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Integrated Vehicle-Propulsion-Control Design for Distributed Electric Propulsion-Enabled Aircraft

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This paper presents the development of the IDEA tool, a conceptual design environment for distributed electric propulsion enabled aircraft that integrates vehicle, propulsion, and control related analyses. With the advancements in technologies across the various disciplines, legacy conceptual design tools developed for traditional tube-and-wing concepts do not adequately address the design of aircraft for the Urban Air Mobility domain. Effectively modeling the highly coupled disciplinary analyses without incurring the significant computational cost associated with higher fidelity modeling is important for the development of electric and hybrid-electric aircraft concepts. The IDEA tool is a multi-fidelity, multi-disciplinary design architecture for aircraft and controller design. Multiple fidelities of aerodynamics are incorporated into the tool to help capture the necessary physics of propulsion-airframe interactions. A multi-fidelity surrogate generation technique enables efficient combination of different fidelities of information to improve the overall model fidelity with reduced computational cost. A high-fidelity structural analysis capability is developed to determine the structural performance and improve the aircraft weight estimation. Including controller synthesis in a conceptual design framework is an important component and is necessary to account for handling qualities and ride comfort in the design stages. This paper describes our ongoing efforts in setting up this framework - including setting up the disciplinary analyses and performing trade studies for an electric Lift+Cruise concept.

I. Introduction

A. Background

NASA is spearheading the efforts on Urban Air Mobility (UAM) and providing impetus to the industry to follow with concepts for the same [1–4]. To develop technologies and capabilities to support this new aviation system, NASA is funding internal research and collaborative research with academia and industry partners [5–7]. Several manufacturers, such as Joby Aviation and Wisk Aero, as well as NASA, have come up with concepts for UAM aircraft, many of which utilize Distributed Electric Propulsion (DEP). DEP is a fast-emerging approach for novel UAM aircraft design due to its profound implications on the future of flight. DEP concepts can offer several opportunities, including: 1) lower noise due to electric propulsion, 2) propellers with potentially-lower disc loading, 3) lift augmentation leading to smaller wing areas, shorter spans, and better aeroelastic performance, 4) propulsor system redundancy, and 5) novel ways of controlling the vehicle. Aero-propulsive-elastic interactions can be exploited to improve aerodynamic performance while meeting flutter constraints; however, propulsors mounted towards the wing tip could reduce the flutter margin if

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the system is not carefully designed [8]. These advantages are more pronounced for some aircraft than others, but they are particularly intriguing for applications such as UAM, where relatively shorter duration flights can be achieved using electric multi-propulsor concepts. The UAM market is one of the most promising contenders to replace and expand existing ground and air transportation modes and business models. Recent advances in sensor technology, control approaches and autonomy, battery and motor technology, and airframe design have provided fertile grounds to adopt DEP for UAM, as seen by the myriad of UAM aircraft prototypes in testing by Joby Aviation, Lilium Jet, Wisk Aero, etc.

However, the understanding of which DEP (or UAM) concept is most suited for a particular mission is missing. For example, UAM aircraft can be used for people transport (where ride comfort is very important) in contrast to cargo movements (where speed and payload are of the essence). To achieve a tailored or a multi-use design, the multidisciplinary interactions of airframe-propulsion system aerodynamics, structural load alleviation, and novel control techniques enabled by multiple electric propulsors need to be captured at an appropriate fidelity. Moreover, electric propulsion offers fundamentally different characteristics providing new degrees of freedom in aircraft design. The Boeing SUGAR Volt concept, for example, provided some of the most promising results for substantial fuel savings of future transport aircraft, but assumed that a properly designed active load alleviation system will reduce the wing weight by 25% and does not incorporate the influence of pressure distribution shape on laminar transition [9]. Such assumptions can miss important trade-offs and constraints that drive the design.

To capture such tradeoffs, existing tools are insufficient for direct characterization of aeroservoelastic interactions in all flight regimes [10]. The availability of high performance computing has made possible a decreased reliance on simple structural models and linear aerodynamic theories, but there is still a need to keep the computational expense in check due to the highly multi-disciplinary nature of the problem. Multi-fidelity methods enabled by a prudent use of appropriate fidelity of information (to enable high-fidelity predictions at a fraction of the cost) are particularly promising in this regard. In addition, aircraft need intelligent controllers to manage the multiple control options afforded by DEP. A carefully-constructed control scheme that realizes complex scheduling of the propulsors can enable efficient maneuverability and disturbance rejection performance far beyond the reach of traditional control surfaces. Moreover, there is a critical need for efficient controllers for distributed actuators whose design can be incorporated in vehicle Multidisciplinary Design Optimization (MDO) architectures.

Advanced aircraft concepts can take advantage of distributed flight control systems that are well suited for DEP. In a traditional aircraft MDO process, flight control is usually not considered in the initial aircraft design until well after the outer mold line (OML), propulsion, and structure have been finalized. As the aircraft industry is moving toward more advanced aircraft concepts with redundant distributed flight control systems, the need for early integration of distributed flight control systems into the aircraft MDO process becomes necessary. For example, high aspect ratio wing aircraft can take advantage of distributed flight control surfaces for drag optimization and structural load alleviation to enable lightweight wing structures. By incorporating flight control into the MDO process, a different OML or wing structure would result that could provide better lift-to-drag ratio (L/D) to increase fuel efficiency and reduced structural loading by active controls to minimize drag and structural loads. Similarly, a UAM aircraft design that integrates DEP into an MDO architecture as a distributed flight control system could result in a more efficient and safer aircraft design.

