Electrical Cable Design for Urban Air Mobility Aircraft

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Urban Air Mobility (UAM) describes a new type of aviation focused on efficient flight within urban areas for moving people and goods. There are many different configurations of UAM vehicles, but they generally use an electric motor driving a propeller or ducted fan powered by batteries or a hybrid electric power generation system. Transmission cables are used to move energy from the storage or generation system to the electric motors. Though terrestrial power transmission cables are well established technology, aviation applications bring a whole host of new design challenges that are not typical considerations in terrestrial applications. Aircraft power transmission cable designs must compromise between resistance-per-length, weight-per-length, volume constraints, and other essential qualities. In this paper we use a multidisciplinary design optimization to explore the sensitivity of these qualities to a representative tiltwing turboelectric UAM aircraft concept. This is performed by coupling propulsion and thermal models for a given mission criteria. Results presented indicate that decreasing cable weight at the expense of increasing cable volume or cooling demand is effective at minimizing maximum takeoff weight (MTO). These findings indicate that subsystem designers should update their modeling approach in order to contribute to system-level optimality for highly-coupled novel aircraft.

Nomenclature

Acronyms

CNT	carbon nanotube
MTO	maximum takeoff weight
OAS	Open Aero Struct
CCBlade	Continuity and Convergence Blade
TMS	Thermal Management System
UAM	Urban Air Mobility
VTOL	Vertical Take-off and Landing
XDSM	eXtended Design Structure Matrix

I. Introduction

Urban Air Mobility (UAM) vehicles have the potential to change urban and intra-urban transport in new and interesting ways. In a series of two papers Johnson et al.[1] and Silva et al.[2] presented four reference vehicle configurations that could service different niches in the UAM aviation category. Of those, this paper focuses on the Vertical Take-off and Landing (VTOL) tiltwing configuration shown in Figure 1. This configuration uses a turboelectric power system, feeding power from a turbo-generator through a system of transmission cables to four motors spinning large propellers on the wings.

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Previous work on electric cable subsystems leaves much yet to be explored, especially in the realm of subsystem coupling. Several aircraft optimization studies[1,3,4] only considered aircraft electrical cable weight and ignored thermal effects. Electric and hybrid-electric aircraft studies by Mueller et al.[5] and Hoelzen et al.[6] selected a cable material but did not investigate alternative materials. Advanced cable materials have been examined by a number of authors: Alvarenga[7] examined carbon nanotube (CNT) conductors for low-power applications. De Groh[8,9] examined CNT conductors for motor winding applications. Behabtu et al.,[10] and Zhao et al.[11] examined CNT conductors for a general applications. There were some studies that examined the thermal effects of cables but they did not allow the cable material to change; El-Kady[12] optimized ground-cable insulation and cooling subject constraints. Vratny[13] selected cable material based on vehicle power demand, and required resulting cable heat to be dissipated by the Thermal Management System (TMS). None of these previous studies allowed for the selection of the cable material based on a system level optimization goal. Instead, they focused on sub-system optimality such as minimum weight, which comes at the expense of incurring additional costs for other subsystems. Dama[14] selected overhead transmission line materials using a weighting function and thermal constraints. However, that work was not coupled with any aircraft subsystems like a TMS.

The traditional aircraft design approach, which relies on assembling groups of optimal subsystems, breaks down when considering novel aircraft concepts like the tiltwing vehicle. In a large part, this is because novel concepts have a much higher degree of interaction or coupling between subsystems. For example, when a cable creates heat, this heat needs to be dissipated by the TMS, which needs power supplied by the turbine, and delivering the power creates more heat. The cable, the TMS, and the turbine are all coupled. A change to one subsystem will affect all the other subsystems, much to the consternation of subsystem design experts. Multidisciplinary optimization is the design approach that can address these challenges. However, to fully take advantage of this, we must change the way we think about subsystem design. Specifically, we must move away from point design, and focus on creating solution spaces.

The work presented in this paper uses the multidisciplinary optimization approach with aircraft level models to study the system-level sensitivity of cable traits: weight-per-length and resistance-per-length. Additionally, we examined the effects of vehicle imposed volume constraints on these traits. This is useful for three purposes: (1) to demonstrate a framework that can perform a coupled analysis between the aircraft thermal and propulsion systems, (2) to provide a method by which future cable designs can be evaluated against each other given a system-level design goal, (3) to provide insight into what cable properties may be promising for future research. This last element is explored given the caveat that the models contained in this analysis do not represent high-fidelity systems. Thus, while we can demonstrate coupling in between systems, the exact system-level sensitivity to a given parameter may change if a subsystem model or the assumptions governing that model change.

