Deutscher Luft- und Raumfahrtkongress 2021
DocumentID: 550130

HUMMINGBIRD HYBRID - MICRO HYBRID ELECTRIC AIRCRAFT PROPULSION SYSTEM

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Abstract

The Hummingbird Gas Turbines (HGT) student research group focuses on the research on small gas turbines. In line with global trends in aviation, HGT is exploring a possible path towards minimising noise and carbon emissions. To this aim, the group is developing the Hummingbird Hybrid, a series hybrid configuration test bench rated at 5 kW electric power, consisting of a gas turbine, battery, and electric propulsors. This paper introduces the concept of the Hummingbird Hybrid, its goals, and the milestones achieved in the individual development areas so far. Furthermore, it relates the investigations done to current research on hybrid powertrains for manned and unmanned aerial vehicles and presents preliminary results of component tests.

Keywords
Hybrid Aircraft Propulsion; Electric Propulsor; Student Research Group

NOMENCLATURE

Symbols

J	cost function	-
k	index of the time step	-
$\dot{m}_F$	fuel mass flow into the gas turbine	g/s
n_1	rotational speed core engine	rpm
n_2	rotational speed output shaft	rpm
n_3	rotational speed electric propulsor	rpm
P	power	W
PE	requirement for pure electric flight	-
SOC	state of charge of the battery	-
t	time	s
U	voltage	V
v_T	duty cycle of the DC/DC converter	-

Indices

DCL	DC link
dem	demanded
Fan	fan (propulsor)
Gen	generator
max	maximal
mech	mechanical
min	minimal
tot	total

Abbreviations

BMS	Battery Management System
DC	Direct Current
DLR	Deutsches Zentrum für Luft- und Raumfahrt (German Aerospace Center)
ECU	Engine Control Unit
HGT	Hummingbird Gas Turbines
ICE	Internal Combustion Engine
LiPo	Lithium Polymer Battery
LTF	Lehrstuhl für Turbomaschinen und Flugantriebe (Chair of Turbomachinery and Flight Propulsion)
PM	Power Module
SoC	State of Charge
SoH	State of Health
TUM	Technical University of Munich
UAV	Unmanned Aerial Vehicle

doi: 10.25967/550130

1. INTRODUCTION

The student group Hummingbird Gas Turbines (HGT) at the Chair of Turbomachinery and Flight Propulsion (LTF) of the Technical University of Munich (TUM) researches model gas turbines. Students from the bachelor and master programs at TUM can work on research projects regarding turbojet and turboprop engines. Since late 2016, HGT has been researching and developing a new hybrid powertrain for small aircraft consisting of a gas turbine driving a three-phase electric generator to charge batteries and power two electric propulsors developed in-house at HGT. The goal of this project is to develop a fully functional hybrid powertrain. Such a propulsion system would allow aircraft to operate electrically with low noise and carbon emissions in environmentally or noise restricted areas whilst maintaining the advantages of fuel-powered aircraft, such as the significantly higher energy density of kerosene compared to batteries [1], [2]. In addition, the control system would allow the gas turbine to operate continually at, or close to, optimum rpm, regardless of current power draw, improving system efficiency. This type of hybridisation could prove especially useful in urban air transport, where aircraft operate in noise-sensitive urban environments while also covering significant distances outside of or between cities. An example of this would be Unmanned Aerial Vehicle (UAV) parcel delivery from remote distribution centres.

2. STATE OF THE ART

With global demands for low emissions transport systems increasing significantly, there has been growing research into the field of "All Electric Aircraft" such as Airbus' "E-Fan 1.1" aircraft [3]. However, implementing all electric powertrains still represents significant challenges and downsides, such as the low volumetric and gravitational energy density of batteries [2] and the lack of fast recharging. This has lead to a trend for the development of hybrid aircraft, allowing the mitigation of these factors. Much of this research has been driven by initiatives such as the vision report "Flightpath2050" by the European Union [4], as well as the European Commissions 2050 long term development strategy [5]. In this context, projects like the MAHEPA project to develop modular hybrid electric propulsion architectures for aircraft [6] are funded by the EU.

In line with Saenger-Zetina et al. [7], a hybrid aircraft shall be defined as using two different energy sources to provide propulsive power. There are currently multiple research projects in this field, a brief overview of which is presented below. A closer comparison to the HGT hybrid powertrain can be found in Sec 3. Hybrid powertrains can be split into two categories:

1) Series hybrid
2) Parallel hybrid

In a series hybrid, energy from both sources is delivered to the propulsor via electric buses. On the other hand, a parallel hybrid delivers fuel energy mechanically, whilst delivering the second energy source electrically [8]. The Hummingbird Hybrid architecture would thus be considered a series hybrid.

