a simplified approach is chosen. The measured torque at the EM is directly fed into the model. The current prediction has a good quality with a maximal error of $\approx 10\%$ and a good trend correlation. However the EM throttle trend and the magnitude is at odds with the experimental results (see figure 7). The error is induced as the maximum available EM torque increases faster, due an decrease in rotational speed, than the torque at the EM. This behaviour leads to an decrease in throttle rather than an increase. The performance of the propulsion system is not influenced by this simulation error though, as it is only integrated for analysis purposes. The last per-

formance parameter the battery voltage shows a good correlation trend to the recorded values (see figure 7). The SoC of the battery is charged as the battery voltage increases over the decrease in rotational speed.

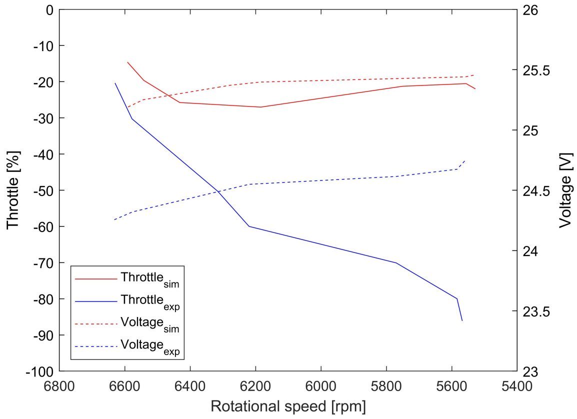

Figure 7: Motor current and battery voltage Simulation results for the *Regenerative Brake* mode

5. Energy Management Strategy and Controller

The two power sources of the parallel hybrid propulsion system, created with the developed component models, are managed by the propulsion system controller and the energy management strategy. Due to its reliability and the successful implementation in multiple projects a rule-based control approach is used in this research project. In total five operating modes are defined for the propulsion system (see table 1). The operating modes of the propulsion system are selected according to the three variables: the required power P_{req}, the maximum EM power P_{EMmax} and the optimal power request P_{opt} (see figure 8). The ICE operates at the optimal power request P_{opt} to guarantee a smooth engine operation. The difference in required power is either provided by the EM (*Dash*, *Normal* and *Fuel Saving* mode) or used to charge the batteries (*Charge* mode). In the *Fuel Saving* mode the ICE only operates at 80% of the optimal power request to save fuel. The aircraft can also be powered by only the EM with the *Stealth* mode, if the power requirement is small enough ($< P_{EMmax}$) and the operational limits of the battery (SoC $> 15\%$ and $< 85\%$) are respected. These limits are included in the controller to achieve long battery life and in case of engine failure power an emergency landing.

The energy management strategy should maximize the performance of the UAV while increasing fuel economy and decreasing emissions. The ideal operating line (IOL) strategy theoretically enables the best performance of the ICE, while being operated at its most efficient point. The formulation of the IOL requires first an engine map with lines

Mode	ICE	EM
Normal	P_{opt}	$P_{req} - P_{opt}$
Fuel saving	$0.8 * P_{opt}$	$P_{req} - 0.8 * P_{opt}$
Dash	$P_{EMmax} - P_{req}$	P_{EMmax}
Charge	P_{opt}	$P_{req} - P_{opt}$
Stealth	-	P_{total}

Table 1: Characteristics for the operating modes of the UAV propulsion system

of constant BSFC values. Afterwards, the intersections between these contour lines and curves of constant power for the engine are computed. The intersection of the power lines with the lowest BSFC contour is the respective IOL data point (see figure 9).[25] As the engine data provided by the manufacturer is not sufficient enough for the IOL determination, the surrogate models are used to obtain extra inputs. The distribution of the IOL points favours interpolation for operation point instead of a fitted polynomial function.