The organization of this paper is as follows, in Sec II we outline a method to combine the VTOL vehicle design and cable information in order to produce cables sensitivity studies. Results analysis and discussion are contained in Sec III. Conclusions are presented in Sec IV.

Figure 1: NASA UAM VTOL concept vehicle

II. Methods

OpenMDAO is the integration framework that was used in this research. OpenMDAO is a flexible and versatile environment, capable of handling multi-fidelity models and providing analytic derivatives for use with efficient gradient based optimization algorithms.[15] Time dependent analyses, including the transient analysis of the TMS, are built using the Dymos[16] library. This library also allows for the optimization of the flight profile for the aircraft.

A cable subsystem was integrated into the tiltwing vehicle model. Connections between the cable and vehicle allowed for cable effects to flow into the vehicle, and vice versa. This created an environment where more cable resistance will increase heat generation and require a larger TMS system. The larger TMS system may demand more power, creating a demand for more fuel, and then for additional thrust to lift that fuel on takeoff. In order to achieve more thrust, the turbine increases in size to produce more power, and more power will be sent to the motors turning the propellers. More power is then sent through the electrical lines, creating more heat for the TMS to dissipate. This cascade of effects is uniquely captured by OpenMDAO and Dymos, allowing for true system level design optimization, based on a metric of the users choosing.

This paper examines the tradeoff between two hypothetical cable conductor materials. The materials will differ in critical aspects such as weight-per-length and resistance-per-length. Additionally, we allowed for a combination of the two materials to be used to provide the optimizer a continuous design space to examine. Volume constraints imposed by the vehicle are applied to one set of cables. The purpose of this thought experiment is to allow cable material selection based on its contribution to the system level optimization goal. This is the first step to creating a fully coupled cable analysis which also varies other design aspects such as voltages, insulation thickness, and cable operating temperature. Analysis like this enable us to change the way we approach cable design for electric aircraft. Rather than pre-supposing a cable material or voltage based on a sub-system level goal, the cable properties can be selected using a system-level goal.

The system level goal or merit function for this optimization is maximum takeoff weight (MTO). MTO is a combination of drymass, passengers, and fuel. Drymass of the aircraft is considered a proxy for initial vehicle cost. Fuel mass is a proxy for reoccurring costs. Therefore, the objective is equivalent to minimizing a combination of initial vehicle cost and reoccurring costs. Using these models created in OpenMDAO, we assessed the responsiveness of the objective function to the different cable materials. The results of the study demonstrate which cable type has the minimum MTO.

The rest of this section covers: a description of the demonstration problem (Sec II.A), the vehicle model and subsystems contained therein (Sec II.B), and the cable model (Sec II.C). The discipline design (Sec II.D) describes initial model sizing for static analysis. Dynamic modeling and analysis is discussed in the final section (Sec II.E).

A. Demonstration Problem

The specific VTOL vehicle models and mission used in this work are based on those presented by Hendricks et al.[3] and Aretskin-Hariton et al.[17] The vehicle model includes a mission profile for the vehicle, weight sizing for other subsystems, a turbine model, a propeller model, and a TMS model. The goal of the analysis is to minimize MTO for the specified flight profile and $1,361kg$ $(3,000lb)$ of passengers. The mission profile for this vehicle commences with executing a vertical takeoff maneuver at $1.5km$ $(5,000ft)$. This maneuver ends at $1.6km$ $(5,328ft)$ at which point a transition to forward flight is made. The transition between these phases itself is not modeled and therefore there are discontinuities between the velocity profiles associated with these two phases. In forward flight, the vehicle travels $740.8km$ (400nautical miles) with a flight ceiling of $3.0km$ $(10,000ft)$ and a final height of $1.6km$ $(5,328ft)$. At this point, the vehicle makes a vertical landing and the mission ends at $1.5km$ $(5,000ft)$.

B. Vehicle Model

The vehicle analysis includes the following subsystems: Propeller effects were modeled using Continuity and Convergence Blade (CCBlade).[18] CCBlade uses blade element momentum theory to predict propeller aerodynamic effects. Electrical power distribution from the turbine to the propellers was modelled in Zappy.[19] Zappy uses load flow analysis to evaluate the required power to be produced by the generator based on a power demand by the motors. The TMS model was designed by Chapman and Schnulo.[20] In the TMS, a fluid cooling loop extracts heat from the electronics, motor plus electrical cables, and generator before radiating the waste heat to the atmosphere. Tandem phases were created for the TMS as described by Hendricks et al.[21] This allows the TMS to be run at higher temporal discretization without requiring additional computational cycles for all the other models. The thermodynamic cycle analysis for the gas turbine was modeled using pyCycle.[22] Aerostructural modeling of the wing was performed using a surrogate model with assumed lift and drag coefficients. Acoustic modeling was not included for this analysis.