Amongst notable hybrid concepts are the Siemens/Diamond *E-Star* aircraft, a series hybrid aircraft that was the first of its kind [9]. The *E-Star* utilises a 70 kW electric motor to drive the propulsor and a Wankel motor operating continuously at 30 kW, driving a generator to keep the batteries charged. On the side of parallel powertrains, the University of Cambridge in 2011 demonstrated a hybrid test aircraft. This was further developed, and in 2014 this demonstrator, based on the *Song* aircraft, became the first parallel electric hybrid aircraft capable of in-flight battery recharging [10]. It achieves this by using a Honda *GX 160* 7 kW piston engine along with a Joby *JM1* 10 kW electric motor/generator [11]. In more recent years, Airbus has launched, and in April 2020 retired, their *E-Fan X* series hybrid demonstrator aircraft. A modified *BAe 146* regional jet had one of its four gas turbine engines replaced by a 2 MW electric propulsor and high power batteries added as a secondary energy source [3]. Further developments regarding hybrid concepts using gas turbines are supported by the company Honeywell Aerospace. Their 1 MW turbogenerator is intended to propel projects such as the Faradair *BEHA M1H* [12]. In addition to the mentioned concepts, hybrid aircraft can also utilise hydrogen instead of kerosene as their primary energy source. An example of this is the *HY4* aircraft developed by H2FLY, a company funded in part by the EU's MAHEPA project, and built in conjunction with Pipistrel and the German Aerospace Center (DLR). This vehicle utilises an 80 kW electric motor with a 45 kW hydrogen fuel cell as well as 21 kWh of battery capacity capable of providing 45 kW of electric power [13], [14]. Lastly, a noteworthy concept is the Quaternium *Hybrix 2.1* hybrid drone. This UAV utilises a modified Zenoah 32 cc two-stroke engine capable of 2.6 kW mechanical output power and two 6S Lithium Polymer (LiPo) batteries. The batteries are continuously recharged during flight and provide power to four MAD Components three-phase electric motors [15]. In 2020 Quaternium was able to use a modified version of this drone to set a new flight time record of 10 hours and 14 minutes [16], vastly outpacing the flight time of traditional all electric drones of typically under one hour, see examples in Ref. [17], [18], [19], and thus proving the benefit of hybrid powertrains. A more in-depth review of different hybrid and all electric concepts in the aerospace sector can be found in Brelje et al. [8].

3. HUMMINGBIRD HYBRID

The Hummingbird Hybrid propulsion system is designed to allow small aircraft to incorporate the benefits of all electric flight, such as reduced noise and carbon emissions, into their flight profiles. HGT decided to develop a series hybrid system using a gas turbine as a primary energy source (instead of using an internal combustion engine (ICE) as used in hybrid electric cars for example), mainly because of the experience of HGT with gas turbines. Furthermore, using a gas turbine provides several benefits such as high power density, lower carbon and noise emission compared to an ICE, simplicity and lower maintenance cost [20]. Additionally, the poor efficiency of micro gas turbines is less pronounced if the gas turbine is part of a hybrid system, as the machine can always run at optimal conditions [20]. Being also aware of disadvantages of gas turbines, such as slow start-up and slow load changing capabilities, HGT wants to show the feasibility of such a propulsion system. The final goal of Hummingbird Hybrid is to have a test rig including all the components of this series hybrid electric propulsion system. The development effort comprises five areas:

- Experimental investigations for modelling and validating purposes on the stationary and dynamic behaviour of powertrain components
- Simulation and control of the power conversion components interaction, including their control system and algorithms for an automated start-up procedure
- Design of the electric propulsors as well as the development of in-house turbomachinery design tools for generating aerodynamic profiles based on mean line calculation and parameter optimisation thereof
- System-level simulation and control to model and optimise flight performance based on a given mission profile
- Experimental tests of the entire powertrain for single operating points as well as for whole flight missions

The key features of the Hummingbird Hybrid are as follows:

- Hybrid electric propulsion system
- Series hybrid layout
- Gas turbine as primary energy source
- Electric system power of 5.00 kW
- Possible applications in aerospace such as UAVs

To compare the Hummingbird Hybrid propulsion system to other series hybrid concepts mentioned in Sec 2, the key parameters are summarised in Tab 1. With relatively low electric system power, the Hummingbird Hybrid is best comparable to the *Hybrix 2.1*. It distinguishes itself in using a gas turbine as a primary energy source, which is otherwise only common in the megawatt category. In addition, the use of the gas turbine is not intended as a mere range extension. Instead, the combination of electric and fuel energy storage is used to minimise the gas turbine fuel consumption through a complex control algorithm described in Sec 3.4.1.

3.1. General System Layout

In Fig 1 the Hummingbird Hybrid propulsion system and its components are shown. A gas turbine (1) serves together with a three-phase generator (2) as the primary power source. The three-phase current is rectified (3) and fed into the intermediate DC power link (4). The DC link provides power to two in-house developed single-stage propulsors (6), powered by electric motors and controlled by three-phase inverters (5). Through the power electronics (8), the DC link can either supply or draw power to/from a battery (7) respectively. This allows pure electric drive or battery charging, both in-flight. An in-house developed control system governs the hybrid propulsion system based on flight mission requirements. Furthermore, in Tab 2 the systems key parameters are presented.

Concept	**Primary energy source**	**Power primary energy source in kW**	**Electric power in kW**	**Fuel**
E-Star	ICE	30	70	Gasoline
HY4	Fuel cell	45	80	Hydrogen
Hybrix 2.1	ICE	2.6	-	Gasoline
Hummingbird Hybrid	Gas turbine	5.62	5.00	Kerosene

TAB 1. Key features of selected series hybrid systems

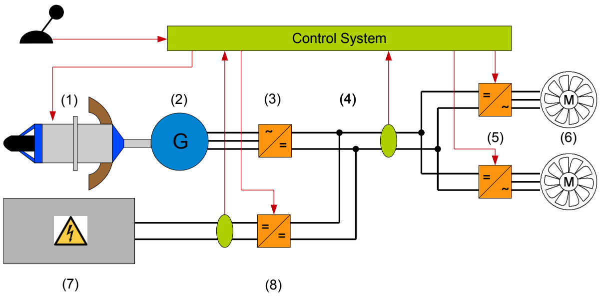


FIG 1. Hummingbird Hybrid schematic overview

Max. shaft power gas turbine	5.62 kW
Max. DC link voltage	120 V
Battery configuration	24S1P LiPo
Nom. battery capacity	5.00 Ah
Max. electric power for propulsors	5.00 kW
Total thrust from propulsors	58.70 N

TAB 2. Hummingbird Hybrid system parameters

Most of the parts of the powertrain are currently in the state of component testing at the Hummingbird Hybrid test facility. At the time of this publication (September 2021), the components have the following state:

