Propulsion System Optimization for a Turboelectric Tiltwing Urban Air Mobility Aircraft

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ABSTRACT

An emerging potential market within the aviation industry is short, frequent air taxi flights within the urban airspace. These air taxis (also called urban air mobility or UAM vehicles) are envisioned to be vertical take-off and landing designs which are capable of carrying 1 to 15 passengers in an intra-urban environment with less than 50 nautical miles of range. Numerous vehicle conceptual designs have been proposed by various industry and government organizations to fulfill these potential missions. These concepts are enabled by recent advancements in a number of areas including propulsion and power systems. While new technologies are making these vehicles possible, this new UAM design space is large, unexplored, and multidisciplinary in nature. New challenges exist in identifying and creating optimized designs for these unique vehicles with new propulsion technologies. This work presents the development of a suite of propulsion system analysis tools, which when coupled together, can improve the multidisciplinary conceptual design and optimization of UAM vehicle propulsion systems. These analysis tools are then applied to the design optimization of a turboelectric propulsion system for a notional UAM tiltwing concept. The optimization demonstration for this vehicle shows how a tightly-coupled multidisciplinary design can be developed which considers both physical design characteristics and operating schedules. Furthermore, the results explore trade-offs in the thermal management system design and how those trade-offs impact the overall vehicle.

NOMENCLATURE

BEMT	Blade element momentum theory
D	Drag
FOM	Figure of merit
h	Altitude
L	Lift
m	Mass
N	Shaft speed
ODE	Ordinary differential equation
P	Power
Q	Heat
$\mathcal{R}$	Residual equation
T	Temperature, thrust
TMS	Thermal management system
UAM	Urban air mobility
V	Velocity
$\bar{X}$	Design vector
XDSM	eXtended Design Structure Matrix
$\bar{Y}$	Output vector
α	Angle of attack

Subscripts, Superscripts and Symbols

$()_\infty$	Freestream
$()^*$	Iteration input
$\dot{()}$	Rate of change

1.0 INTRODUCTION

In the first century of human flight, aviation advanced from short demonstration flights by the Wright brothers to modern commercial flights that cover 8000 nautical miles in 18 hours. While this expansion in range and speed has facilitated human travel around the globe, it is now the shorter, local travel that is gaining renewed attention for aviation development in the second century of flight. While local travel within metropolitan areas has historically been the realm of automobiles and public transportation, the increased population density in urban areas has resulted in increased congestion on roadways.(1) As a result, there is now a growing interest in developing a fleet of air taxis capable of carrying 1 to 15 passengers less than 50 nautical miles to enable a new market: Urban Air Mobility (UAM).(2) Historically, a number of urban centers have used helicopters for this role, but large scale adoption has been limited by "accidents, noise and air pollution, and cost."(3) However, new aerospace technologies are being developed that could lessen these impediments, potentially making UAM a reality in the near future.

NASA's Aeronautics Research Mission Directorate is focused on conducting research to overcome the technical challenges needed to make UAM vehicles possible. These challenges involve reducing energy or fuel usage, emissions, and noise while improving safety. The

Figure 1. NASA Urban Air Mobility Concept Vehicles.

UAM design problem is large and multidisciplinary in nature because these design requirements and their effects must be considered simultaneously. To aid in developing and evaluating technologies for UAM concepts, NASA's Revolutionary Vertical Lift Technology Project has developed four conceptual aircraft designs as shown in Figure 1 which differ significantly in their design, size, payload, range, propulsion system, and operation.(4,5) Although these configurations are not expected to ultimately be manufactured, they help guide NASA, industry and academic research on the technologies needed to make UAM vehicles a reality.(4)

As part of the initial studies creating these vehicles, a technology deemed critical for each concept was an electrified propulsion system. This technology can be implemented in several ways as demonstrated by the concept vehicles in Figure 1. For example, the quadrotor on the left would have an all-electric propulsion system while the side-by-side rotor concept (2nd from right) is envisioned to have a hybrid propulsion system with some power coming from batteries and the rest coming from fuel via a turboshaft engine. The Lift+Cruise concept (right) and tiltwing design (2nd from left) are likely to use turboelectric propulsion systems where a turboshaft engine is used to produce electric power which is transmitted to electric motors for each rotor. In each of these concepts, the electrified propulsion system enables novel aircraft configurations that have the potential to reduce energy consumptions and emissions while also generating lower noise levels. It is the turboelectric propulsion system for the tiltwing concept (2nd from left in Figure 1) which will be examined in this paper.

The electrified propulsion systems under consideration for these concept vehicles are unconventional and will require extensive research to achieve a technology readiness level sufficient for mass implementation. The development of these systems is further complicated by the need to consider several different disciplinary and component analyses in the design process. These disciplines include the propeller aerodynamics, electrical system, and thermal management system (TMS), as well as the gas turbine for hybrid and turboelectric configurations. While it is necessary to include these individual disciplinary analyses in the development of UAM vehicles, it is also important to recognize the high degree of coupling between these systems. For example, a thrust demand increase to the propellers increases the power which must be passed through the electrical system. The increased power will lead to more heat loss which must be dissipated by the TMS system. Dissipating this heat will potentially require a larger, more powerful TMS system. The increased mass and power requirements of the TMS may then necessitate the use of a more powerful gas turbine which in turn increases the propulsion system and vehicle weight. The weight increase will drive a further increase in thrust demand by the propeller to achieve the same trajectory creating a feedback loop. Alternatively, instead of redesigning the thermal management system, previous research has shown that altering the operation and trajectory flown by electric aircraft might serve as an effective strategy for managing thermal constraints.(6)

The initial designs developed for the conceptual UAM vehicles used relatively simple models with significant assumptions for the various disciplines in the propulsion system. While these models enabled a rapid exploration of the UAM design space, it was noted that improving the modeling and assumptions for the propulsion system, vehicle weights, aerodynamics and acoustics is required for further refinement of these concepts.(4) Furthermore, the conceptual design process did not capture the tight coupling between the disciplines and did not explore altering the trajectory in conjunction with changing the vehicle designs. The authors of this study also noted that the traditional design process needs to be modified to perform an integrated multidisciplinary optimization to further improve the overall design.

Given these identified needs, this work first summarizes the development of several propulsion discipline analysis tools which can be coupled together to improve the conceptual design of electrified propulsion systems, with a focus on those for UAM vehicle concepts. These tools, described in Section 2, provide thermodynamic cycle, propeller performance, electrical system, and thermal management system modeling capabilities. During development of these tools emphasis was placed on ensuring they would work well in a tightly integrated multidisciplinary optimization for UAM aircraft design. Therefore, significant effort went into building highly stable numerical solver schemes and providing analytic derivatives for all analyses. Therefore, the developed tools implement advanced methods, such as analytic derivative calculations, to better support the application of gradient-based optimization methods within this environment. While the development of the individual propulsion system modeling tools is valuable, they are more powerful when combined into a multidisciplinary environment where tight disciplinary coupling can be enforced and optimizations can be performed. The development of this environment builds off of previous work(7) and is described in Section 3. Gradient-based optimization methods are of particular value in this multidisciplinary environment as they provide a viable approach for efficiently exploring the large, tightly coupled design spaces which characterize novel UAM concept vehicles. Furthermore, unique to this approach is the coupling of the propulsion system design optimization with optimization of the aircraft trajectory. Following the description of the tools and the multidisciplinary optimization environment, Section 4 presents the application of this capability to the design of the propulsion system, in conjunction with the trajectory, for the turboelectric tiltwing concept shown in Figure 1. Finally, following this optimization demonstration, conclusions and future work are discussed in Section 5.

2.0 PROPULSION SYSTEM DISCIPLINARY ANALYSIS TOOLS AND MODELS

Developing optimized propulsion system designs for unconventional UAM concepts requires a set of disciplinary analysis tools for each of the propulsion subsystems. Where possible, existing modeling tools can be used provided that they have several key characteristics. First and foremost, the disciplinary tools must be capable of modeling the physical system at a fidelity appropriate for the analysis and design being completed. Beyond this basic requirement, the tools must also have been written in a fashion that makes them easy to integrate into a larger, multidisciplinary analysis environment. This integration is important for the electrified propulsion systems being considered for UAM vehicles since tight coupling exists between many of the systems. Lastly, the disciplinary design tools must analytically compute the derivatives needed for gradient-based optimization. While finite-difference approaches are often used to compute these derivatives, previous research has found these approaches to be computationally inefficient and result in inaccurate derivatives.(8,9) Given these requirements for the disciplinary tools, particularly those related to the analytic derivatives, existing codes were deemed insufficient for this research effort and a new set of propulsion tools were developed to provide these capabilities.