To simplify the coupling between the models, only the maximum power required by the TMS was fed back into the electrical system. This assumption supposes that the TMS is working at full power throughout the mission. This leads to a slight increase in the power required during the whole flight. In actuality, the TMS power usage dips during forward flight by around 10%. The TMS still requires significant power during forward flight to achieve the required pressure drop on the air coolant cooler. This is because the flight ceiling of $3.0km$ $(10,000ft)$ is relatively low, and the maximum speed of $370km/h$ $(230mph)$ is also low.

C. Cable Modeling

In this subsection we discuss the specific design parameters of the hypothetical cable models. The resistance-per-length and weight-per-length model of each cable material is explained. Because of the simplified nature of this analysis, the weight of the insulation material is neglected. We also neglect cable failure modes such as cut cables. Additionally since the power distribution system is DC, we neglected effects of resistance changes due to bends in the cable. We then cover the method used to scale the cable models to handle the large amount of power required by the tiltwing. Lastly, thermal coupling is discussed.

1. C-Cable

The first hypothetical cable model, C-cable, was based on a cable identified for use with the X-57 aircraft.[23] This is nominally a copper-based cable model with a geometry configuration shown in Fig 2. The cable was constructed of twelve strands of 10 AWG copper cable laid flat and held together with insulation. The nominal capacity for this cable is $335A$ at $600V$ DC.[24] However the voltage of the tiltwing electrical system was fixed at $540V$. The C-cable has an assumed base weight-per-length of $0.56kg/m$ and base resistance-per-length of $3.3e^{-4}\Omega/m$. This approximates a copper conductor at $51°C$.

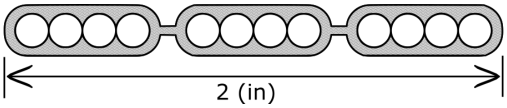

Figure 2: Basic cable design with insulation (grey) and conductor (white). To supply the amount of power required, six of these cables are used in parallel to connect between each point on the electrical system.

2. AR-Cable

The second hypothetical cable model, AR-cable, was based on scaling the first cable following a few assumptions. The copper conductor was replaced with an aluminum conductor with equivalent resistance. This is an example of a non-volume constrained cable where the new cable is allowed to exceed the dimensions of C-cable. The cable gauge was increased using the method described by de Groh.[8] The weight per length was then recalculated. AR-Cable has a resulting base weight-per-length of $0.304kg/m$ and base resistance-per-length of $3.3e^{-4}\Omega/m$. This approximates an aluminum conductor at $30°C$ over ambient temperature.

3. AA-Cable

The third hypothetical cable model, AA-cable, was also created using an aluminum conductor. However, volume constraints were applied, forcing this cable to occupy the same volume as C-cable. This caused an increased the resistance of the AA-cable. The basic weight-per-length and resistance-per-length were then recalculated. AA-cable has a resulting weight-per-length of $0.170kg/m$ and a resistance-per-length of $5.25e^{-4}\Omega/m$.

4. Combination Cables

Combination cables were created by combining strands of AR-cable material and C-cable. Similarly, combinations of AA-cable and C-cable were also created. The combination cable was created by linearly interpolating between the two weight-per-length and resistance-per-length values. This works under the assumption that it is possible to create a cable from strands of both materials. While this may not be physical, it does allow for a continuous solution space which is useful in the context of optimization. If an intermediate cable is found to be most optimal, this would indicate that a copper or aluminum alloy would be most effective at minimizing MTO.

5. *Scaling the Cable Models*

Scaling the cable models was based on the following considerations. Each connection between points of the electrical system consists not of just a single cable, but of six parallel cables. Thus, the connection between the generator and one of the wing motors would have six parallel cables supplying DC power. Return cables required for DC power distribution were incorporated by doubling the connection length. Connection lengths are fixed and do not change during the analysis. Thus, the scaled weight-per-length of each cable is six times the basic weight-per-length described above. Additionally, the resistance-per-length is one sixth of the basic resistance-per-length described above.