- Gas turbine (1)
  A bought component, model *Wren 50i TP*, which is installed on one test bench and ready for operation. An in-house control system is implemented to allow for automated start-up procedure and speed controlled operation [21].
- Generator (2)
  A modified *Turnigy RotoMax 50cc* which is installed on the same test bench as the gas turbine. It is in operation and its interaction with the gas turbine has

been tested. A model has been derived for controlling the generator's electric power output by controlling the gas turbine [22].
- Rectifier (3) and DC link (4)
  These components are designed and manufactured as part of [23]. The electricity coming from the generator is currently dissipated as heat in a load resistor. This load resistor is designed by HGT and can model the behaviour of the electric propulsors. Therefore it is used to develop control strategies for the gas turbine [22]. Still missing is the connection from the DC link to the batteries and/or the rectifier. This calls for the design of a battery management system to recharge the batteries in-flight.
- Electric propulsor (6), inverter (5) and battery (7)
  Two single-stage axial compressors or propulsors aerodynamically designed by HGT [24], fabricated by an external supplier and assembled by HGT. The one produced so far is installed on a separate test bench and is undergoing extensive testing. For the tests it is supplied with electric power from *TopFuel LiPo 20C ECO-X 5000mAh 6S MTAG* batteries used in model helicopters. In addition, a *YGE 120 HV* motor controller from a model helicopter is used as an inverter to supply the motor inside the electric propulsor with an alternating current. As a control input for the motor controller, a potentiometer is used. Using the "governor mode", a built-in control mode, the motor controller can maintain a constant motor speed even with reducing battery voltage due to discharging. In parallel, there is development effort on the design side to create a more efficient version of the propulsor. Based on the calculations from [24], a new design tool for axial compressor stages is developed in [25] and [26].
- Power electronics (8)
  These will enable the DC link to draw energy from the battery, supply electricity to the electric propulsor and supply or draw power to/from the battery respectively. Despite having been designed in [23], this component has not yet been manufactured.

In the following sections, all the components are discussed in detail.

3.2. Gas Turbine and Three-Phase Generator

The turbine mounted on the test bench is a turboshaft gas turbine of twin-shaft design from Wren by Turbine Solutions, model *Wren 50i TP*. The manufacturer's data of the turbine is listed in Tab 3.

Shaft power	5.62 kW
Max. speed core engine n_1	195,000 rpm
Max. speed output shaft n_2	9000 rpm
Weight	1.7 kg
Brake specific fuel consumption	1548 g/(kW h)

TAB 3. Manufacturer specifications for the Wren 50i turboprop [21]

Initially, it was bought and used by HGT as a turboprop engine in combination with a propeller. The turbine is operated with a kerosene-oil mixture of 95% kerosene and 5% fully synthetic turbine oil. A small part of the mass flow of the kerosene-oil mixture is used to lubricate the ball bearings [21]. The core engine consists of a single-stage centrifugal compressor, a combustion chamber and a single-stage axial turbine. The power turbine also consists of a single-stage axial turbine, the shaft of which is connected to the output shaft via a planetary gearbox [27].
Still operating with a propeller, an automated start-up procedure is implemented to eliminate the Engine Control Unit (ECU) supplied by the manufacturer. This automated start-up procedure is part of a control system developed by HGT. It consists of a *LabVIEW* program, which runs on a *cRIO* real-time computer from National Instruments [21]. The control system allows automated engine start-up and the selection of required core engine speeds during operation. This is done by controlling the voltage applied to the fuel pump and thus indirectly controlling the amount of fuel supplied to the gas turbine.

For the Hummingbird Hybrid concept, the propeller is replaced by a generator. Therefore the output shaft is connected to the generator via a flexible shaft coupling to compensate for slight misalignment. A picture of the combined installation of gas turbine and generator on the test bench is shown in Fig 2.

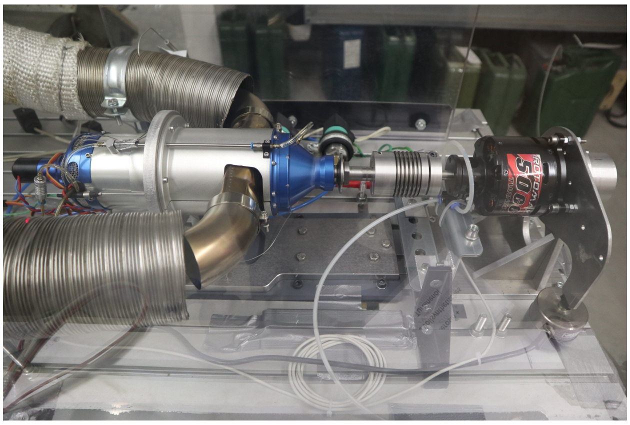


FIG 2. Gas turbine and generator on the test bench

The generator on the Hummingbird Hybrid test bench converts the mechanical power from the power turbine stage of the gas turbine into electric power. It is mounted so that the casing can tilt slightly around its axis, allowing a mounted lever arm to be supported on a load cell. Thus, the torque can be calculated by knowing the lever arm length and using the measured support force. In the steady-state case, the torque of the output shaft of the gas turbine and that of the generator casing are identical [23]. The generator installed on the test bench is a three-phase synchronous machine with permanent magnets in external rotor design (Model *Turnigy RotoMax 50cc*). It uses 28 permanent magnets; thus, the number of pole pairs is 14. The generator is rewound to adjust the characteristics to the desired values allowing it to reach the required voltage [23]. Measuring the rotational speed of the core engine and the output shaft, a power map of the gas turbine is calculated, shown in Fig 3. On the test bench, a maximal speed of 190,000 rpm is reached for the core engine of the gas turbine. At this operating point, the output shaft of the gas turbine is turning at up to 7000 rpm. For the shaft power values around 4.20 kW are achieved, thus staying below the manufacturer specifications [23].