B. Our Contributions

The multidisciplinary interactions involved and the ability to utilize the distributed propulsors for improved control are not fully understood. To achieve this and use such capabilities in design, we are developing IDEA, a design optimization architecture that includes multidisciplinary multi-fidelity analyses for integrated airframe-DEP design. The key innovation in this work is the development of a design framework integrating multi-fidelity analysis capabilities for vehicle, propulsion, and control law development for DEP-enabled aircraft. In this paper, we present a proof-of-concept of the technology, including development of conceptual level analyses for various disciplines, and integrating them into a design architecture for a 'Lift+Cruise' aircraft concept. In addition, standalone higher fidelity methods have been developed for aerodynamics, structures, and controls. Furthermore, a capability to combine multiple fidelities of aerodynamic information for propellers has also been developed.

The overall architecture and vision for the IDEA tool, which is still under development, is shown in Fig. 1. In the development of the IDEA tool, we leverage the Stanford University Aerospace Vehicle Environment (SUAVE)*, which is an open source aircraft design environment written in Python [11]. Multiple fidelities of aerodynamics combining conceptual-level blade element momentum theory (BEMT)and general vortex wake methods were developed to help capture the necessary physics of propulsion-airframe interactions. These multi-fidelity information sources can be fused

*SUAVE GitHub Repository: https://github.com/suavecode/SUAVE into a multi-fidelity surrogate to be used for both simulation of entire missions and optimization. High-fidelity structural analysis was performed using finite element analysis (FEA) through a nested optimization architecture (to avoid large computational expense at the system optimization level). Novel control system synthesis and sizing procedures were developed incorporating the distributed propulsors/actuators available for enhanced stability/maneuverability. Additional disciplinary analyses, including battery modeling for the electric propulsion system and component weight buildup for electric vertical take-off and landing (eVTOL) aircraft weight estimation were developed. The conceptual level analyses of each discipline were incorporated in an MDO architecture for performing integrated vehicle-propulsion-control design for a relevant UAM mission.

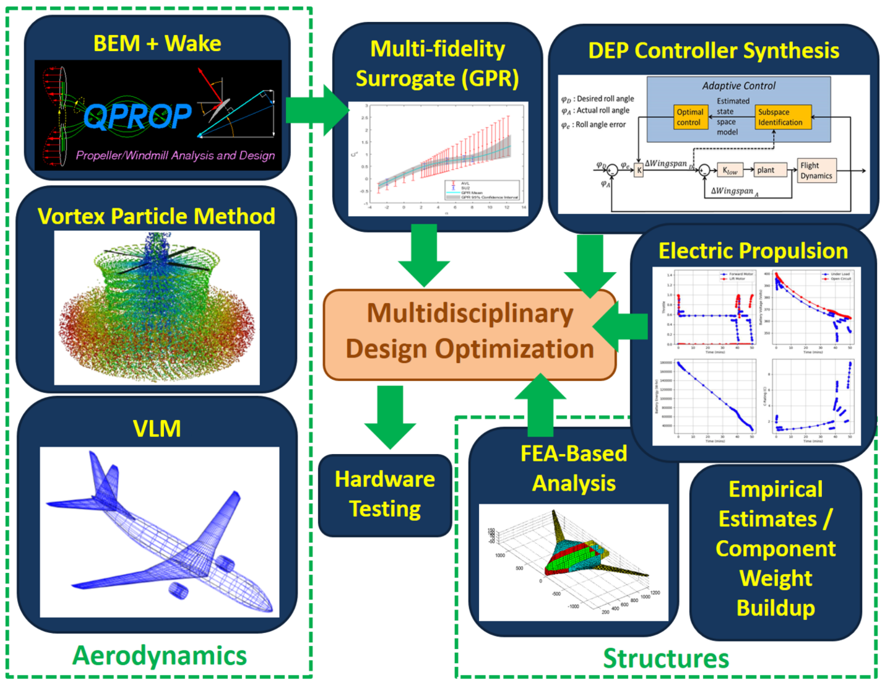


Fig. 1 Overview of IDEA approach

In this paper, we begin by discussing the various disciplinary analyses: the Aerodynamic Analyses in Sec. II, the Multi-fidelity Surrogate Generation in Sec. III, the Structural Analysis and Weight Estimation in Sec. IV, and the Controller Synthesis in Sec. V. These are followed by a discussion of the initial implementation of the MDO architecture in Sec. VI. Finally, we will demonstrate the initial MDO architecture with a case study of a Lift+Cruise concept in Sec. VII.

II. Aerodynamic Analyses

This effort leverages multiple fidelities of aerodynamic methods for modeling lifting surfaces, rotor performance, and wake interactions. A vortex lattice method (VLM) is used to evaluate forces on lifting surfaces, as well as compute induced velocities for assessing component interactions elsewhere in the flow. A blade element theory (BET) model of the rotor is used and coupled with three different wake models: a momentum wake, a prescribed helical fixed-wake (HFW), and a viscous vortex particle method (vVPM) wake. These methods can be paired together easily to assess the effect of component interactions, as well as nonuniform flows into the rotor. An overview of these methods are provided here, with a detailed description of each method provided in [12–14].