6. *Thermal Coupling*

In previous work[17, 19] it was assumed that cables were able to convectivly cool themselves. In this study, similar to the Vratny approach,[13] we required the TMS to process all heat generated by the cables. The TMS could do this by changing the size of the heat exchangers, or changing the speed of the cooling fans. This created coupling between electrical, thermal, and power generation systems. The thermal coupling was conducted under the assumption that any heat generated by the cables was moved to the heat exchangers located on the motors. The specifics of how heat is moved was not explored in this study because the focus of this study is to demonstrate system coupling and system-level optimization.

D. Discipline Design

In the discipline design, sometimes referred to as the static design process, each subsystem on the vehicle is sized with the goal of calculating MTO and fuel mass. This process is illustrated in the eXtended Design Structure Matrix (XDSM) diagram shown in Fig 3. In this process, the solver takes an initial guess for MTO which is used to create an estimate for the thrust power in hover. That thrust power is sent to the propeller model (CCBlade) which also has an initial propeller design configuration ($X_{propeller}$). The propeller model calculates an output power required by the motors and a weight for the propeller. This power demand ($P_{propeller}$) is then fed into the electrical system (Zappy) which calculates a required output power to be produced by the turbine (pyCycle surrogate model). Additionally, the electrical system also calculates a weight of each component inside it (motors, cable, transformers, etc.). The turbine then sizes itself so that it can provide the require power in hover, and the resulting turbine weight is an output. Lastly, the TMS is sized based on initial assumptions, and the weight of that system output and summed with the other weights to create the updated estimate for MTO. The solver then compares the guessed MTO against the calculated MTO and iterates until convergence. The final results of all the system sizing is sent to the dynamic model.

E. Dynamic Modeling

The dynamic cable model produces a time-dependent analysis that outputs heat loss estimates throughout the mission. This happens in both vertical and forward flight. These two phases were modeled separately.

The VTOL phase XDSM is shown in Fig 4. This two-minute phase encompasses the takeoff and landing segments of the flight. Ground level is considered to be at $1.5km(5,000ft)$. The maximum altitude that the vehicle travels in VTOL is $100m(328ft)$. The propeller, electrical, and turboshaft systems all accept their sizing information from the discipline design process. This design information is used to produce the transient output. The wing surrogate model is neglected in this phase. The outputs from this phase, Q_{loss} represents the amount of heat given off by the entire electrical system. This is further broken out into electrical subsystems like the cable assembly (Q_{cable}). These losses, are fed to the thermal phases which is then forced to dissipate the heat.

The forward flight phase XDSM is shown in Fig 5. This phase starts at $1.6km(5,328ft)$ which is 100m above ground level. The phase covers the following elements: climb to $3.0km(10,000ft)$, cruise for $740.8km$(400nautical miles), and then descent to $1.6km(5,328ft)$. The propeller, electrical, turboshaft, and