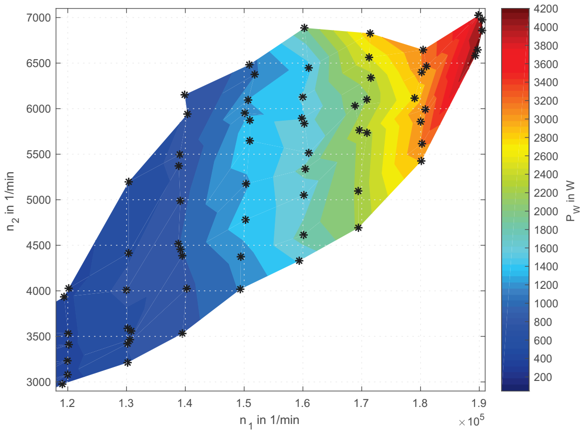


FIG 3. Measured power map of the gas turbine [23]

The produced generator current is fed via a three-phase rectifier (a *Powersem PSDS 83/08* B6 bridge) into the DC link. The load of the generator and thus its torque can be adjusted.

3.3. Electric Propulsors

The electric propulsors responsible for generating thrust are designed entirely in-house. It is a clean-sheet design, for which a custom aerodynamic design tool was developed [24]. In parallel, Hummingbird is developing a more versatile design tool also allowing for multistage configurations, which is beyond the scope of this article [25], [26].

The design boundary conditions are summarised in Tab 4. The power constraint is derived from the Hummingbird Hybrid system architecture as described in Sec 3.1. The annulus shape is constrained in the hub region by the dimensions of the electric motor, and the casing dimension is selected based on the available testing facilities. The maximum flow velocity is based on the legislative constraints for a possible future flight demonstrator, which is bound to be operated within line of sight [24].

Rotor inner radius	30 - 50 mm
Max. rotor outer radius	100 mm
Max. flight velocity	30 m/s
Rated mechanical power	2000 W

TAB 4. Electric propulsor design boundary conditions

The 1D mean line design is done at the relative height corresponding to the Euler radius of the mean flow area [24]. The 2D aerodynamic design is based on the free vortex flow, chosen primarily due to the relative ease of calculation associated with the constant meridional velocity and mass flow across the relative blade height [24]. The blade sections are designed using the NACA-65 profile series due to its suitability for subsonic compressors and abundance of empirical documentation. The blade metal angles are determined using the Lieblein method, which is based on the studies of NACA-65 series profiles [24].

The aerodynamic design tool is developed in Microsoft *Excel*. Because of the relative velocities in the rotor exceeding Mach number of 0.3, it considers compressible flow effects, which leads to the need for iterative calculations of the flow state variables. This is handled using the *Goal Seek* feature in *Excel*. Furthermore, the design variables are optimised for maximum thrust within the limits of aerodynamic boundary conditions using the *Excel Solver* toolbox. The determination of rotor blade and stator vane numbers is not embedded into the design tool and is determined analytically with aeroacoustic considerations based on the tool outputs.

The resulting aerodynamic design uses the thickness distribution of the NACA65(261)-010 profile applied on a circular arc camber line. The rotor relative outflow angle β_2 is 135° and the absolute stator outflow angle α_3 is 90° at the mean line. As the blades are designed for constant loading across the blade height, the chord length gets visibly shorter towards the casing. The calculated thrust of each propulsor is 29.35 N. The key parameters of the electric propulsors' aerodynamic design are summarised in Tab 5 and the propulsor design is depicted in Fig 4.

Hub radius	32.00 mm
Case radius	57.41 mm
No. of rotor blades	9
No. of stator vanes	8
Aerodynamic profile	NACA65(261)-010
Design speed n_3	20,200 rpm
Rotor rel. outflow angle β_2	135°
Stator abs. outflow angle α_3	90°
Mass flow	0.5 kg/s
Thrust	29.35 N

TAB 5. Summary of the electric propulsor design properties [24]

So far, only one of the electric propulsors is available for testing purposes. The individual parts are machined from an aluminium alloy. The propulsor is powered by a model-aircraft motor *RotorStar R5700-560KV*, which is chosen based on the nominal operating point, rated power and the initial dimension constraint. Nevertheless, in the future this electric motor will need updates regarding winding and cooling to match requirements,

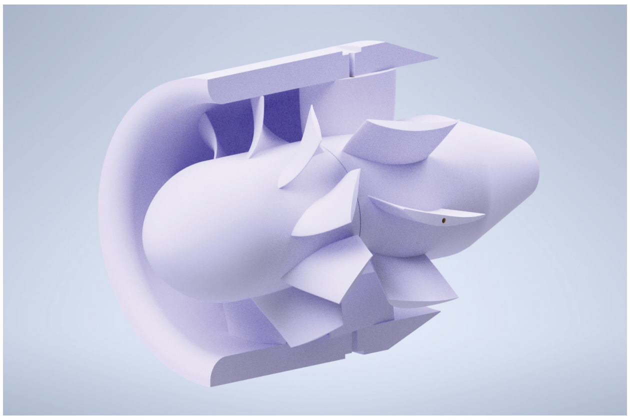


FIG 4. Electric propulsor design

such as the DC link voltage of 120 V. The motor is governed using a three-phase inverter, the final choice of which is yet to be made.

The propulsor properties are being evaluated on an in-house developed test bench, namely through measuring thrust characteristics, flow velocity, and flow angles of the outflow. As the experimental evaluation of the propulsor is currently Hummingbird's main focus, only limited results are available at the time of this publication. So far, preliminary results are presented for the zero-speed thrust characteristic and single-point flow velocity measurement at the exit plane.

The preliminary results are shown in Fig 5. They only show measured values up to 14,000 rpm as vibration related concerns require further investigations before operating the propulsor at higher speeds. Future measurements will also be carried out after re-calibration of the thrust measurement, which now has significant uncertainty towards higher rotational speeds, likely associated with the vibration issues. Nevertheless, the initial thrust and mass flow measurements show trends that are largely consistent with the design parameters (0.5 kg/s and 29.35 N at the design speed of 20,200 rpm).