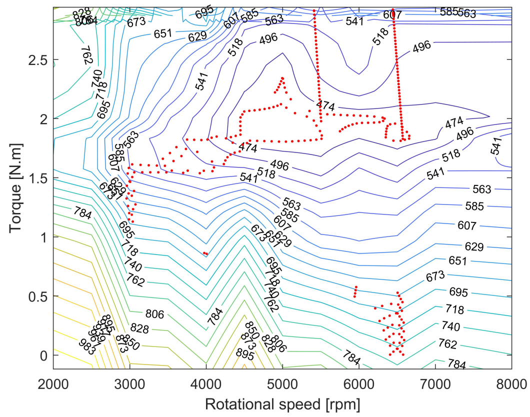

Figure 9: IOL data points from the constant power and constant BSFC graphs

6. Mission Analysis

The surveillance mission type is a widespread application for civil and military UAVs and is therefore going to be analyzed in the evaluation of the different propulsion system architectures. The aircraft endurance and range are the two most important performance parameters for these mission types.

		Value		Unit
Flight altitude		300		[m]
Target distance		50		[km]
Climb angle		2-15		[°]
Descent angle		- 5		[°]
		Electric	Gas	Hybrid
Fuel mass	[kg]	-	3.4	1.4
Battery capacity	[A.h]	40	-	10
Take-off weight	[kg]	~ 26	~ 26	~ 26