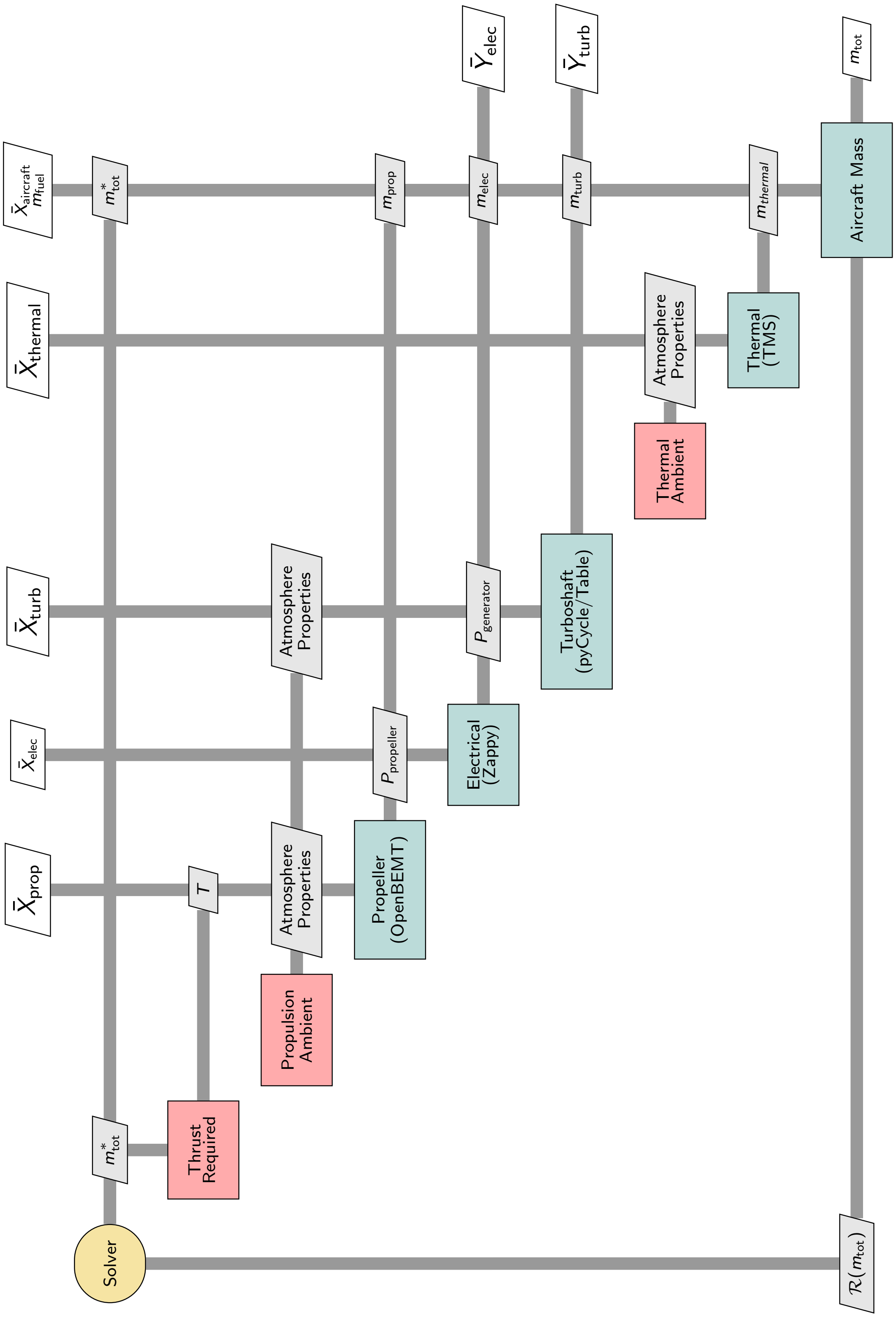

Figure 3: NASA Discipline design modeling with cable weights

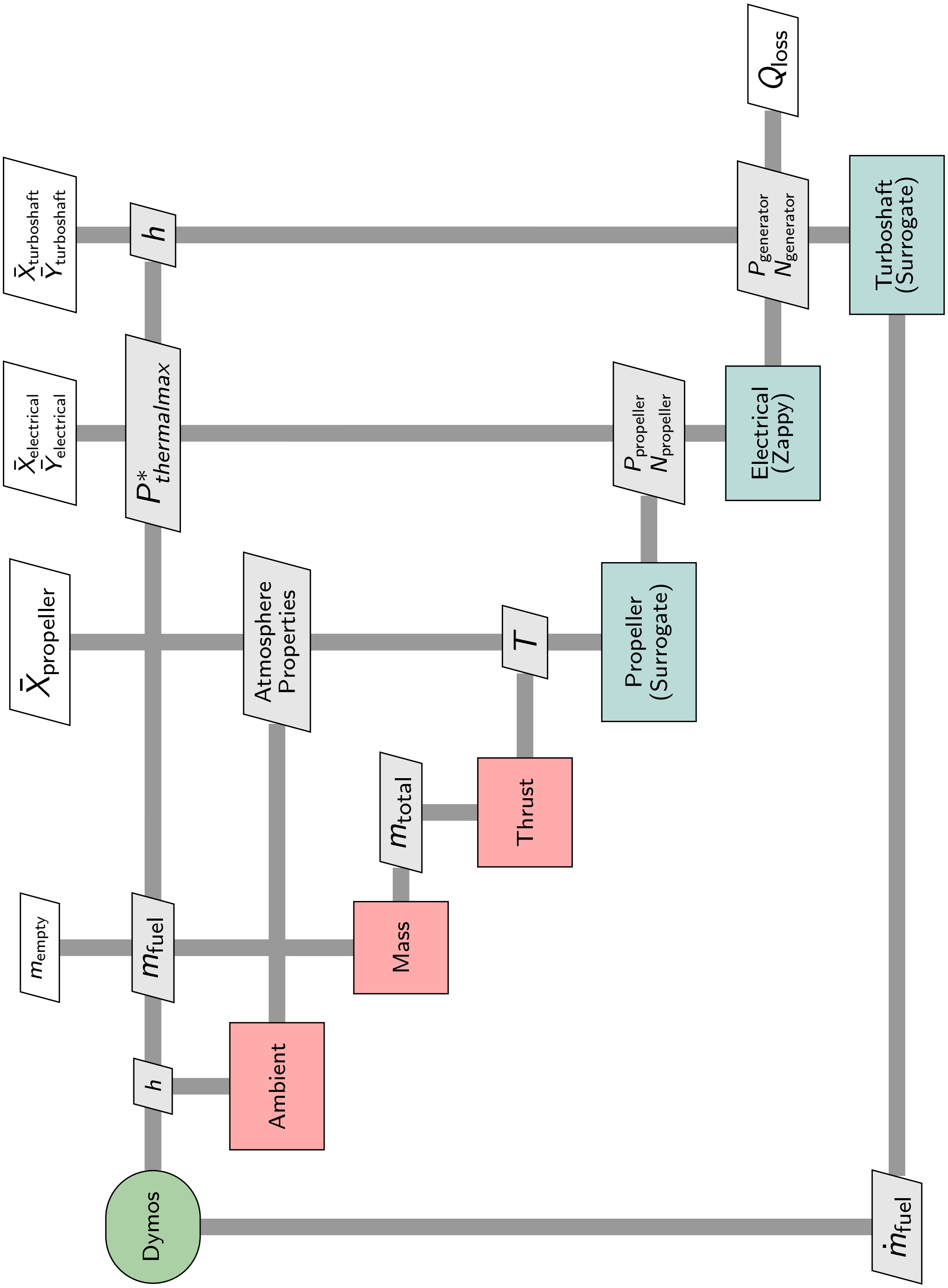

Figure 4: NASA Dynamic modeling for VTOL phases

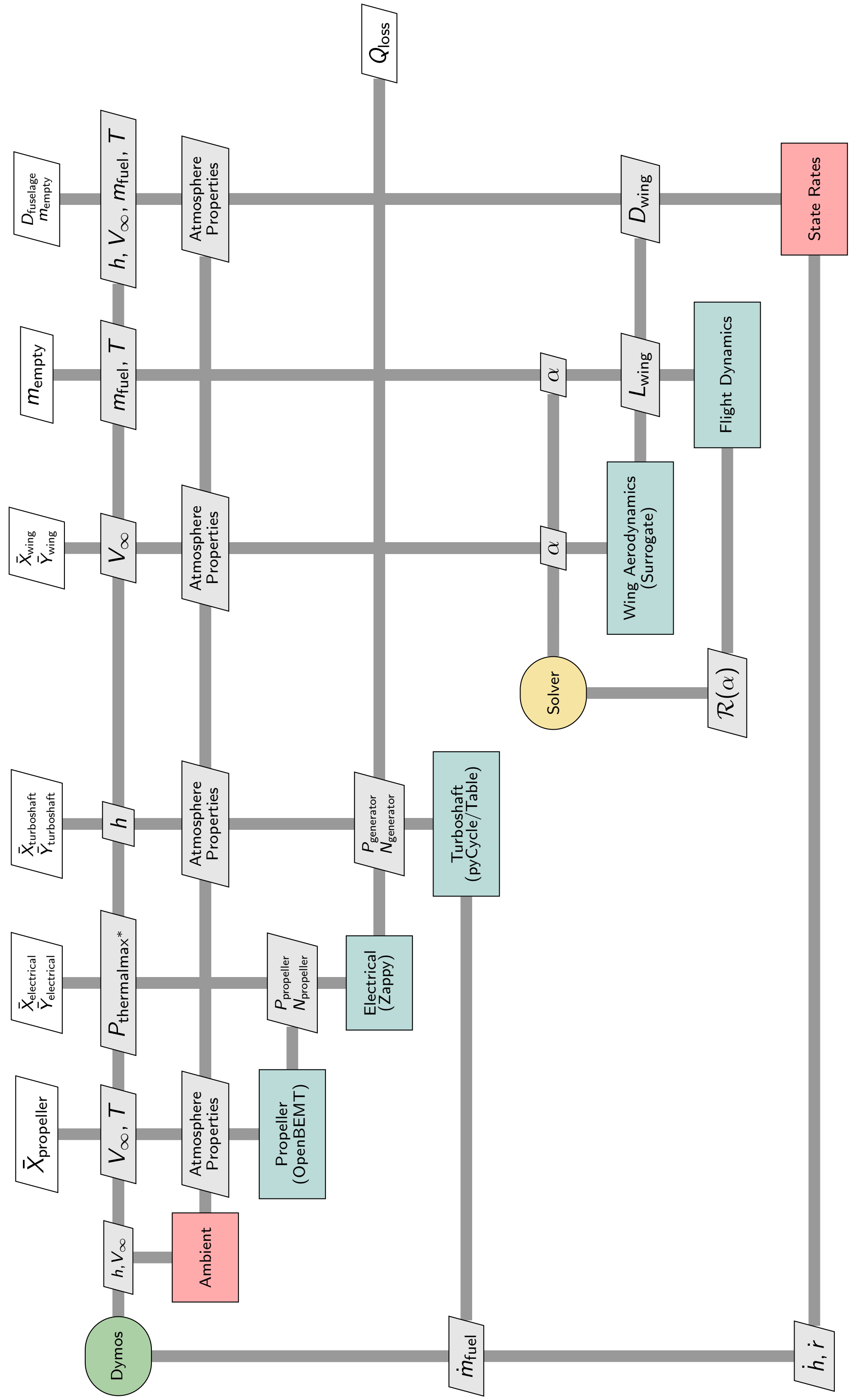

Figure 5: NASA Dynamic modeling for forward flight phase

wing surrogate models are all active during this phase. The outputs from this phase, Q_{loss} is again the amount of heat given off by the electrical systems, including the cable during this phase.

The last phase is a tandem thermal phase. This phase uses Q_{loss} calculated in VTOL and forward flight in order to update the temperature state of all the components in the thermal system. The maximum power required from these phases, $P_{thermalmax}$, is fed back into all the phases as the power demanded by the TMS during the whole mission. The amount of power used by the TMS