Four different subsystems were identified for the electrified propulsion systems being considered for UAM concepts. These subsystems include the propeller/rotor, electrical system, thermal management system, and gas turbine (for hybrid and turboelectric systems). For each of these subsystems, a new modeling tool was developed which provided the desired derivative features. Development of each of these tools was facilitated by building them on top of NASA's OpenMDAO framework.(10) Building the tools on top of this framework takes advantage of its unique capabilities for calculating analytic derivatives across complex models. Furthermore, this approach facilitates coupling the disciplinary tools together to form the multidisciplinary design environment as OpenMDAO is applied in this capacity as well.

The following subsections provide a short description of the disciplinary tools developed in support of creating the multidisciplinary propulsion system design and optimization environment. These disciplines include propeller, electrical, thermal, and cycle analysis. In each discipline, a brief description of the specific model developed for the tiltwing turboelectric concept examined in this paper is also presented. Following these brief summaries, Section 3 will describe how the disciplinary tools were combined to form a multidisciplinary optimization environment.

2.1 Propeller Analysis

The thrust required for both forward and vertical flight of the tiltwing concept comes from four propellers/rotors distributed across the span of the wing. Developing optimized designs for these propellers is therefore important to achieving the desired performance for the overall vehicle. To design and analyze these propellers, a number of propeller performance methods and tools are available ranging from high-fidelity computational fluid dynamics approaches to lower-fidelity momentum based methods.(11)

For this initial study of the propulsion system design, the propeller aerodynamic performance was modeled using blade element momentum theory (BEMT). The BEMT method was selected for this study as it provides a relatively simple physical representation which can quickly compute the output thrust and required shaft power. The specific BEMT implementation used in this work is called OpenBEMT and was selected for several reasons. First, OpenBEMT applies a modified BEMT approach which was developed to address numerical convergence issues commonly present in BEMT codes. The modified formulation guarantees convergence of the BEMT equations, which is of great importance when applying the code in optimization use cases.(12) Second, OpenBEMT provides analytic derivatives across the analysis to support the use of gradient-based optimization. Finally, OpenBEMT has been previously used to predict performance as part of design optimizations for two other aircraft: NASA's X-57 electric distributed propulsion concept(13) and a small single person RVLT UAM quad-rotor concept.(14)

While BEMT methods can provide valuable performance data, it is recognized that BEMT codes (including OpenBEMT) often make a number of assumptions which limit their accuracy for complex applications such as the tiltwing concept. Most significantly, BEMT does not compute the induced flow into the rotor and does not contain models of the wake which are important in vertical flight. In addition, in this work the propeller model examined an isolated rotor and therefore the analysis did not capture interactions between the individual rotors or between the wing and the rotors. Given this isolated model, the propeller analysis also assumed a uniform inflow which was specified to be approximately 6.5 feet/second (2 meters/second) for the hover design condition and equal to the vehicle forward flight velocity during cruise. Additional assumptions made for this concept were that the propeller hub diameter was fixed at about 12 inches (30 centimeters), with the tip diameter set such that the four propeller diameters covered the entire wingspan with some small overlap. With the hub and tip diameters fixed, the propeller physical design variables considered for the BEMT model in this study were the chord and twist distributions along the blade as listed in Table 1. The power required to spin the propellers must be generated by the motors in the electrical system which is discussed in the next subsection.

Table 1
Propeller Physical Design Variables.

Design Variable	Lower Limit	Upper Limit
Blade chord distribution (in)	2.00	9.85
Blade twist distribution (deg)	10.0	70.0

2.2 Electrical Analysis

The four propellers on the proposed tiltwing UAM concept vehicle are powered by a set of four electric motors. These motors (with associated inverters) are connected to a single generator (with an associated rectifier) by an interconnected grid of DC power cables as shown in Figure 2. This grid structure is proposed as a means of providing redundancy in the system to protect against faults. In addition to these components, the electrical system for the tiltwing concept vehicle includes a battery used only for emergency backup power as well as loads for running auxiliary systems and the thermal management system.

The electrical components of this system are modeled using a power system analysis library called Zappy.(15) This library is a set of analysis components built on top of the OpenMDAO framework, which include analytic derivatives as part of the implemention. The electrical system calculations within this tool for the motors and generator apply performance maps to determine the efficiency based on shaft speed and torque. Furthermore, the calculations within the power transmission grid are based on methods used in hybrid AC-DC load flow analysis(16) with input line impedances. The electrical system did not have any physical design variables in this study, but the shaft speed of the motors and generator were allowed to vary throughout the flight. In addition to these calculations, all of the components in the electrical system model compute the heat generated by the component inefficiencies. This heat must be dissipated by the thermal management system discussed in the next subsection.

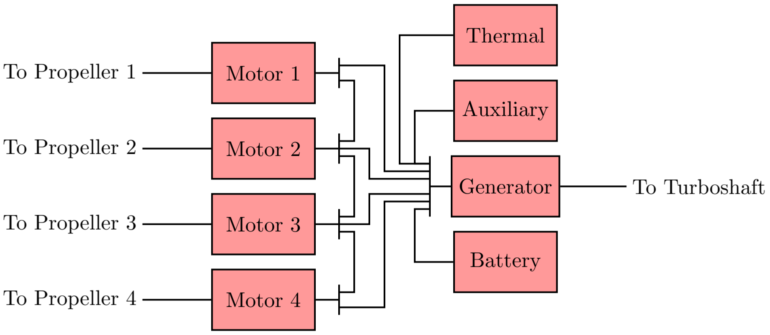

Figure 2. Electrical Power System Schematic.

2.3 Thermal Analysis

Each of the components of the electrical system described in the previous section generates waste heat due to inefficiencies in the system. If not managed effectively, the waste head could impact the performance by damaging the electronics. Therefore, a thermal management system (TMS) is required to ensure the various electrical components stay below specified temperature limits.

For this initial design study, a liquid based TMS is considered. The architecture for the tilt-wing TMS assumed in this study is shown in Figure 3. This system was designed as a single coolant loop that removes heat from the inverters and rectifiers first, followed by the motors and finally the generator. Following the generator, the liquid cooling flow (assumed to be water/glycol under pressure) is pumped through the heat exchanger which transfers the heat to air moving through a duct. The air required for this system is drawn through the duct by a puller fan, which draws power from the electrical system along with the pump.

In the simulation, two transient quantities are considered: the generator temperature and the coolant tank temperature. Response times for the other loads were found to be too fast to be considered for this study, as they would reach steady state in less than the 2 minutes so these were represented by a quasi-steady state model. Heat loads enter the coolant stream via a cold plate with constant effectiveness and coolant pressure loss. Design variables for a cooling loop consist of cooling fluid flow (both coolant and air flow, in the case of a heat exchanger), heat exchanger size, and cooling reservoir tank size which result in a weight and power usage that is used for optimization purposes. Coolant flows are generated using fluid pumps, while air flows are based on a heat exchanger exhaust area and the assumption that puller fans run to maintain a specified exhaust nozzle pressure ratio.

With this assumed TMS architecture, the cooling temperature requirements were based on conservative assumptions for each components max temperature, with each constraint defined relative to the coolant fluid temperature at the exit of that component. The maximum temperature limit of the power electronics cold side was assumed to be 589 R (327 K) and the power electronics hot side was assumed as 619 R (344 K). The cooling fluid temperature was limited is 684 R (380 K). Furthermore, it was assumed that the cooling fluid limits would ensure reasonable cooling temperatures for the motors and generator. For the heat exchanger, the effectiveness and pressure loss were calculated based on an assumed architecture of alter-

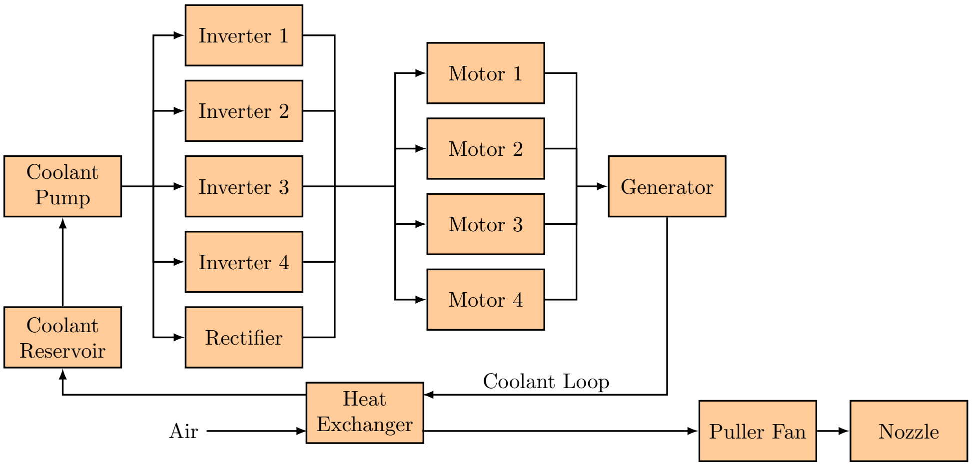

Figure 3. Thermal Management System Schematic.