A. Lifting Surface Analysis with Vortex Lattice Method

To analyze aerodynamic forces and moments of lifting surfaces, SUAVE's vortex lattice method (VLM) discretizes the surface into a lattice of panels. Each panel has a horseshoe vortex of constant strength, made up of a bound vortex positioned at the quarter chord of the panel and two trailing vortex filaments that follow the panel lines until the trailing edge of the surface, at which point the trailing vortices extend to infinity following the camber line. Once the vortex distribution is computed for the surface, the Biot-Savart law is used to obtain velocities induced by all horseshoe vortices at each control point on the surface. The influence coefficient matrix, $C_{m,n}$, contains the influence of each of the n panels at each of the m control points. Flow tangency is then enforced at each control point, and the vortex strengths are computed and used to calculate the aerodynamic forces on the wing.

$$V_m = \sum_n C_{m,n} \Gamma_n \tag{1}$$

$$V_m = 0 \text{ (Flow Tangency)} \tag{2}$$

The VLM in SUAVE has undergone thorough validation by the developers, as detailed in Ref. [15]. An extension to the VLM includes a semi-empirical viscous correction for the wing wake, which becomes important when considering propellers in pusher configuration [12].

B. Blade Element Theory for Propeller/Rotor Analysis

The propeller and rotor aerodynamic analysis uses a BET model, which requires an additional model of the wake to account for the wake-induced inflow velocities at the blade. A simple momentum theory wake model allows for analysis of a simplified propeller flow, which does not account for effects such as tip vortices or radially induced flow, but instead provides a computationally inexpensive analysis suitable for conceptual-level design and analysis. The rotor blades are divided into radial stations, at which a user-specified airfoil may be applied. The effective angle of attack is computed for each station, accounting for the wake-induced inflow velocities. In the presence of a disturbed freestream flow, as is the case for propellers in a pusher configuration, this analysis may include the effect of the disturbed freestream velocity at each radial section. The lift and drag at each two-dimensional radial section are computed using the airfoil's polar data for the given Reynolds number, with a post-stall correction that follows the AERODAS formulation [16]. The resulting lift and drag forces are then decomposed to obtain the elemental thrust and torque along the blade for each azimuthal station. The propeller performance is then established by time-averaging the total thrust and torque forces over the azimuth. The results of this propeller analysis have been validated against experimental data using several propellers with ranging advance ratios, incidence angles, and blade pitch angles [14, 17].

C. Other Rotor Wake Models

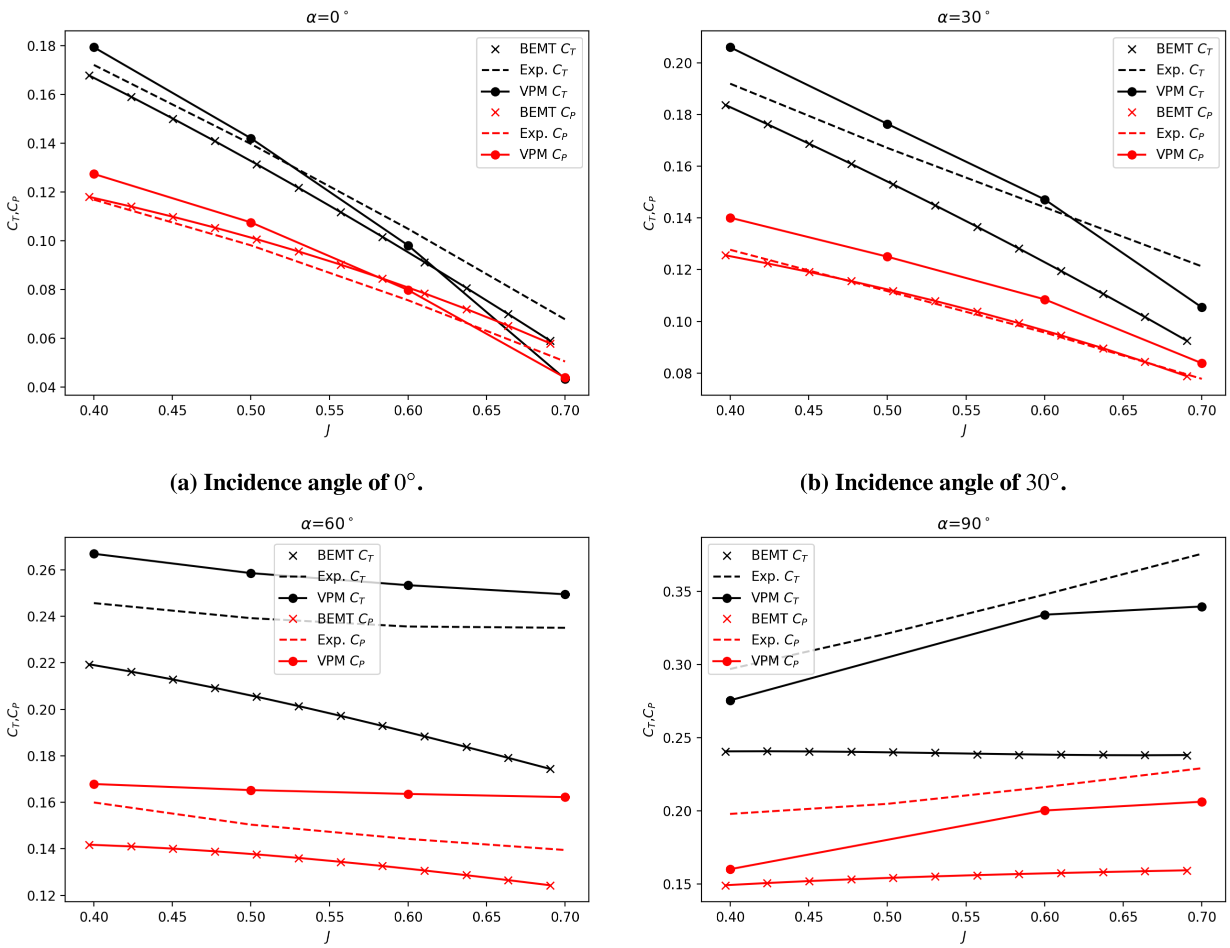
In addition to the momentum wake model, a prescribed helical fixed vortex wake (HFW) and a viscous vortex particle method (vVPM) wake are also leveraged, providing increasing complexity to the wake modeling. Detailed descriptions of the vVPM and HFW methods can be found in [13] and [14], respectively. The prescribed helical wake model uses the circulation at each radial blade station to define the vortex strength of shed vortex rings at each timestep. The vortex rings together form a helical wake that is convected downstream. A wake skew angle is implemented to account for rotors that encounter edgewise velocity components. Using this wake method allows for more accurate prediction of the interactions of the rotor wake with downstream surfaces, since momentum theory is often not sufficient for such cases.