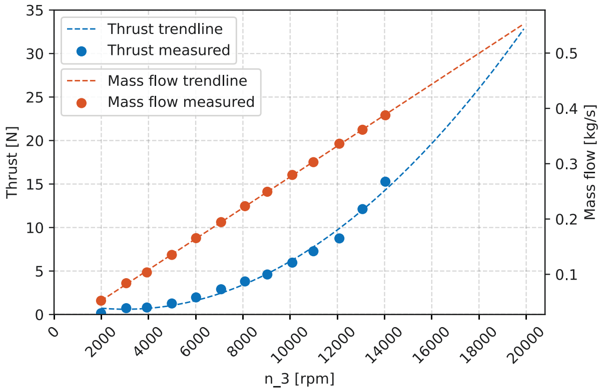


FIG 5. Propulsor characteristics measurement

Experiments in the near future will also include flow measurements using an in-house developed traversing mechanism [28] for a more detailed understanding of the flow behaviour at the exit plane.

3.4. Control System

After discussing the hardware components, this section focuses on the control system necessary to operate the hybrid electric powertrain. As, for its nature, the hybrid powertrain has two energy sources, a strategy needs to be established to distribute the power demand of the electric propulsors on the sources, namely the battery and DC/DC-converter compound and the gas turbine and generator compound. To face the problem, first the degrees of freedom of the whole powertrain are analysed. While doing this, the propulsors are considered a black box, only having a specific power demand $P_{Fan,tot}$ and a minimum required DC link voltage $U_{DCL,min}$ for reaching the required rpm. Furthermore, the flight control system can require pure electric flight PE (*silence mode* in [29]). Thus, the control problem can be written in the following set of equations:

$$\text{(1)} \qquad \begin{pmatrix} P_{Gen,dem} \\ U_{DCL,dem} \end{pmatrix} = f_{OS} \begin{pmatrix} P_{Fan,tot} \\ U_{DCL,min} \\ PE \end{pmatrix}$$

$$\text{(2)} \qquad \begin{pmatrix} \dot{m}_F \\ v_T \end{pmatrix} = f_C \begin{pmatrix} P_{Gen,dem} \\ U_{DCL,dem} \end{pmatrix}$$

Equation (1) is defined as the operational strategy of the powertrain, giving demand values for the power of the generator $P_{Gen,dem}$ and the DC link voltage $U_{DCL,dem}$. Equation (2) is the control law of the two subsystems gas turbine - generator and battery - DC/DC converter. Additionally, the speed control of the propulsors can be treated as another part of the control system. Therefore the whole control structure divides up into the following subsystems:

- The power-split algorithm or operational strategy, which distributes the power demand of the pilot/flight mission to the gas turbine and the battery
- The gas turbine and generator compound's control system
- The battery management system and control of the DC/DC converter
- The speed control of the electric propulsors

These subsystems are discussed in the following sections.

3.4.1. Operational Strategy and Power-split Algorithm

The operational strategy, i.e. the distribution of the power demand on the energy sources, does not have a unique solution. Having a closer look at equation (1) shows that different design targets can lead to different solutions for the operational strategy. Hummingbird is designing its system to minimise the overall fuel consumption of a certain mission. This leads to a dynamic optimisation problem.

One way to solve this problem is optimisation via discrete dynamic programming as it is applied in [29]. The key idea of dynamic programming is Bellman's optimum principle, which states that every remaining trajectory of the optimum control trajectory is optimal itself to get the system from the present state to the final state. This enables the possibility to optimise the whole mission from the final state working backwards recursively, minimising the cost-to-go ([30], pg. 357ff). Similarly to [29], the optimisation problem for the hybrid powertrain can be written as: [23]

(3)

$$
\begin{aligned}
\min J = \sum_{k=0}^{K-1} & \dot{m}_F(k) \cdot T \\
& + m_{Start} \cdot (P_{Gen}(k) \neq 0 \wedge P_{Gen}(k-1) = 0) \\
& + m_{Penalty} \cdot (P_{Gen}(k) \neq 0 \wedge PE(k)) \\
s.t. & \begin{cases} \frac{dSOC}{dt} = f_{Bat}(SOC,\ P_{Bat}) \\ GT_{on} = (P_{Gen} \neq 0) \\ 0,3 \leq SOC \leq 0,9 \\ P_{Bat} + P_{Gen} = P_{Fan,tot} \\ (P_{mech},\ n_2) = f_{Gen}(P_{Gen},\ U_{DCL}) \\ (n_1,\ \dot{m}_F) = f_{GT}(P_{mech},\ n_2) \\ \text{OP. limits} \end{cases}
\end{aligned}
$$

In [23] the optimisation is performed for different flight profiles. Fig 6 shows the optimised transport mission of a package drone with a travel distance of 80 km. Pure electric flight phases are introduced at the beginning and end of the mission to minimise noise emissions. It can be seen that after the start, the battery is further discharged and then recharged by the gas turbine. After recharging, the gas turbine solely delivers the power requirement of the propulsors until the remaining required energy to complete the flight matches that of the batteries.