Table 2
Thermal Management System Physical Design Variables.

Design Variable	Lower Limit	Upper Limit
Coolant flow rate (lbm/s)	0.22	44.1
Coolant reservoir mass (lbm)	55.1	440.1
Heat exchanger width (ft)	0.33	6.56
Heat exchanger length, coolant side (ft)	0.33	6.56
Heat exchanger length, air side (ft)	0.33	6.56
Nozzle throat area (ft^2)	0.54	2.69
Design TMS power (hp)	1.34	460.4

nating plate-fin or strip-fin surfaces with unmixed flows moving perpendicular to each other. This is consistent with a cross-flow, single-pass heat exchanger. Overall, the physical design variables associated with the TMS system considered in this study are listed in Table 2 along with their associated lower and upper limits. The power required by the TMS, and all other subsystems is supplied by the turboshaft engine detailed in the next subsection.

2.4 Thermodynamic Cycle Analysis

The power required to drive the entire propulsion for the tiltwing concept vehicle is provided by a gas turbine engine. The turboshaft engine architecture assumed for this system is shown in Figure 4 and is described in more detail in previous work by Chapman.(17) In this architecture, the airflow passes through inlet, compressor, burner, turbine, power turbine and nozzle. The compressor and turbine are connected to a shaft, with the power turbine connected to separate shaft to drive the electrical system generator.

Modeling the thermodynamic cycle for this engine architecture was completed in this study using the pyCycle analysis code.(8) This code was selected as it again is built on top of the OpenMDAO framework and provides analytic derivatives that are beneficial for gradient-based optimization. Supplementing the thermodynamic cycle calculations, a simple weight correlation was developed from historical data for turboshaft engines based on the overall airflow through the engine. For the turboshaft model, the physical design variables available for modification were the design overall pressure ratio and design combustor exit temperature with the ranges specified in Table 3.

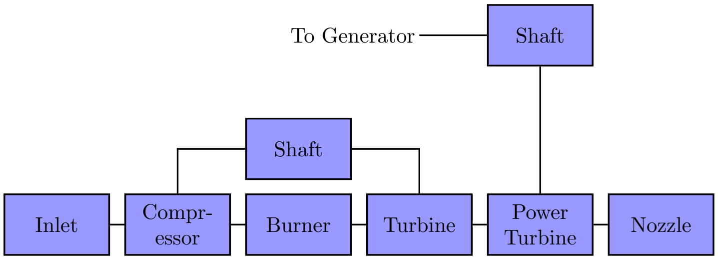

Figure 4. Thermodynamic Cycle Schematic.

Table 3
Gas Turbine Physical Design Variables.

Design Variable	Lower Limit	Upper Limit
Design overall pressure ratio	10.0	20.0
Design combustor exit temperature (R)	2800	3200

3.0 MULTIDISCIPLINARY DESIGN ENVIRONMENT

The disciplinary tools and models described in the previous section were created with the intent for them to be combined to complete a multidisciplinary design optimization of the propulsion system for the turboelectric tiltwing concept. This section describes the approach implemented in this research to create a multidisciplinary design environment. The environment described here builds on previous work in which disciplinary analysis tools for some propulsion elements were combined with analysis tools for the wing and mission performance.(7)

However, prior to describing this multidisciplinary environment, it is necessary to briefly describe two additional analysis tools used in this development. First, OpenMDAO was used as the overall framework code for coupling the disciplinary analyses together. OpenMDAO has been mentioned throughout this paper in regards to its use as the base layer for development of disciplinary analysis tools. In this application, analysis libraries were built on top of the base OpenMDAO objects enabling use of their analytic derivative calculation features. Furthermore, using OpenMDAO in this application allowed for the use of a variety of numerical solvers which were needed to converge the disciplinary analyses. Beyond this application, OpenMDAO was also used to integrate the various disciplinary analyses and compute the necessary total derivatives needed for optimization. The code also includes a selection of optimization algorithms which can be easily applied to the multidisciplinary model. For this research, the SNOPT optimization algorithm(18) was applied.

In addition to OpenMDAO, the Dymos modeling library(19) was applied in this research. Dymos is a general transient modeling library that enables dynamic mission trajectory and performance modeling in an optimal control context. Dymos is also built upon OpenMDAO. Using Dymos in this research, therefore, enables a full mission trajectory analysis to be included in the optimization, rather than relying on a fixed, pre-determined reference trajectory. For this work, the Radau pseudospectral scheme was selected for its relatively low computational cost and good numerical stability.

The overall multidisciplinary UAM design environment developed in this research effort is summarized by the eXtended Design Structure Matrix (XDSM) diagram shown in Figure 5. In this diagram, major elements of the analysis are shown along the diagonal in the colored boxes in their execution order. The parallelograms and lines above the diagonal show inputs (in white) and data connections (in gray) which are fed forward from the box on the left to the box below. The parallelograms below the diagonal represent connections which feedback data to previous analysis elements. As shown in this figure, the multidisciplinary design environment is controlled by a gradient-based optimizer in the green oval. This optimizer sets design variable values which are passed into the two major analysis blocks, the first of which executes disciplinary design models and the second executes mission performance models. These two major analysis elements in the environment are shown as a stack of boxes as there are numerous steps present in each of the elements.

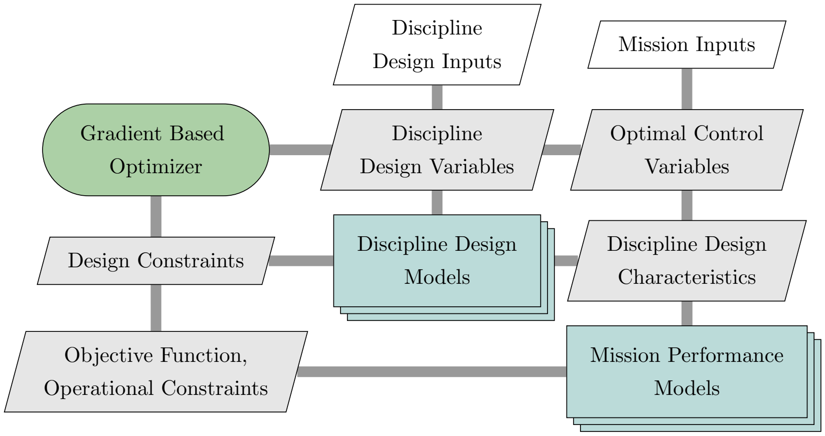

Figure 5. Multidisciplinary Analysis Environment.

The disciplinary design element of the environment focuses on executing the design mode of the various disciplinary tools to size their associated subsystems. In this major element, each of the four propulsion disciplinary codes described in Section 2 are executed along with several other calculations as shown by the XDSM in Figure 6. In this process, a nonlinear Newton solver (represented by the yellow oval) is used to drive the execution of the various calculation and ensure overall vehicle and propulsion system convergence. To do this, the solver guesses the total takeoff mass of the aircraft (m^*_{total}) as well as the power required ($P^*_{thermal}$) to run the TMS. With these values, the thrust required for a hover condition is first computed along with the atmospheric properties at that flight condition (shown by the two red boxes). Following these calculations, the propeller, electrical, thermal and turboshaft disciplinary models are executed in sequence with power (P) and heat loads (Q) being passed between disciplines as necessary. Each of the disciplinary design models also compute a subsystem mass which is passed to an aircraft mass block which combines these propulsion system masses with other vehicle systems to generate an overall vehicle mass. This computed total mass as well as required thermal management system power are used to form two residual equations ($\mathcal{R}$) which are iteratively converged by the solver. Upon convergence of the disciplinary design solver, the sized subsystems output their design variables ($\bar{Y}$'s).

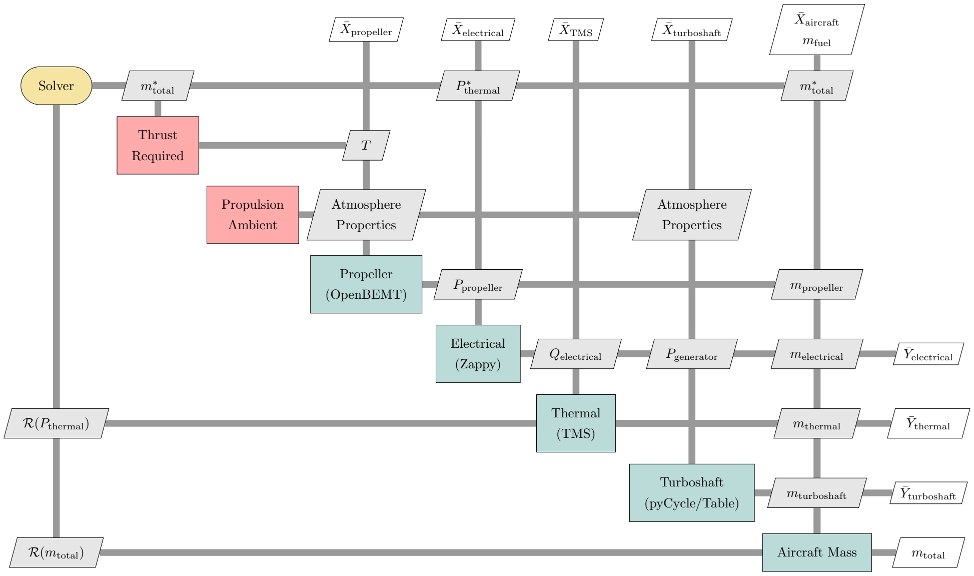

Figure 6. Discipline Design Modeling.