typically varies between $38kW(51hp)$ for VTOL and $32kW(43hp)$ for forward flight. Thus the error created by this assumption consistently overestimates TMS power usage by approximately 20% for all cases studied. This simplification was made to decrease the amount of information flowing between phases and increase convergence speed.

III. Results and Discussion

In this section we present the final results of the tiltwing optimization produced by OpenMDAO and Dymos. The goal of the optimization was to minimize initial takeoff mass MTO subject to a number of constraints and initial conditions described in Sec II.

The results from evaluating C-cable, AR-cable, AA-cable, and combination cables, are presented in Fig 6 and Table 1. In each of the points in this figure, the system has been re-optimized and the trend line was added. The results show that C-cable is the heaviest configuration with an MTO of around $5,322kg(11,733lb)$. AR-cable, the cable configuration with the same resistance as C-cable, demonstrates significant weight reductions with an MTO of $5,091kg$. Combination cables, made from some strands of AR-cable and some strands of C-cable, present varying MTO values from $5,091kg$ to $5,322kg$. AA-cable, the cable configuration forced to maintain equivalent conductor area as the C-cable, demonstrates even better MTO of $5,015kg$. Lastly combination cables, made from some strands of AA-cable and some strands of C-cable, also present varying MTO values from $5,015kg$ to $5,322kg$.

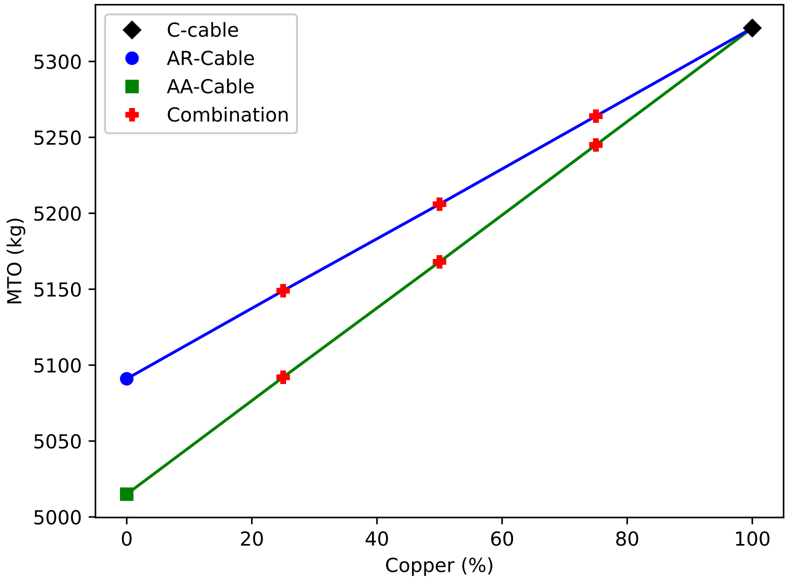

Figure 6: Test of cables and resulting maximum takeoff mass (MTO). 100 represents a pure C-cable and 0 represents a pure AR-cable or AA-cable. Composite cables are shown in-between the extremes.