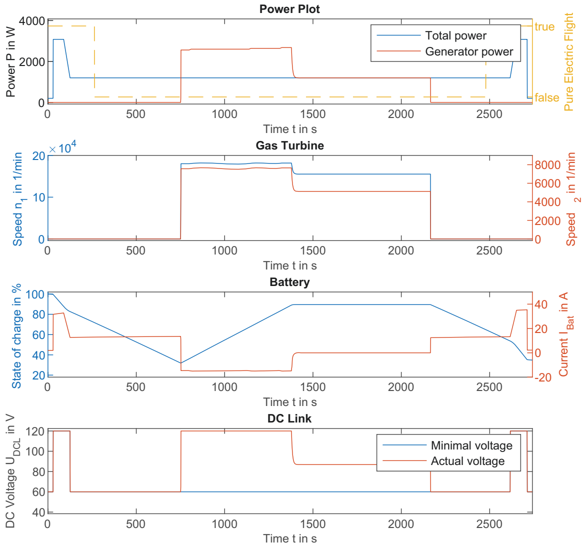
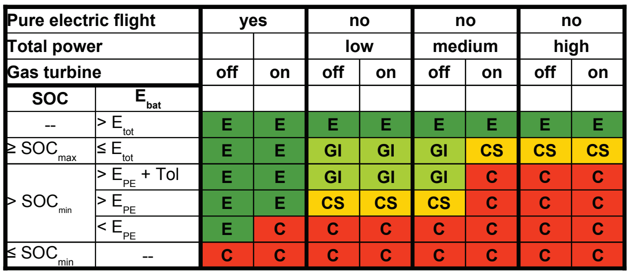


FIG 6. Optimisation result for a standard flight profile

Because of the high computational effort, dynamic programming is not suitable for an in-flight (real-time) control law. One way to solve the issue is iterative dynamic programming, as proposed for the hybrid application in [29]. In [23] it is decided to follow a different approach, which consists in deriving a deterministic, real-time capable algorithm, which intends to give a similar power-split behaviour as the optimisation. The algorithm works with a 4-dimensional decision matrix. Based on the actual flight state (power requirement and requirement for pure electric flight), the state of charge (SoC) of the battery and the operating state of the gas turbine, the operational category of the powertrain can be obtained. In addition, the remaining required total energy and the remaining total energy for pure electric flight need to be known from the flight mission. However, no actual details of the time-distribution of these quantities have to be known. Fig 7 shows the decision matrix in a flattened form. The operational categories are pure electric (E), gas turbine in idle (GI), charge sustaining of the battery (CS) and recharging the battery with maximum power (C).



Pure electric flight		yes		no		no		no	
Total power				low		medium		high	
Gas turbine		off	on	off	on	off	on	off	on
SOC	E_{bat}								
--	$> E_{tot}$	E	E	E	E	E	E	E	E
$\geq SOC_{max}$	$\leq E_{tot}$	E	E	GI	GI	GI	CS	CS	CS
$> SOC_{min}$	$> E_{PE}$ + Tol	E	E	GI	GI	GI	C	C	C
	$> E_{PE}$	E	E	CS	CS	CS	C	C	C
	$< E_{PE}$	E	C	C	C	C	C	C	C
$\leq SOC_{min}$	--	C	C	C	C	C	C	C	C

FIG 7. Decision matrix for the real-time operational strategy

Once the operational category is determined, the power demand of the gas turbine and generator compound and the DC link target voltage can be calculated with the following set of equations: [23]

(4)

$$
P_{Gen,dem} = \begin{cases} 0 & \text{, for } E,\ GI \\ P_{Fan,tot} & \text{, for } CS \\ P_{Fan,tot} + P_{Bat,C,max} & \text{, for } C \end{cases}
$$

(5)

$$
U_{DCL,dem} = \begin{cases} U_{DCL,min} & \text{, for } E,\ GI \\ \max\{k_{UDCL} \cdot P_{Gen,dem} + \\ U_{DCL,0},\ U_{DCL,min}\} & \text{, for } CS,\ C \end{cases}
$$

The parameters for applying the decision matrix, see Fig 7, and the power-split equations, see equations (4) and (5), were adjusted in simulation [23], but have not been validated in real-time operation yet. Applying the real-time algorithm in simulations indeed shows a very similar system performance compared to the optimisation [23].

3.4.2. Gas Turbine and Generator Control

As stated by the first line of equation (2), the task of the gas turbine and generator control is to adjust the fuel mass flow into the turbine, so that the generator's output power fulfils the demand of the operational strategy. The gas turbine - by its nature - is a highly nonlinear system and cannot directly be controlled using a linear controller. To face the problem, the behaviour of the whole turbine and generator compound is linearised in real-time using exact linearisation. This filtered system behaviour can then be controlled using a linear two-degree of freedom controller. A rate limiter is used to prevent the turbine from going beyond operational limits. The controlled system shows a good step response in the electric power at the generator, as can be seen in Fig 8 [22].

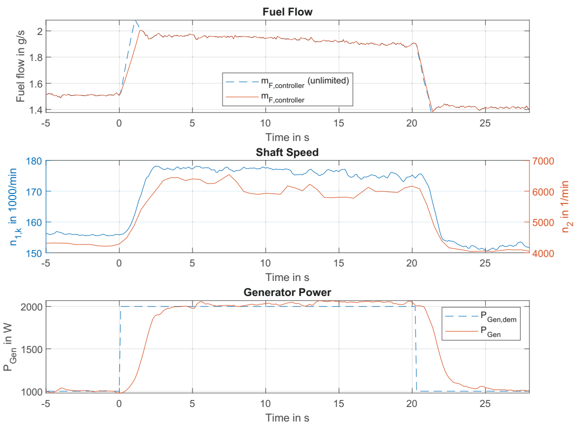


FIG 8. Step response of the controlled gas turbine and generator compound

To start-up the gas turbine, a separate control algorithm is developed. This algorithm consists of a state machine going through the phases of the start-up procedure, namely turn the starter motor, ignition phase, preheat the combustion chamber with the preheat burner, ignition of the main burners, spool up to self-sustaining speed with the help of the starting motor and finally to idle speed by ramping up the amount of fuel. After the start-up, the turbine is at idle speed with a constant fuel flow [21].
To switch between the two operating modes *idle* and *power-controlled mode*, a bumpless transfer algorithm is implemented in the control system of the gas turbine [22]. The resulting control structure is shown in Fig 9.