The disciplinary design characteristics determined in the previous calculations are used as inputs to the second major element in the multidisciplinary environment, the mission performance calculations. The mission performance element is more complex than the disciplinary design element due to the need to model four separate phases of flight (takeoff, cruise, landing, hover) with varying physics and different time discretizations. The trajectory and phases included in this element for the tiltwing vehicle are shown in Figure 7. The baseline tiltwing trajectory assumed in this study consists of three primary flight phases: takeoff, cruise, and landing. In addition, there are two branch phases which represent a possible 2 minute hover following takeoff or cruise. While these two hover phases are not part of the primary mission, their inclusion in this analysis is important because the highest temperatures occur during these optional mission segments. In addition to these branch phases, Figure 7 depicts a second important element of the mission performance analysis element: the use of tandem phases. The solid lines in Figure 7 indicate vertical and forward flight calculation phases which capture the performance of the propeller, electrical, turboshaft and overall aircraft at a relatively coarse discretization. Meanwhile, the dashed lines indicate thermal calculation phases which calculate the electric component temperatures and cooling system requirements. The relatively slow dynamics of the aircraft motion allow for a fairly coarse time discretization, which is advantageous because the analyses for the aircraft phases are fairly expensive. However, the thermal transients occur much faster and require a finer time discretization. Since the thermal analyses are also much less expensive, the finer time discretization is not a computational hindrance. The Dymos library allows for two separate phases to be integrated over the same time period using different time discretizations, which are referred to as tandem phases. Dymos automatically interpolates the relevant time-varying information from one phase's time-discretization to the other, using the same underlying polynomial basis as the Radau pseudospectal scheme. The decomposition of the model into these tandem phases is shown in Figure 8.

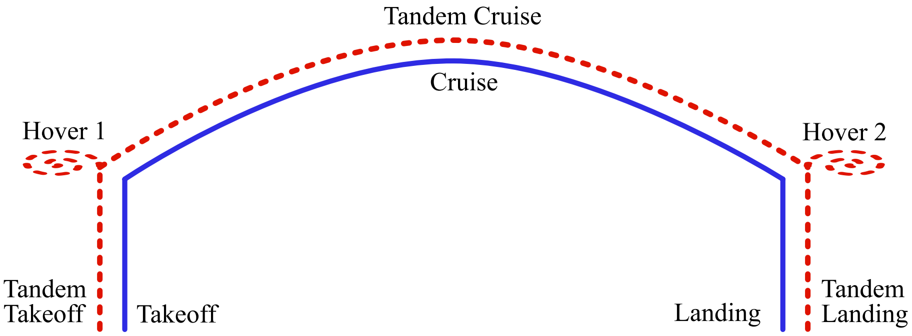

Figure 7. Mission Trajectory and Phases.

As indicated in Figures 7 and 8, there are three unique ordinary differential equations (ODEs) which were used to capture the physics in the mission analysis phases. In each analysis phase (e.g. vertical takeoff or forward flight), Dymos is responsible for integrating one of the three ODEs over time. The first ODE represents vertical flight (for takeoff and landing) and includes the calculations shown in Figure 9. In this ODE, the ambient air properties, aircraft mass, and required thrust are first computed given the flight conditions at each time step. This information is then passed to the propeller analysis, which in this case is a reduced-order model based on the rotor Figure of Merit (FOM). This Figure of Merit was computed from an OpenBEMT analysis of the rotor in a reference vertical climb condition during the disciplinary design element. We acknowledge that BEMT has limited accuracy in this flight regime, but it provided a link between the rotor geometry and performance for vertical flight which prevented the optimizer from designing a heavily cruise biased rotor. Future work will aim to replace BEMT with a higher-order analysis. Following the propeller analysis, the electrical system and turboshaft models are then executed at each time step. For the turboshaft model, several options were available including the full pyCycle model as well as using a set of tabulated data for a baseline design. The full pyCycle model was used when possible, but the tabulated data was used in some studies to reduce the computational expense of the analyses.

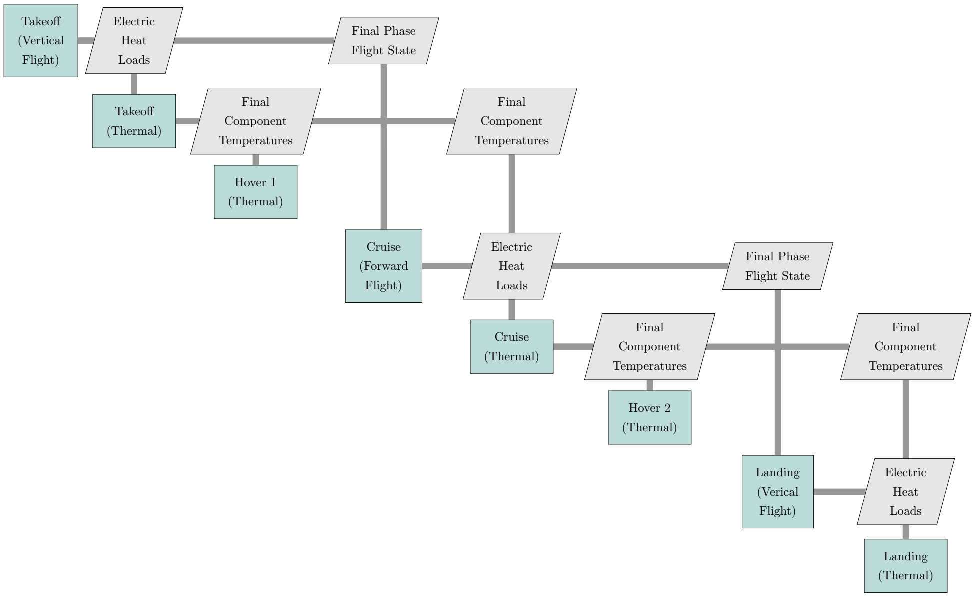

Figure 8. Mission Performance Environment.

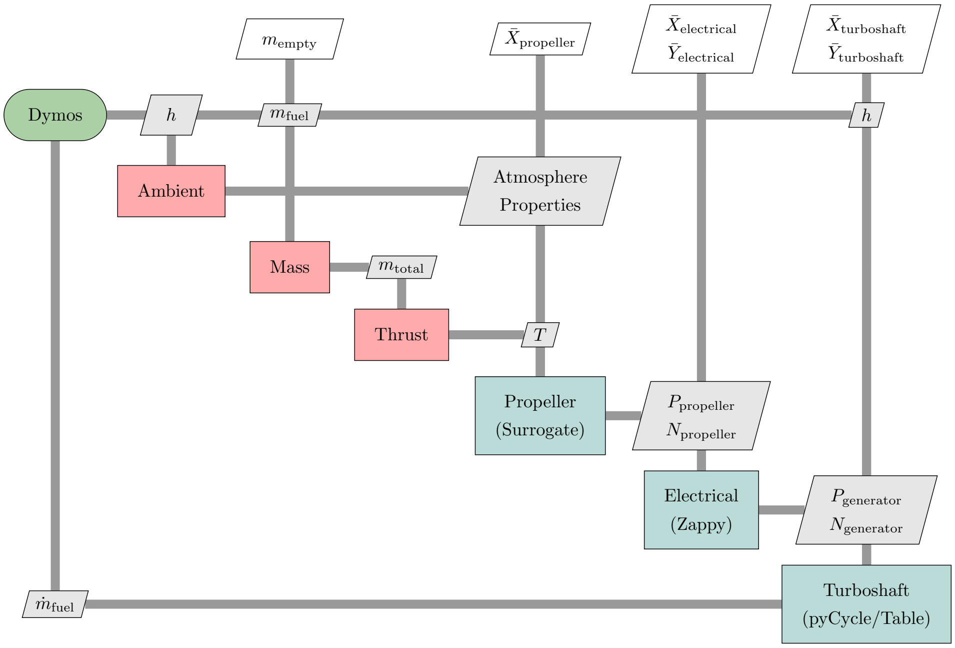

Figure 9. Vertical Flight Performance Modeling.