Table 2: Surveillance mission characteristics and UAV configurations

The details of the flight scenarios are presented

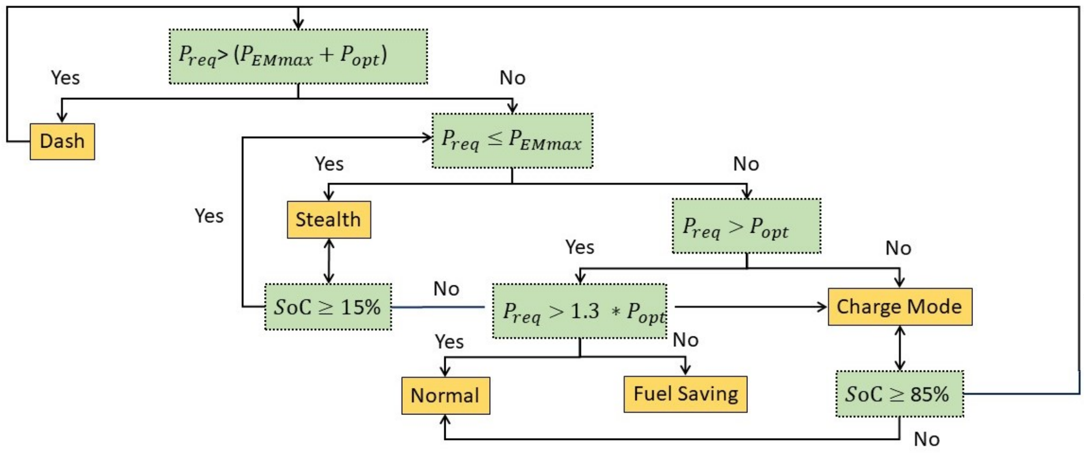

Figure 8: Flowchart of propulsion system controller

in table 2. The QT1 research fixed-wing UAV designed at CfAR is the employed aircraft. The empty mass of the aerial vehicle is 16.34kg and it is capable of carrying a payload up to 3.5kg. In the mission analysis four configurations are analyzed the *Electric*, the conventional *Gasoline* and two hybrid versions *Hybrid1* and *Hybrid2*. *Hybrid1* has the classic parallel configuration without a transmission, therefore it has no implemented energy management strategy, while the *Hybrid2* version is modeled with an transmission and the according IOL strategy. The MTOW of each configuration needs to be similar to guarantee comparability, thus the energy levels vary (see table 2). In the evaluation the small impact of the climb angle on the loiter time ($< 3\%$) is proven. The *Electric* configuration is only able to achieve climb angles up to 9.25°, while the other propulsion systems can achieve angles up to 20°. At the start of the evaluation the optimal power request P_{opt} of the hybrid-electric controller is based on the mean power request in the *Electric* configuration. In order to obtain the maximum performance this parameter is swept between 112 and 270W for the two hybrid configurations. The results are fitted with a polynomial regression of the 3^{rd} and 5^{th} order for the *Hybrid1* (opt. 152W) and *Hybrid2* (opt. 121W), respectively, and are fed into the controller. The results of the endurance analysis for the four configurations are presented in figure 10. The *Electric* configurations is able to achieve a loiter time of 287 minutes. This endurance value is only a fraction (13%) of the *Gasoline* version (2133 minutes). In case of low endurance requirements or necessary stealth operation the *Electric* propulsion system still presents to be a viable solution. The hybrid system with an extra transmission and IOL energy management strategy (*Hybrid2*) outperforms the *Hybrid1* configuration by $\approx 28\%$ for a loiter time of 997 minutes. Therefore the *Hybrid2* configuration could reduce the amount of fuel by 60% and still achieve 48% of the endurance. In the next step the range analysis is performed with a prescribed loiter time of 120 minutes. In this simulation the trends from the endurance examination continue (see figure 11). The *Electric* propulsion system achieves with 133km only 8% of the dash distance from the *Gasoline* type. The potential of the parallel hybrid configuration using the IOL strategy is emphasized again as 46% of the dash distance compared to the *Gasoline* version could be achieved with the same fuel reduction as previously mentioned. In this analysis type the *Hybrid2* outperforms the classic parallel hybrid configuration by even a larger margin of 46%.

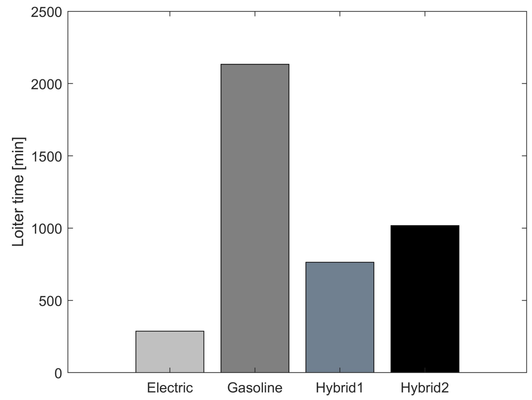

Figure 10: Maximum achievable loiter time in the baseline mission for each configuration

7. Conclusions

A numerical model for a parallel hybrid-electric propulsion system of an UAV and the results of a mission analysis were provided. In the first step the simulation model for each component of the propulsion system was separately developed. Afterwards the models were validated in different operating strategies of the system with experimen-

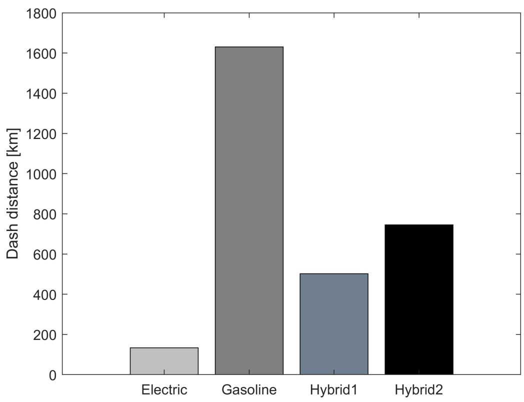

Figure 11: Maximum achieveable dash distance for each propulsion type with 120min of prescribed loiter time

tal data from a previous researcher. The propulsion system was equipped with a rule-based controller and the IOL energy management strategy for the ICE. Therefore the complete propulsion module can be implemented into any airframe simulation model. The different propulsion systems were evaluated in a surveillance mission analysis with the focus on the endurance and the range of the aircraft. The parallel hybrid configuration with an engine transmission and therefore the IOL strategy showed the greatest potential for greener aviation. Through this propulsion configuration the burned fuel could be reduced by 60%, while still providing between 46-48% of the performance.
Future works related to this research project are an extensive experimental test campaign, the implementation of a serial hybrid propulsion configuration and the development of more sophisticated energy management strategies. The additional experimental data is needed to tune the models and simulate the interactions of the power source in the hybrid modes more accurately. Through an additional generator model a serial hybrid architecture could be developed and its performance studied. The energy management strategy and the coupled controller provide efficient use of the available energy on board. However more sophisticated control approaches like fuzzy or neural network logic could minimize the energy consumption of the UAV further.

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