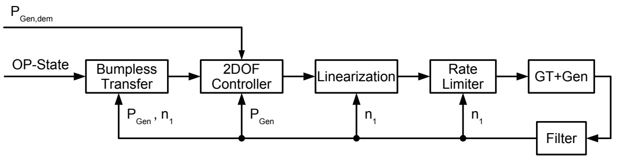


FIG 9. Control structure of the gas turbine and generator compound

3.4.3. Battery Management and DC/DC Converter Control

As mentioned in Sec 3.1, the electric propulsors are powered by LiPo batteries. The development of a complete in-house battery system requires implementing a Battery Management System (BMS). The purpose of a BMS is to guarantee the safe operation of batteries by avoiding the risk of battery damage due to hitting voltage, current or temperature limits. The process of charging and discharging the battery is therefore monitored and controlled by the BMS [31]. A DC/DC converter, part of the power electronics and linked to the BMS, is necessary to transform the voltage supplied by the battery into the voltage required by the motor inside the electric propulsor. It can also modify the charging and discharging of the batteries [32]. A control system for this component is foreseen and will be integrated in the future as part of the overall control system described in Sec 3.4. Fig 10 shows the architecture of the BMS.

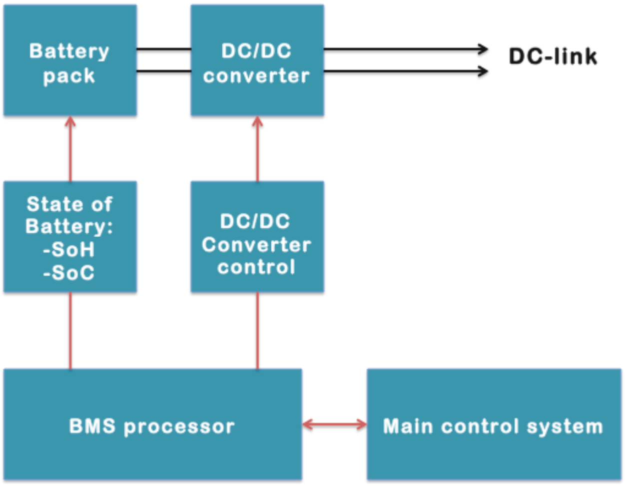


FIG 10. General diagram of the battery management system

The state of the batteries in the system is monitored through two parameters, the state of health (SoH) and the state of charge (SoC). The processor in the BMS uses this information to define the system's operation, which includes the DC/DC converter and its controller. The energy from the batteries is fed into the DC/DC converter and to the DC link of the complete system shown in Fig 1. As mentioned in Sec 3.4, the BMS is part of the complete control system and is therefore linked to it.
The final design and architecture of such a system will be based on existing configurations and the specific power demand and supply of the other components in the Hummingbird Hybrid system. A separate case study will be dedicated to this matter.

3.4.4. Electric Propulsors Speed Control

The speed control of the electric propulsors is an integral component of the three-phase inverters for the motors. From the flight control system a rotational speed demand value is given to the propulsion system. The target of the speed control is then to actually reach the desired speed value. To satisfy this need, a sensorless speed control system for the synchronous motors will be built. Until then, the motor of the electric propulsor is driven by a stock inverter for model applications, model *YGE 120 HV*. However, this inverter is not capable of handling DC link voltages of up to 120 V and thus needs to be replaced.

4. CONCLUSION AND OUTLOOK

Over the course of the next semester, HGT will focus on measuring a complete power map of the electric propulsor as well as on measuring the flow behaviour at the exit plane. Thus having the experimental data, it will be possible to evaluate the design of the electric propulsor and identify improvement possibilities regarding the design itself and the design tools.

Furthermore, the testing of the complete hybrid system requires developing some subsystems and components, which do not yet exist. Comparing Sec 3, Fig 1 and the parts on which this paper elaborates, future work is left in adapting a suitable battery (7) and power electronics (8), as well as closing the gap in the DC link (4). The subsequent integration of all necessary elements like the battery management system, the DC/DC converter control, the speed control of the electric propulsors, as well as the implementation and validation of the operation strategy in the real-time control system, is key to allow for the full operation of the entire hybrid system.

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Acknowledgement

The student group would like to thank the Technical University of Munich for funding and the Chair of Turbomachinery and Flight Propulsion for providing facilities and supporting the project.

References

[1] Willy J. Bräunling. *Flugzeugtriebwerke. Grundlagen, Aero-Thermodynamik, ideale und reale Kreisprozesse, Thermische Turbomaschinen, Komponenten, Emissionen und Systeme*. Springer Vieweg, Berlin, Heidelberg, 2015. ISBN: 3642345387.

[2] Peter Kurzweil and Otto K Dietlmeier. *Elektrochemische Speicher. Superkondensatoren, Batterien, Elektrolyse-Wasserstoff, Rechtliche Rahmenbedingungen*. Springer Vieweg, Heidelberg, 2018. ISBN: 3658218282.

[3] Airbus. E-Fan X - A giant leap towards zero-emission flight. `https://www.airbus.com/innovation/zero-emission/electric-flight/e-fan-x.html#concept`, Accessed on 16/07/2021.

[4] Marek Darecki et. al. Flightpath2050 - Europe's Vision for Aviation. Technical report, EUROPEAN COMMISSION, Directorate-General for Research and Innovation, Directorate-General for Mobility and Transport, Luxembourg: Publications Office of the European Union, 2011. DOI: 10.2777/50266.

[5] European Union. 2050 long-term strategy. `https://ec.europa.eu/clima/policies/strategies/2050_en`, Accessed on 16/07/2021.

[6] MAHEPA project. Modular Approach to Hybrid Electric Propulsion Architecture - The Project. `https://mahepa.eu/the-project/`, Accessed on 16/07/2021.

[7] Sigfried Saenger-Zetina and Markus Wagner. *Hybride Antriebsstrukturen*, chapter 2, pages 7–74. Springer-Vieweg, Wiesbaden. 2012.