The forward flight ODE represents the operation of the tiltwing as an airplane rather than a helicopter. This ODE contains the same propulsion systems calculations as the vertical flight ODE. However, it also includes additional calculations for the wing drag polar as well as the flight dynamics of the vehicle as shown in Figure 10. The Dymos phase that uses this ODE includes time varying controls for altitude, forward flight speed, and thrust which are chosen by the optimizer.

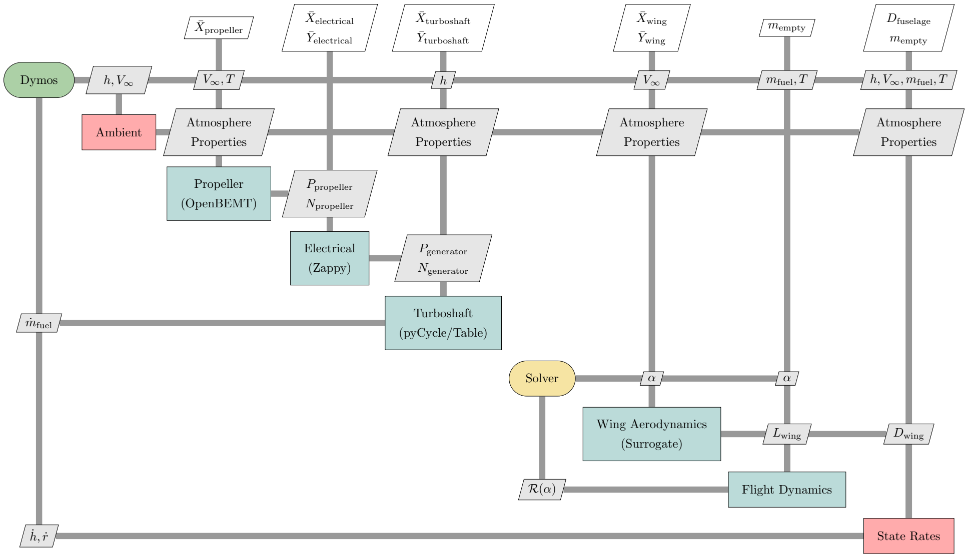

Figure 10. Forward Flight Performance Modeling.

The third and final ODE required for analyzing the tiltwing vehicle and propulsion system captures temperature changes in key electrical components as shown in Figure 11. Here, Dymos tracks the temperature of the electrical components, specifically the generator, and computes the rate of change in this temperature over time. While this phase is relatively simple, the separation of the thermal management system model in a tandem phase enabled different time discretizations to be applied in different phases of the analysis.

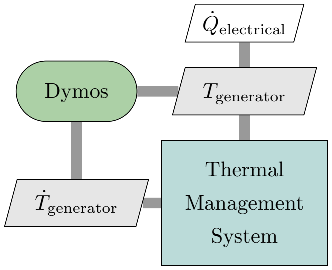

Figure 11. Thermal Management System Modeling.

In summary, a complex multidisciplinary design, analysis and optimization environment was created in this research to support the development of tiltwing UAM propulsion system concepts. While the majority of the calculations in this environment focus on the four propulsion subsystems (propeller, electrical, thermal management and turboshaft), it is recognized that the analysis and design of these systems depend on the transient operation of the vehicle. Therefore, simple representations of the aircraft aerodynamics and other vehicle systems are included. The multidisciplinary environment also includes an optimal control approach through Dymos which is capable of analyzing transient systems with different discretization requirements for various subsystems. The application of this complex multidisciplinary environment to the tiltwing UAM concept will be presented in the next two sections.

4.0 TURBOELECTRIC TILTWING DESIGN PROBLEM AND RESULTS

The multidisciplinary optimization environment described in the previous section was developed to enable the propulsion system to be designed while considering the tight coupling between the various subsystems as well as the operation of the aircraft. To demonstrate the capabilities of this design environment, it was applied in the study of the propulsion system for the turboelectric tiltwing UAM vehicle described in the Introduction. This vehicle was nominally designed to carry 15 passengers (3000 lbm) on eight 50 nm flights before needing to be refueled. Given that this vehicle could operate in a wide number of metropolitan areas, a minimum capability for takeoff and landing at high altitudes (5000 ft) on hot days (ISA + 36 °R) was also required with the maximum allowable altitude at any point in the flight capped at 10,000 ft. As previously described, the tiltwing conceptual design included a battery backup capable of providing propulsive power for a 2 minute hover in the case of an emergency landing.

For the propulsion design studies considered in this research, several simplifying assumptions were made for designing and analyzing this concept. First, although the concept was initially designed for multiple short flights, this work considers a single 400 nm mission thereby covering the same total distance. This assumption simplifies the trajectory and the models required to complete the analysis. Furthermore, transition between vertical and forward flight was not explicitly modeled in this work because, despite the obvious complexity and importance of this flight condition, its short duration gives it minimal impact on the overall energy usage. While this approach does not capture all details of the proposed tiltwing concept mission, it provides a valuable evaluation and demonstration of the multidisciplinary propulsion environment which can be improved by removing these assumptions in future iterations of this research.

Several different optimizations and trade studies were completed using these assumptions with the models described in the previous sections to demonstrate the multidisciplinary propulsion system modeling environment and evaluate the impact on the tiltwing design. The primary optimization study included all of the disciplinary analysis and is formally defined in Table 4. The objective of the optimization, as stated in the top portion of the table, was to modify the disciplinary designs and operating characteristics of the vehicle to minimize the takeoff mass of the aircraft. The middle section of the table lists the disciplinary design variables considered for the tiltwing vehicle. This section is subdivided into five smaller sections to identify design variables associated with each disciplines under consideration: propeller, electrical, thermal, gas turbine, and trajectory. In this section, many of the design variables listed represent a vector of values that correspond to discretizations across time or space (e.g. the blade chord distribution is specified as several radial locations, the altitude is specified as each time step, etc.). The size column in the table specifies the length of the vector for each design variable. The last major section of table defines the constraints placed on the design characteristics and trajectory along with the disciplines to which they apply. Again in this section, there are numerous constraints collapsed under a single name with the size column specifying the length of the constraint vector. In total, 210 design variables and 715 constraints were considered in this primary optimization study, resulting in a large but highly constrained design space for exploration by the optimizer.

Table 4
Tiltwing Optimization Problem Formulation.

	Variable/Function	**Size**	**Discipline**
minimize	Initial takeoff mass		
with respect to	Blade chord	6	Propeller
	Blade twist	6	
	Generator speed	18	Electrical
	Motor speed	18	
	Coolant flow rate	1	Thermal
	Coolant reservoir mass	1	
	Heat exchange dimensions	3	
	Nozzle throat area	1	
	Design TMS power	1	
	Design overall pressure ratio	1	Gas Turbine
	Design combustor exit temperature	1	
	Altitude	38	Trajectory
	Range	26	
	Velocity	26	
	Fuel mass	38	
	Thrust (forward flight)	10	
	Acceleration (forward flight)	4	
	Blade pitch (forward flight)	6	
	Phase time boundaries	5	
subject to	Fuel burn residual	1	Aircraft mass
	TMS power constraint	1	Thermal
	Coolant temperature path constraint	114	Thermal
	Electronics temperature path constraint	114	Thermal
	Generator temperature path constraint	114	Thermal
	Pseudospectral constraints	371	Trajectory

The results from running this primary optimization study are shown in Table 5 and Figures 12 to 16. Table 5 provides the final design variables of the TMS and turboshaft model along with the initial design used to start the optimization. These results show that the optimizer changed the design substantially within the allowable design space in order to produce the best design. The optimal TMS design was found to lie near the lower end of the design range for each variable, with the reservoir mass, heat exchanger coolant side length, and nozzle throat area sitting on the lower bound. For the turboshaft, the optimizer found that increasing combustor exit temperature to its maximum allowable value while also moderately increasing the overall pressure ratio resulted in the best performance. For the propeller design, Figures 12 shows the optimal chord and twist distributions along the blade span.

Table 5
Optimized TMS and Turboshaft Design Variables.

Design Variable	Initial Value	Optimal Value
Coolant flow rate (lbm/s)	2.20	1.56
Coolant reservoir mass (lbm)	110.2	55.1
Heat exchanger width (ft)	3.28	3.77
Heat exchanger length, coolant side (ft)	3.28	0.33
Heat exchanger length, air side (ft)	3.28	0.97
Nozzle throat area (ft^2)	2.15	0.54
Design TMS power (hp)	201.2	50.1
Design overall pressure ratio	15.0	18.8
Design combustor exit temperature (R)	3000	3200

In addition to these physical design parameters, the analysis also identified the optimal trajectory and control schedule which would lead to the best performance. First, the optimal trajectory identified for the vehicle is shown in Figure 13. The optimized trajectory shows the aircraft completes a short vertical takeoff, then climbs quickly to a cruise altitude of 10,000 feet before descending and completing a vertical landing. While the flight profile follows that of a typical aircraft, there are some apparent fluctuations in the cruise altitude. These fluctuations are an artifact of the polynomial curves used in the Dymos optimal control analysis coupled with a relatively coarse discretization. In reality, the aircraft would want to maintain a level flight at the maximum altitude during this cruise segment. A more refined profile with a constant cruise altitude could be created by using a finer discretization along the trajectory, but would increase the computational cost of the model. The discretization selected and shown in this study was selected as it provided representative results at a reasonable computational expense.