Although the HFW method used for capturing the propeller wake effect in SUAVE provides a reasonable approximation in many cases, certain configurations and flight conditions may require higher fidelity methods to more accurately capture the complex rotor and wing interactions for a distributed propulsion aircraft. High fidelity CFD methods such as uRANS or RANS simulations can more accurately capture the true physics of the flow but can be computationally prohibitive for early-stage design. The vVPM offers a mid-fidelity solution for the modeling of rotor and propeller wakes, which can provide increased accuracy over the momentum wake and HFW methods, and at a significantly reduced cost when compared to CFD methods. In the vVPM, the vorticity field is discretized into a number of vortex particles, and the vorticity form of the Navier-Stokes equation is used to update the circulation strength of each particle. The vVPM simulations in this project used the FLOWVPM code.

D. Multi-Fidelity Test Case: High-Incidence Rotor

Various complex flow conditions have been studied using each of the wake methods previously described, including rotors with high-incidence of the rotor shaft axis relative to the freestream, in pusher configurations, and in tractor configurations [12, 14]. In this paper, we will use the results from the high-incidence case study to conduct a multi-fidelity analysis of the propeller performance. We consider an isolated rotor in edgewise flight, with an incidence angle of the rotor relative to the freestream flow. We use the TUD F29 rotor, which has recently been tested in a wind tunnel at a range of incidence angles [18]. This rotor has four blades and a tip radius of 0.1524m. The full geometry of the propeller and experimental results are detailed in their paper.

For this high-incidence case, the angle the rotor makes to the freestream introduces an oscillatory variation in the inflow over time as the propeller blades rotate. A comparison of propeller performance at various incidence angles and across a range of advance ratios is given in Figure 2 using the BEMT and vVPM. It is clear from these plots that the BEMT is quite accurate at low incidence angles, but becomes progressively worse as the incidence angle is increased. This is to be expected, since the underlying assumptions of the momentum wake model begin to break down. It is in these regions where the vVPM begins to provide a better solution, more closely matching the experimental results from Ref. [18] at high incidence.



(a) Incidence angle of $0°$**.**

(b) Incidence angle of $30°$**.**

(c) Incidence angle of $60°$**.**

(d) Incidence angle of $90°$**.**

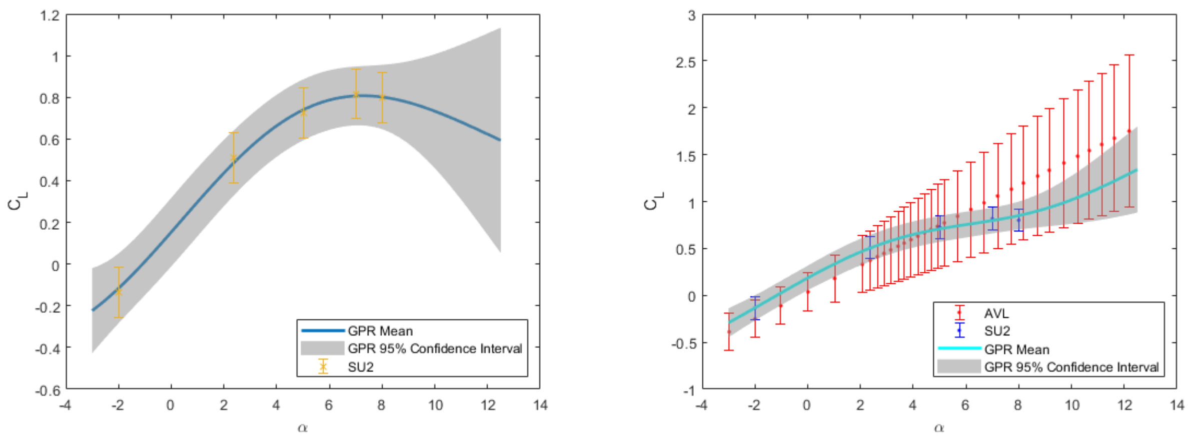
Fig. 2 Comparison of BEMT and vVPM performance at incidence.

The results from this high-incidence angle study led to further development of a surrogate modeling technique in which the user can leverage a multi-fidelity dataset to obtain a surrogate for the model that also quantifies the model uncertainty. This will be discussed in the section to follow.