[8] Benjamin J. Brelje and Joaquim R.R.A. Martins. Electric, Hybrid, and Turboelectric Fixed-Wing Aircraft: A Review of Concepts, Models, and Design Approaches. *Progress in Aerospace Sciences*, 104(1), January 2019. DOI: 10.1016/j.paerosci.2018.06.004.

[9] Siemens AG. Erstes seriell-hybrides Elektroflugzeug der Welt fliegt in Le Bourget, June 2011. `https://assets.new.siemens.com/siemens/assets/api/uuid:2b14fea1-6d20-4a17-b5b4-461ebb25bdc0/AXX20110666d.pdf`, Accessed on 16/07/2021.

[10] University of Cambridge. Watts up - aeroplanes go hybrid-electric, December 2014. `https://www.cam.ac.uk/research/news/watts-up-aeroplanes-go-hybrid-electric`, Accessed on 16/07/2021.

[11] Paul Robertson. Hybrid Power in Light Aircraft: Design Considerations and Experiences of First Flight. `https://www.aerosociety.com/news/proceedings-general-aviation-conference-2016/`, Accessed on 16/07/2021.

[12] Honeywell Aerospace, Adam Kress. Honeywell's Newest Turbogenerator Will Power Hybrid-Electric Aircraft, Run on Biofuel. `https://aerospace.honeywell.com/us/en/learn/about-us/press-release/2021/03/honeywell-newest-turbogenerator-power-hybrid-electric-aircraft-biofuel`, March 2021. Accessed on 18/08/2021.

[13] DLR - Institut für Technische Thermodynamik. Hy4 - Emissionsfreie Passagierflüge. `https://www.dlr.de/tt/desktopdefault.aspx/tabid-10743/`, Accessed on 16/07/2021.

[14] HY2FLY. HY2FLY. `https://h2fly.de`, Accessed on 16/07/2021.

[15] Rory Jackson. Quaternium Hyrbix 2.1. *Unmanned Systems Technology*, 31(1), April 2020. https://www.ust-media.com/ust-magazine/UST031/, Accessed on 16/07/2021.

[16] Quaternium. Quaternium partners with Löweheiser EFI startup to achieve a new Flight Record of 10 hours 14 minutes with HYBRiX drone. https://www.quaternium.com/new-flight-record-of-10-hours-14-minutes-with-hybrix/, November 2020. Accessed on 16/07/2021.

[17] CONDOR Multicopter Drones. Altura Zenith ATX8. https://www.condor-drones.de/drohnen-showroom/detailanzeige?ai%5Bd_name%5D=Altura_Zenith_ATX8&ai%5Bd_pos%5D=19&ai%5Bcontroller%5D=Catalog&ai%5Baction%5D=detail, Accessed on 16/07/2021.

[18] Homeland Surveillance and Electronics - Unmanned Aerial Vehicles. Drones with long flight times. https://hse-uav.com/uav-industries-and-applications/drones-with-long-flight-times/, Accessed on 16/07/2021.

[19] Multirotor. Surveying Robot. https://www.multirotor.net/de/produkte/flugsysteme/surveying-robot, Accessed on 16/07/2021.

[20] Sebastian Bahamonde Noriega, Carlo De Servi, and Piero Colonna. Hybrid electric powertrain for long-haul trucks and buses: preliminary analysis of a new concept based on a combined cycle power plant. *Journal of the Global Power and Propulsion Society*, 4:63–79, 2020. DOI: 10.33737/jgpps/118979.

[21] Niklas Deschner. Integration of a kerosene start mechanism in a control software. Bachelor's thesis, Technical University of Munich, Garching, Germany, December 2019.

[22] Moritz Rumpf. Model adaptation and power control of a turboshaft gas turbine for use in a hybrid system. Master's thesis, Technical University of Munich, Garching, Germany, March 2021.

[23] Daniel Jäger. Modelling, Operational Strategy and Control of a Small Hybrid-Electric Flight Propulsion System. Master's thesis, Technical University of Munich, Garching, Germany, March 2019.

[24] Maximilian Klotz. Auslegung der Fanstufe eines elektrischen Antriebsystems für Modellanwendungen. Term paper, Technical University of Munich, Garching, Germany, May 2018.

[25] Patrick Bachmann. Development of a design tool for axial fan stages in Python. Term paper, Technical University of Munich, Garching, Germany, October 2020.

[26] Patrick Bachmann. Calculation of the Performance Map of an Axial Compressor Stage with a Streamline Curvature Method Considering Different Loss Correlations. Master's thesis, Technical University of Munich, Garching, Germany, July 2021.

[27] Wren Power Systems Ltd. Wren 44i TurboProp - Installation and operating manual. Barnsley, United Kingdom, September 2016.

[28] Vojtech Vavra. Development of Flow Field Measurement System for Small Electric Propulsion Unit. Term paper, Technical University of Munich, Garching, Germany, June 2021.

[29] Elisabetta Bongermino, Michele Tomaselli, Vito G. Monopoli, Gianluca Rizzello, Francesco Cupertino, and David Naso. Hybrid aeronautical propulsion: Control and energy management. *IFAC PapersOnLine*, 50(2):169–174, 2017. DOI: https://doi.org/10.1016/j.ifacol.2017.12.031.

[30] Markos Papageorgiou, Marion Leibold, and Martin Buss. *Optimierung. Statische, dynamische, stochastische Verfahren für die Anwendung*. Springer Vieweg, Berlin, Heidelberg, 4th edition, 2015.

[31] Valer Pop, Henk Jan Bergveld, Dmitry Danilov, Paul P. L. Regtien, and Peter H. L. Notten. *Battery Management Systems*. Springer Science + Business Media B.V., Netherlands, 2008. ISBN: 9781402069444.

[32] Mukund Patel. *Introduction to Electrical Power and Power Electronics*. CRC Press, Boca Raton, London, New York, 2012. ISBN: 9781466556614.