Beyond examining the flight profile, the performance of the TMS over the flight provides valuable insights about the ideal operation of a turboelectric tiltwing aircraft. For example, Figure 14 shows the temperature of the coolant as it exits the inverters and rectifier before being used to cool the motors. Note that for the thermal phases evaluated, a finer time discretization was implemented in the tandem phase enabling a more refined transient analysis. In this figure, the coolant initially starts off at a high temperature representative of a hot day takeoff. This temperature decreases as the aircraft climbs in altitude and the heat exchanger dissipates heat to the air. At the end of takeoff, two possible trajectory branches were evaluated. The first is for an emergency hover and results in the coolant temperature increasing. In the cruise phase, the coolant temperature also increases initially as the aircraft has higher power requirements to climb in altitude. Following this initial climb however, the coolant temperature decreases to a nearly steady-state lower value as the aircraft cruises at altitude. The coolant temperatures again increase during the descent, second hover branch and landing phases as a result of both higher power levels and higher ambient air temperatures at lower

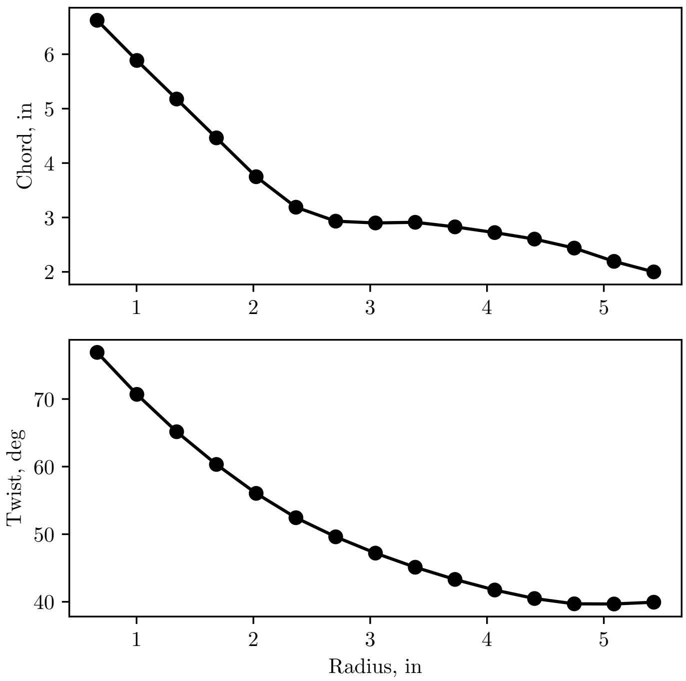

Figure 12. Optimal Rotor Design Characteristics.

altitudes. Overall, this figure shows that the coolant temperature varies throughout the flight, although by a relatively small amount.

Dissipating the heat generated by the electrical components using the TMS requires additional power to be produced by the gas turbine to power the coolant pump and puller fan. Figure 15 shows how the power required to drive these components varies over the course of the flight. The power required by these components is the highest during the vertical flight and hover phases as well as at the start and end of the cruise phase. The higher power levels are required at these flight conditions primarily as a result of the increased power required to drive the puller fan to maintain airflow through the heat exchanger. The aircraft level power requirements are also higher during these flight conditions as more power must be delivered to the propellers for vertical flight and hover.

The overall power required to be produced by the gas turbine and pass through the generator is shown in Figure 16. As indicated by the blue and red dots, the power required for takeoff and landing are the two highest power levels required during the flight, with the power during landing lower due to a lighter vehicle at the end of the flight. During the cruise phase, the power required to operate the aircraft is significantly reduced as the wing lift reduces the power required to maintain flight.

In addition to this primary optimization, an optimization design sweep was executed to

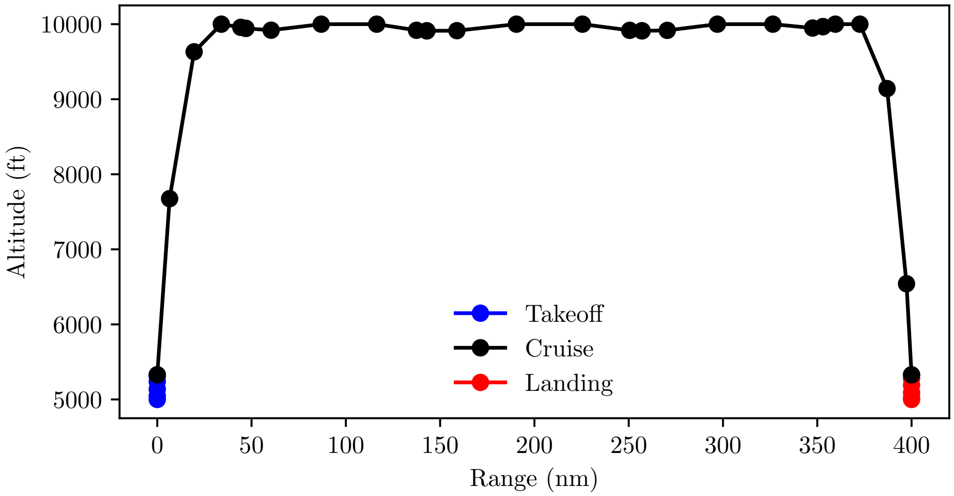

Figure 13. Optimal Mission Trajectory.

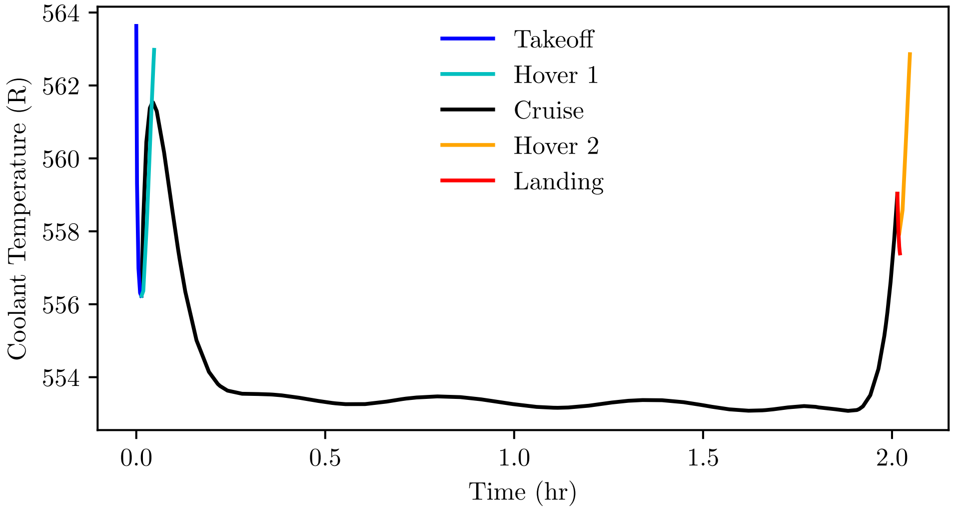

Figure 14. Optimal TMS Coolant Temperatures Exiting Power Electronics.

better understand the results produced by in the primary optimization study. This design sweep focused on examining how changes to a specific design input for the TMS altered the overall optimized design. In these cases, the length of the heat exchanger side where air entered the device was varied while the other dimensions of the heat exchanger and the coolant reservoir mass were held constant. Furthermore, the gas turbine cycle model was replaced by a scalable surrogate model of the baseline design to minimize the computational

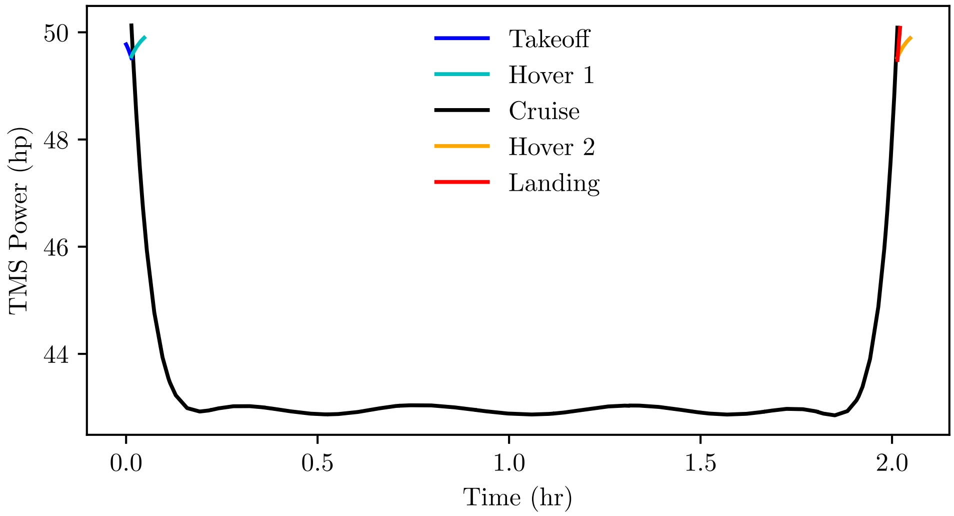

Figure 15. Optimal TMS Power Profile.