III. Multi-fidelity Surrogate Generation

A. Gaussian Process Regression

A previous effort, detailed in Ref. [19], focused on developing a capability to combine multiple fidelities of data in a mathematically rigorous fashion. In this work, such a capability can more efficiently and effectively capture the interaction between rotors and the airframe. To this end, we successfully developed and demonstrated a multi-fidelity Gaussian Process Regression (GPR) using two levels of fidelity. GPR is a statistical technique for regression (or curve fitting). However, in addition to providing the mean data fit, it also provides an uncertainty over the fit, based on the noise in the source data. This can be used for adaptive DOE or adaptive sampling of the input space in order to iteratively reduce the database uncertainty as needed. The standard GPR method is aimed at a single fidelity fit, as shown in Fig. 3a for the lift coefficient of NASA's Common Research Model (CRM). Details of the test case can be found in Ref. [19]. The actual data points from SU2 (an open source aerodynamics solver) simulations and associated error bars (estimates of errors are assumed to be provided by a Subject Matter Expert (SME)) are shown in yellow and the resulting uncertainty of fit is shown in gray. As we can observe, the resulting uncertainty matches the error well, and is larger in areas where we do not have enough data (as expected).



(a) **(b)**

Fig. 3 Single fidelity (a) and two-fidelity (b) fits using SU2 and AVL data

Also, compared to standard GPR, our implementation allows specification of a different noise value for each data point at each fidelity level. To combine multi-fidelity data, we use the additive correction model as proposed by Huang et al. in Ref. [20]: $f_l(x) = f_{l-1}(x) + \delta_l(x)$ where, l is the higher fidelity and $l-1$ is the lower fidelity. Figure 3b shows a GPR fit on the coefficient of lift, using data from AVL and SU2. As we can see, the multi-fidelity fit uses several AVL simulations, but only a handful of SU2 runs to get a fit that matches the high-fidelity data very well. Moreover, the uncertainties in the multi-fidelity fit are close to the higher-fidelity errors, as expected.

To illustrate the cost savings from multi-fidelity fits, consider a case where we combined SU2 and wind tunnel (WT) data. Figure 4 shows a case where the lift curve using only high-fidelity data (as a function of Mach number and angle of attack) required about 100 data points from wind tunnel tests. However, with the use of SU2 to provide lower fidelity data, only 19 wind tunnel test points were required to get a very similar data fit. This idea can be similarly applied to combine the information from the BEMT and vVPM methods to better capture the interaction effects between rotors and the airframe.

B. GPR Case Study: High-Incidence Rotor

Towards the application of the multi-fidelity analysis capability for capturing the interaction between rotors and the airframe, we first apply the technique to an isolated propeller with non-uniform inflow caused by a high incidence angle relative to the freestream flow. The specific example discussed here was also analyzed as a validation study of the BEMT and vVPM methods in Sec. II, which compared to results for the TUD F29 rotor provided in Ref. [18]. The goal of this example is to demonstrate the effectiveness of combining the BEMT and vVPM methods and act as a first step

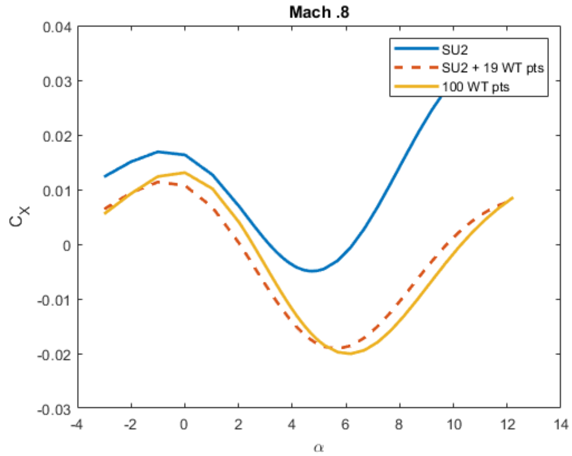


Fig. 4 Illustration of cost savings using multi-fidelity fits

towards the application of GPR to capturing the airframe-DEP interactions.

Data were compiled for the same geometry and conditions for the TUD experiment using the IDEA tool BEMT and vVPM capabilities. The BEMT, because it is a low computational cost calculation, was used to generate a grid of 380 points. The vVPM, on the other hand, due to its high computational cost was used to generate a grid of 16 points. The experimental data were included only for comparison to the generated data from the BEMT, vVPM, and their multi-fidelity GP combination. The breakdown of the sample points used to develop the multi-fidelity surrogate is described in Table 1.

Table 1 Test matrix for the three different data sources

DOF	BEMT	vVPM	Experimental Data
Advance Ratio, J	0.4 to 0.7 (20 pts)	$[0.4, 0.5, 0.6, 0.7]$	$[0.4, 0.5, 0.6, 0.7]$
Incidence Angle, α (deg)	0 to 90, (19 pts)	$[0, 30, 60, 90]$	$[0, 30, 60, 90]$

The compiled data for the propeller thrust coefficient and power coefficient are shown in Fig. 5 with the associated uncertainty at each data point. Only a subset of the BEMT data are included in the visualization. Uncertainty information is not a natural output of the two computational methods and were therefore estimated based on previous experience. Uncertainty quantification methods may prove useful as a replacement to the manual uncertainty approximations. In general, the uncertainty associated with both the BEMT and vVPM data increase with the incidence angle. Disregarding certain outliers at higher incidence angles, the uncertainty associated with the vVPM data was, for the most part, lower in magnitude than the uncertainty in the BEMT.