The equal resistance AR-cable is lighter than the C-cable configuration, as expected. If there are no volume constraints, an increase in the specific conductivity of the conductor should decrease cable weight-per-length, which then leads to a decrease in MTO. Because these two cables have equal resistance-per-length, no additional thermal penalties are imposed on the AR-cable configuration. The TMS system, weighing $65.6kg(144.6lb)$, continuously dissipates approximately $0.1kW(0.13hp)$ of AR-cable waste heat. A supporting analysis of the insulation material for these two cables would contribute to a change in specific conductivity and subsequently MTO. However, we would still expect that the cable with the highest specific conductivity would produce the best results, assuming equal resistance cables without volume constraints.

Table 1: Change in masses of VTOL aircraft due to cable material switch

Cable Type	C-Cable	AR-Cable	AA-cable	Units
Max Takeoff Mass (MTO)	$5,322$	$5,091$	$5,015$	(kg)
Fuel Mass	684	669	664	(kg)
Cable Mass	235	112	71	(kg)
TMS Mass	66.2	65.6	65.5	(kg)
Cable Resistance (Scaled)	$5.55e^{-5}$	$5.55e^{-5}$	$8.75e^{-5}$	(ohm/m)
Cable Heat at Cruise	0.1	0.1	0.2	(kW)

Our critical finding in this study shows that the AA-cable, which was volume constrained to occupy the same cross-sectional area as C-cable, actually performed even better than the unconstrained cable! This happens despite the fact that increased resistance due to the small cross-sectional area creates double the thermal load during cruise (Table 1). However, the TMS system has essentially the same mass and power consumption. This happens because the cable cooling demand of $0.2kW(0.27hp)$ is small compared to the cooling required by other systems on the aircraft which is approximately $162kW(217hp)$. Additionally, since the overall vehicle weight has decreased, the total amount of fuel required for this case also shows a net decrease in Table 1. Broadly speaking, this indicates that based on the assumptions given, this vehicle is more sensitive to cable mass than resistance. Additionally the lower density of aluminum more than compensates for its lower conductivity compared to copper; thus making aluminum the better design choice for this particular application.

The implications of these findings clearly illustrate that selecting a cable for novel aircraft configurations should not be performed at the subsystem level. In our case, choosing a heavy cable for maximum efficiency (C-cable) or a light-weight but efficient cable (AR-cable) are both suboptimal at the system level compared with selecting an extremely lightweight cable that creates lots of heat (AA-cable). Similarly, the TMS should not be designed independently of the cables. If we had attempted to minimize TMS power usage, this would have also resulted in a suboptimal MTO as can be seen in Table 1. This example demonstrates how choosing an optimal point design for a subsystem can result in system-level suboptimality. This happens because every subsystem in this vehicle is highly-coupled with each other subsystem. If this coupling is ignored, it can lead to a vehicle that has either a reduced mission distance or a reduced payload.

The engineering community has long relied on subsystem experts to create a single point design for elements such as cables and thermal systems. However, to create system-level optimality a new multidisciplinary optimization approach is required which takes full advantage of the computational savings of gradient based optimization.[15] In this approach, subsystem experts create a solution space of all valid configurations. The solution space is represented as a set of equations and their partial derivatives. The solution spaces for the different disciplines are combined in an optimization environment like OpenMDAO and Dymos. Finally, system-level goals can be applied and the results computed in an iterative process. This allows multiple sensitivity studies to be compared against each other, and leads to an in-depth understanding of the vehicle-level solution space.

IV. Conclusion

This paper has shown that given the Vertical Take-off and Landing (VTOL) vehicle and assumptions described in this work, the system has a clear preference to minimize maximum takeoff weight (MTO) by using a low weight-per-length, high resistance-per-length electrical cables. MTO is defined as the sum of vehicle drymass, fuel, and payload. The results show that the system has a high sensitivity to weight and a low sensitivity to resistance. In this case, the penalty of increased thermal management mass and fuel consumption due to high cable resistance is outweighed by the savings of decreasing drymass. Generalization of these findings to VTOL aircraft design should be performed cautiously as these results were obtained using a highly-coupled analysis using the specific subsystems detailed in the paper. As those assumptions change and the models used increase in fidelity, the applicability of these sensitivities may change.

The resulting optimal-aircraft configuration was created out of sub-optimally designed subsystems. A traditional design approach focused on creating optimal subsystems (e.g. efficient cabling and low power Thermal Management System) would have caused MTO to increase. This multidisciplinary analysis clearly demonstrates the capabilities of OpenMDAO and Dymos to produce non-intuitive results for a highly-coupled systems. These methods can be fully leveraged when subsystem design experts focus on creating solution spaces rather than point designs.

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