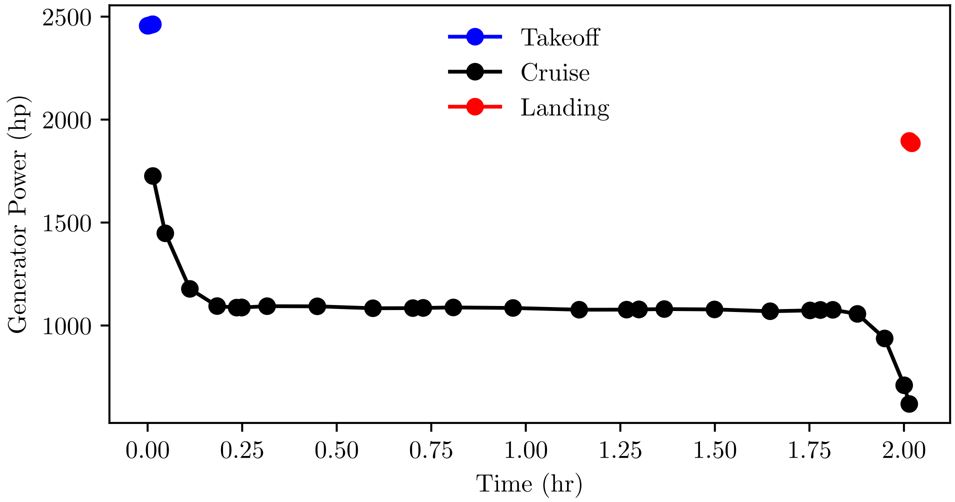

Figure 16. Optimal Generator Power Profile.

cost of this study. While most of the TMS and TMS design variables were held constant, the design of the propeller system, electrical system and trajectory were allowed to be optimized during each of the cases.

The results from this example TMS design sweep study are shown in Figure 17. The top graph in this figure depicts how the takeoff mass of the vehicle, which was the objective function for the optimization, changes as the heat exchanger length on the air side was varied.

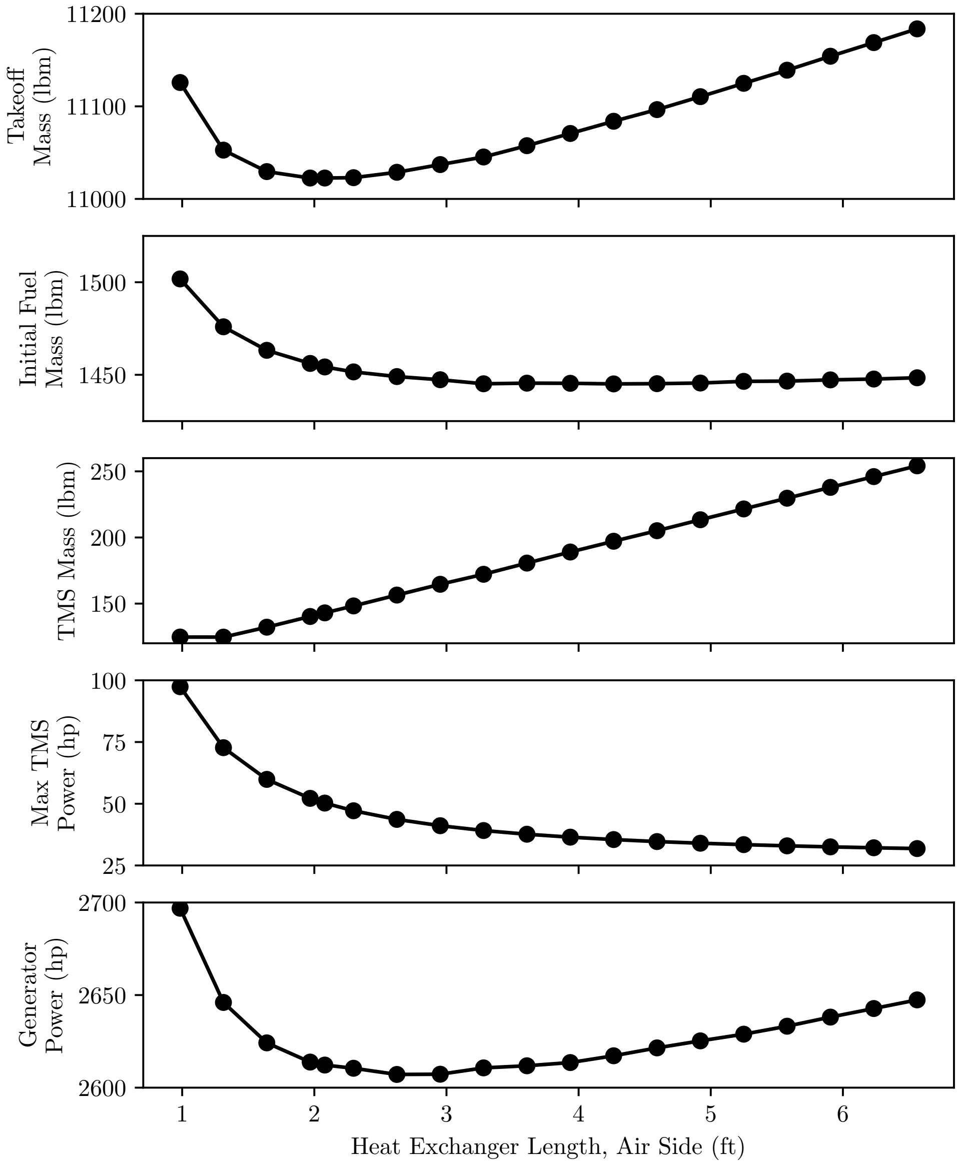

Figure 17. Heat Exchanger Design Sweep.

It is clear from this data that the model found the minimum takeoff mass to occur at a length of approximately 2.08 feet. While this length minimizes the takeoff mass of the overall aircraft, it is not the design that would result in the minimum fuel mass required for operation as shown in the second plot. To minimize fuel burn, a larger heat exchanger with a longer air side length would be desirable despite its increased weight. However, increasing the heat exchanger size results in a heavier TMS as shown in the third graph which causes the increase in takeoff mass. The reduction in fuel burn for a larger heat exchanger length primarily result from the decrease in power that would be required to drive the puller fan and coolant pump to sufficiently remove heat from the electric system components as shown in the fourth plot. The last graph in Figure 17 shows how the overall generator (and by extension gas turbine) power changed across this design sweep. The results show that the minimum power occurs closer to the baseline design heat exchanger length as it balances increased power needed to drive the TMS and the power required to lift a heavier aircraft.

Overall, the results from this design sweep study provide a better understanding of the design space and the trade-offs being performed as part of the optimization. Additionally, the results demonstrate the sensitivity of the final design to the objective function selected for the optimization. Minimizing the takeoff mass was initially selected, as this option typically produces a low empty mass design (which corresponds with lower vehicle unit cost) while also minimizing fuel consumption (which corresponds with lower operating cost). However, if the operating costs (represented by fuel mass) was deemed to be more critical, a different design with a larger heat exchanger might be preferable at the expense of a slightly heavier aircraft.

Finally, these results demonstrate the importance of developing the design of the various propulsion system components in a tightly-coupled design process. For example, if the heat exchanger was designed in isolation, the engineer might aim to reduce the TMS power required (or keep it below a specified level) based on specified electric heat loads. Designing to this type of power requirement seems practical for an isolated TMS design process. However, in designing subsystems in this way fails to capture the impact of other design characteristics such as the TMS on the overall system. As shown in this study, keeping the TMS power below 30 hp would have added approximately 100 lbm to the TMS weight causing an increase in the overall vehicle weight. Alternatively, if a the vehicle weight was constrained, this subsystem design would necessitate a reduction in the payload by that 100 lbm thereby effectively removing one passenger from the flight. These tradeoffs shown in this simple study highlight the value of designing the vehicle subsystems, particularly the TMS, in a tightly-coupled multidisciplinary environment such as that developed in this research.