While the developed GPR method is conducive to an adaptive design of experiment approach, we can demonstrate the effectiveness of the overall method by estimating a Gaussian Process using all of the available estimation data from the BEMT and vVPM analyses. Example results of the estimated GP from the multi-fidelity GPR method implemented for the IDEA tool are shown in Fig. 6. The figure shows a 1D slice of the data and the estimated GP model at an advance ratio of 0.6 for both the thrust and power coefficients. From a qualitative perspective, the GP model most closely follows the higher fidelity data, and in the absence of such data, is informed by the lower fidelity data.

Conducting the propeller aerodynamics analysis with only the BEMT would result in sizable errors, most notably at high incidence angles. The multi-fidelity regression, with relatively few samples from the higher fidelity source (vVPM), results in both a lower error with respect to the experimental data and a lower overall uncertainty. Combining a large number of low-fidelity data and a relatively small number of medium-fidelity data via multi-fidelity GPR can enable medium-fidelity predictions at a fraction of the cost. The improved representation of the flow physics with a reduced computational cost is crucial for the analysis of the complex flow interactions exhibited by DEP aircraft concepts (e.g. transition between hover and forward flight).

The procedure for probabilistic database generation presented here, where batch simulations for the various fidelities

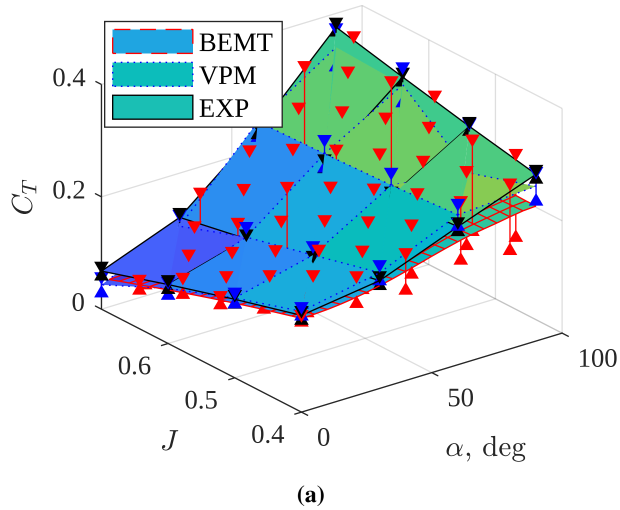


Fig. 5 Propeller thrust coefficient (a) and power coefficient (b) data with associated uncertainty information with respect to advance ratio (J) and incidence angle (α)

were conducted across the input space, could be taken a step further. An adaptive design of experiment framework could be used to selectively sample the input space for maximum benefit. A balance between accuracy and computational cost can be achieved through this approach of sampling the appropriate fidelity only where necessary, reducing the burden on the higher fidelity methods.

In an MDO framework, this approach can improve the fidelity of the aerodynamic modeling at a reduced computational cost for a single iteration. Another possible computational cost savings can be achieved by using information from previous iterations of the optimization procedure. Instead of performing the multi-fidelity analysis from scratch at each iteration, the new probabilistic aerodynamic database could be informed by that of the previous iteration. Extension of an aerodynamic database from one configuration to another of the same design family can reduce the required number of sample points to achieve a desired database uncertainty level.

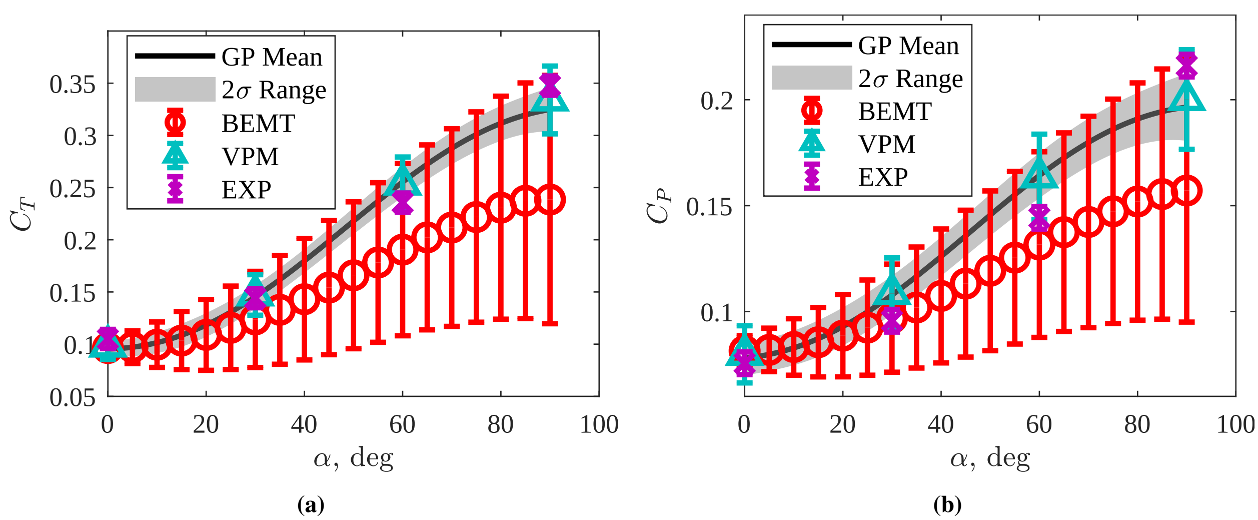


Fig. 6 Slice of the GP results at an advance ratio of 0.6 for the (a) thrust coefficient and (b) power coefficient