5.0 CONCLUSION

The design of propulsion systems for emerging urban air mobility concepts presents a challenging design environment for propulsion system engineers. First, these systems are commonly considering the use of unconventional configurations that implement electrified propulsion in the form of all-electric, hybrid electric or turboelectric designs. The development of electrified propulsion system requires analysis tools for the various disciplines, such as the propeller/rotor, electrical system, thermal management system and gas turbine. Creating these analysis tools and their associated models, however, is not sufficient for designing these propulsion systems as the individual subsystem design and performance characteristics are highly coupled. Furthermore, many of the new disciplinary analyses required for electrified propulsion concept analysis cannot be designed at a single operating condition as their transient behavior, which depends on the mission flow, must be considered. Therefore, to capture the coupled effects between subsystems a multidisciplinary design and optimization approach is necessary.

This work presented the development of the tools and a multidisciplinary environment to enable design, analysis and optimization of these electrified propulsion concepts for UAM vehicles. First, a set of analysis tools were developed covering the four disciplinary analyses composing hybrid and turboelectric propulsion systems. While a number of existing analysis codes could be used in this application, the analysis tools created as part of this research are unique in their ability to provide analytic partial derivatives in support of the multidisciplinary propulsion and vehicle system optimization. Analytic derivatives are considered a key technology for this type of integrated analysis as they accurately compute gradient values with minimal computational expense. These tools were then used to create representative models of the subsystems that would be present on a turboelectric tiltwing concept vehicle.

With the propulsion disciplinary tools and models representative models created, a multidisciplinary design environment was constructed. This environment couples the various propulsion discipline models to each other and also integrates models to assess other elements of the aircraft including the wings, flight dynamic characteristics and trajectory analysis. The integration of these disciplinary models into a multidisciplinary design environment was completed using the OpenMDAO framework as it facilitates calculation of derivatives across complex models and provides an array of optimization algorithms.

Finally, this multidisciplinary propulsion system design environment was used to complete initial design studies for the tiltwing UAM concept. In the primary optimization study, a large design space consisting of 210 design variables and 715 constraints was evaluated. The optimization objective was to minimize the aircraft takeoff mass by modifying both the propulsion system design and the mission trajectory over which it would operate. The results of this optimization and supporting design sweeps found that the optimal solution represented a design that did not optimize the performance or weight of any given subsystem. For example, a thermal management system requiring lower power input could have been designed which would have decreased the mission fuel consumption, but resulted in an increased vehicle weight and larger overall power demand from the gas turbine engine. Trade-offs such as these show the importance of coupling the disciplinary analysis tools as part of the design process.

The work presented in this paper provides an initial demonstration of a multidisciplinary design optimization capability for electrified propulsion aircraft concepts. This initial work focused on applying relatively simple physical models for the various disciplines to complete the demonstration with the intention of improving the fidelity in future iterations. Future work will therefore partially focus on improving the propulsion subsystem model, particularly for the propeller as blade element momentum theory is limited in its ability to model hover conditions. Furthermore, the design of UAM vehicles for operation in densely populated metropolitan areas is likely to require other metrics to be considered as part of the design process. Of critical importance will be the acoustic characteristics associated with the vehicles during the entire flight. Therefore, future work will also aim to integrate addition disciplinary analyses such as acoustics to assess the vehicles against these constraints and objectives. These modeling improvements will also be applied to the analysis of other UAM concepts implementing hybrid or all-electric propulsion systems. Applying the environment to other concepts will help refine those designs while simultaneously allowing the research team to explore the flexibility and adaptability of the developed environment to a wide range of conceptual design studies.

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REFERENCES

1. Schrank, D., Eisele, B., Lomax, T., and Bak, J., 2015 Urban Mobility Scorecard, *Texas A & M Transportation Institute* and *INRIX*, Aug. 2015, Accessed: 8 July 2019, `https://static.tti.tamu.edu/tti.tamu.edu/documents/mobility-scorecard-2015.pdf`.
2. Moore, M.D., Personal Air Vehicles: A Rural/Regional and Intra-Urban On-Demand Transportation System, *AIAA International Air and Space Symposium and Exposition: The Next 100 Years*, July 2003, doi:10.2514/6.2003-2646, AIAA-2003-2646.
3. Wright, K., Urban Air Mobility Adds a New Dimension to Travel, *Mitre Corporation: Project Stories*, July 2018, Accessed: 8 July 2019, `https://www.mitre.org/publications/project-stories/urban-air-mobility-adds-a-new-dimension-to-travel`.
4. Johnson, W., Silva, C. and Solis, E., Concept Vehicles for VTOL Air Taxi Operations, *AHS International Technical Meeting on Aeromechanics Design for Transformative Vertical Flight*, 2018.
5. Silva, C., Johnson, W., Antcliff, K.R. and Patterson, M.D., VTOL Urban Air Mobility Concept Vehicles for Technology Development, *2018 AIAA Aviation Technology, Integration, and Operations Conference*, June 2018, AIAA 2018-3847, doi:10.2514/6.2018-3847.
6. Falck, R.D., Chin, J.C., Schnulo, S.L., Burt, J.M. and Gray, J.S., Trajectory Optimization of Electric Aircraft Subject to Subsystem Thermal Constraints, *18th AIAA/ISSMO Multidisciplinary Analysis and Optimization Conference*, June 2017, AIAA 2017-4002, doi:10.2514/6.2017-4002.
7. Hendricks, E.S., Falck, R.D., Gray, J.S., Aretskin-Hariton, E.D., Ingraham, D., Chapman, J.W., Schnulo, S.L., Chin, J.C., Jasa, J.P. and Bergeson, J.D., Multidisciplinary Optimization of a Turboelectric Tiltwing Urban Air Mobility Aircraft, *AIAA Aviation 2019 Forum*, June 2019, AIAA 2019-3551, doi:10.2514/6.2019-3551.
8. Hendricks, E.S. and Gray, J.S., pyCycle: A Tool for Efficient Optimization of Gas Turbine Engine Cycles, *Aerospace*, 2019, **6**, (8), doi:10.3390/aerospace6080087.
9. Hendricks, E.S., A Multi-Level Multi-Design Point Approach for Gas Turbine Cycle and Turbine Conceptual Design. PhD dissertation, Georgia Institute of Technology, School of Aerospace Engineering, 2017.
10. Gray, J.S., Hwang, J.T., Martins, J.R.R.A., Moore, K.T. and Naylor, B.A., OpenMDAO: An Open-Source Framework for Multidisciplinary Design, Analysis, and Optimization, *Structural and Multidisciplinary Optimization*, 2019, **59**, (4), pp 1075-1104, doi:10.1007/s00158-019-02211-z.

11. Zondervan, G.J.D. A Review of Propeller Modelling Techniques Based on Euler Methods, 1998, Delft University Press.
12. Ning, A.S., A Simple Solution Method for the Blade Element Momentum Equations with Guaranteed Convergence, *Wind Energy*, June 2013, **17**, (9), pp 1327-1345, doi:10.1002/we.1636.
13. Hwang, J.T. and Ning, A.S., Large-Scale Multidisciplinary Optimization of an Electric Aircraft for On-Demand Mobility, *2018 AIAA/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference*, Jan 2018, AIAA 2018-1384, doi:10.2514/6.2018-1384.
14. Ingraham, D., Gray, J.S. and Lopes, L.V., Gradient-Based Propeller Optimization with Acoustic Constraints, *AIAA Scitech 2019 Forum*, Jan 2019, AIAA 2019-1219, doi:10.2514/6.2019-1219.
15. Hendricks, E.S., Chapman, J.W. and Aretskin-Hariton, E.D., Load Flow Analysis with Analytic Derivatives for Electric Aircraft Design Optimization, *AIAA Scitech 2019 Forum*, Jan 2019, AIAA 2019-1220, doi:10.2514/6.2019-1220.
16. Ahmed, H.M., Eltantawy, A.B., and Salama, M., A Generalized Approach to the Load Flow Analysis of ACDC Hybrid Distribution Systems, *IEEE Transactions on Power Systems, 2017*, **33**, (2), pp 21172127.
17. Chapman, J.W., Multi-point Design and Optimization of a Turboshaft Engine for Tiltwing Turboelectric VTOL Air Taxi, *AIAA Scitech 2019 Forum*, Jan 2019, AIAA 2019-1948, doi:10.2514/6.2019-1948.
18. Gill, P.E., Murray, W. and Saunders, M. A., SNOPT: An SQP Algorithm for Large-Scale Constrained Optimization, *SIAM Journal on Optimization*, 2012, **12**, (4), pp 976-1006.
19. Falck, R.D. and Gray, J.S., Optimal Control within the Context of Multidisciplinary Design, Analysis, and Optimization, *AIAA Scitech 2019 Forum*, Jan 2019, AIAA 2019-0976, doi:10.2514/6.2019-0976.