IV. Structural Performance and Weight Estimation

Advanced aircraft designs cannot be informed by traditional empirical structural performance estimates. Consequently, accurate weight estimation becomes an issue. In place of the traditional empirical models we employed a component-by-component, loading-driven buildup of the weight estimate. Analysis of the structural performance, due to, for example, the installation of propulsors at various locations along the wing(s), can quickly become a complex multi-disciplinary problem that is often out of the scope of a conceptual aircraft design. Beyond the traditional drivers of the structural performance analysis, for DEP-enabled aircraft it is important to understand the structure design potential and requirements given significant multi-disciplinary interactions. For example, novel control approaches could take advantage of the new degrees of freedom offered by distributed propulsion but the designer must also account for any effects on the structure that the control approach may produce. As with the approach to the aerodynamic analysis, the structural analysis and weight estimation, through a coarse FEA-based analysis, aims to balance accuracy with computational cost.

Employing finite element modeling in the conceptual design of aircraft has several key benefits. Discretization of the structure, in combination with the ability to add or change unique material properties, provides flexibility in the design and a more accurate weight estimation, which can be updated following any design changes to the model. The coupling between weight estimation and component design also grants the ability to optimize the design of the structure for minimal weight while maintaining required structural limits.

The developed structural analysis and weight estimation is a medium- to high-fidelity analysis using coarse-FEA techniques. The FEA capability was developed for a Lift+Cruise DEP-concept aircraft similar to the Boeing/Wisk Cora eVTOL design using ANSYS Mechanical. The OpenVSP model shown in Fig. 7 was exported and used to create the finite element model. The overall process was crafted and conducted such that it may be automated in the future for integration within our multidisciplinary design architecture.

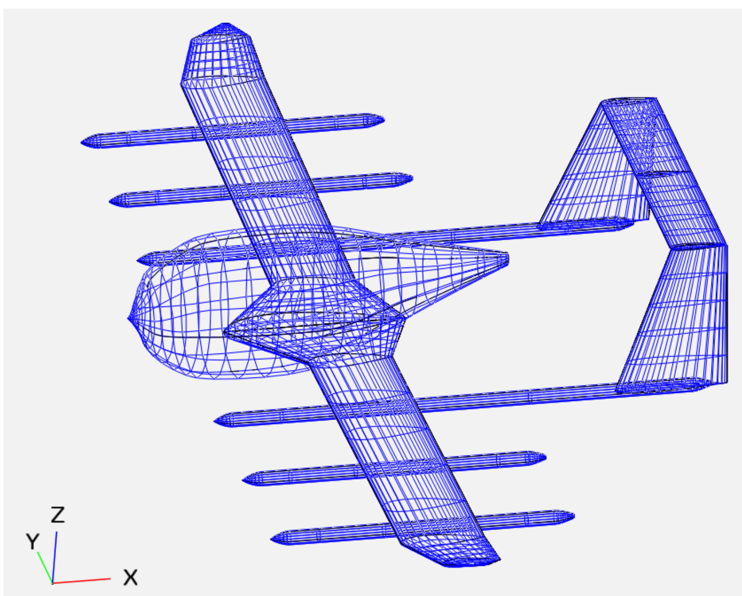


Fig. 7 Aircraft concept model in OpenVSP

The assumptions and modeling details for FEM are described below:

- The FEM included wing structural members such as spars, ribs, and skin.
- For simplification and reduced computational costs, shell elements were used for the fuselage and wing structures. Additionally, point mass elements were applied in the model to consider the structural mass of connection, joints, and accessories.
- Aerodynamic pressure loads from an initial aerodynamic analysis were transferred to the FEM, and static simulations were performed

The mesh was granted material properties, which enabled the automatic output of the estimated structural weight. The spar and rib components of the wing were designated as aluminum 6061. The skin components of this aircraft are made of a specific layered carbon composite, as seen in Fig. 8. ANSYS ACP was used to replicate the desired carbon composite for the structural analysis and weight estimation. Using the parametric design features in ANSYS, the mass of the initial baseline structural model was found to be approximately 450 kg.

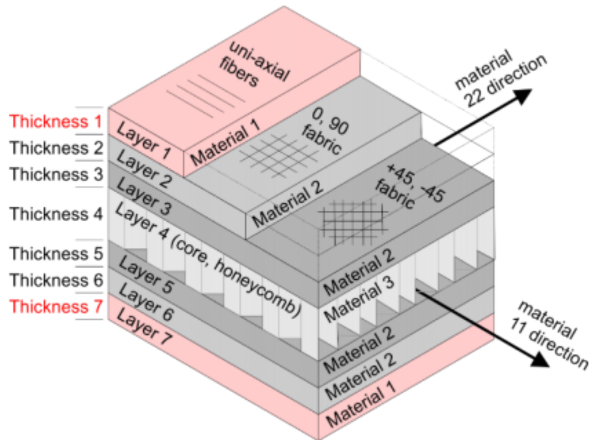


Fig. 8 Carbon composite layup properties [21]

Aerodynamic loads were implemented in the form of pressure loads derived from aerodynamic analysis of the wing at a cruise speed of 110 mph and an altitude of 1,000 ft, as shown in Fig. 9. Example stress fields resulting from a structural analysis are shown in Fig. 10. With these loads defined, the stress distribution can be input into an internal structure sizing optimization scheme.

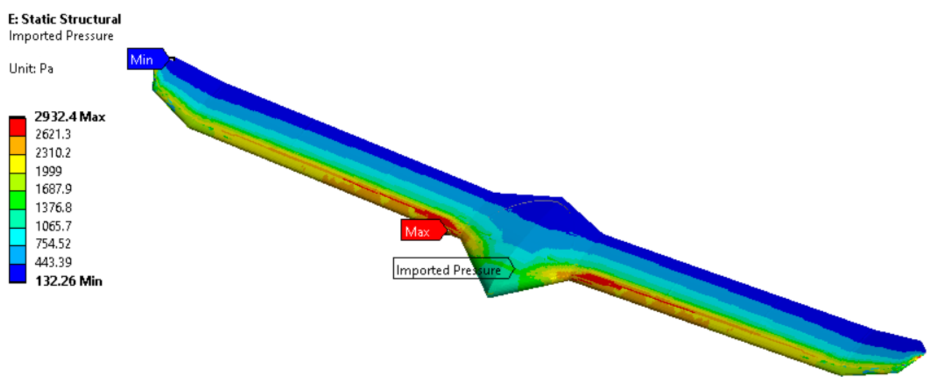


Fig. 9 Aerodynamic pressure loading applied to wing structure

This scheme will control the sizing of internal wing structures, which can be varied according to the stress distribution input. This automatically determines whether the structure is too weak and requires additional strengthening at the cost of more weight, or if the structure is safely above the mechanical limitations and can have some supports reduced in size to reduce weight.

V. Controller Synthesis

In order to incorporate control considerations in the design process, we need to understand the open-loop and closed-loop characteristics of the system. For this purpose, we need to be able to design the controllers for each design candidate automatically within the optimization loop. This process is illustrated in Fig. 11. For each design iteration geometry, the tool performs an aerodynamic analysis and estimates the vehicle inertia to obtain a new flight dynamics model. A suitable controller can then be synthesized, e.g. using standard optimal control methods, using the calculated

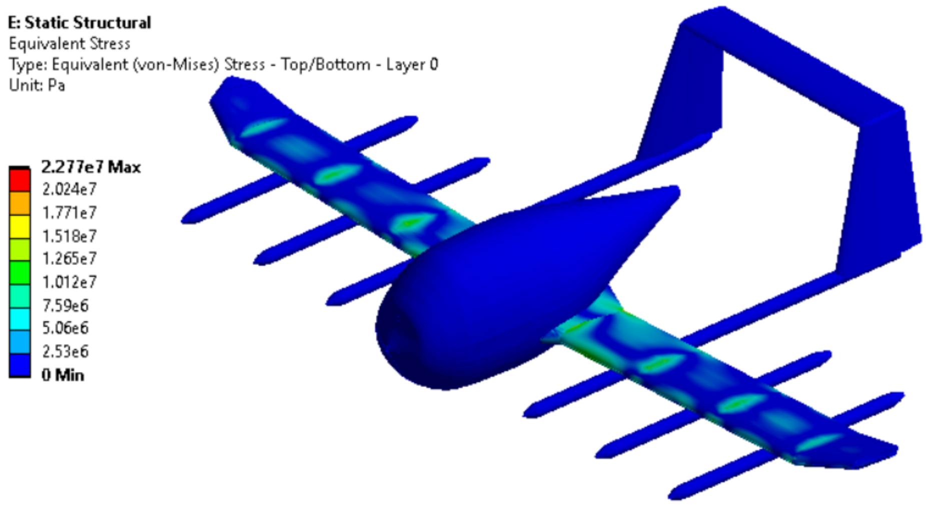


Fig. 10 Static structural analysis results for baseline aircraft concept

dynamic model. Metrics from the evaluation of the closed-loop performance can then become integrated into the system level optimization.

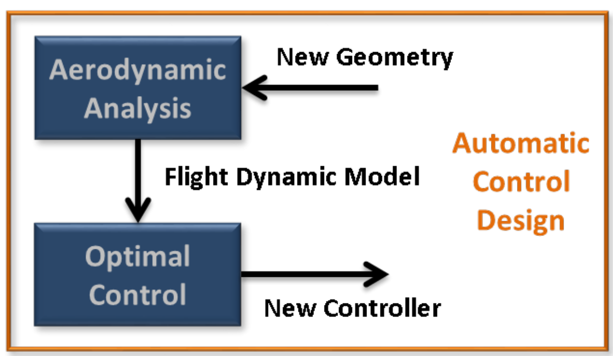


Fig. 11 Automatic controller design process

In this effort, we developed the capability to determine the state space model of the aircraft, given the output from the aerodynamic analysis, and the weight estimation. Estimation of the aircraft inertia was based on the results of the component-weight build-up estimation. The basic process for the development of the flight dynamics model is illustrated in Fig. 12. Specifically, we follow the procedure outline by Schmidt [22] for this purpose.

Our initial investigation focused on the longitudinal dynamics in a cruise condition. The longitudinal flight dynamics, decoupled from the lateral motion, are represented by the equation below.

$$\begin{bmatrix} \dot{V} \\ \dot{\alpha} \\ \dot{q} \\ \dot{\theta} \end{bmatrix} = \begin{bmatrix} D_V & D_\alpha + g & D_q & -g \\ L_V & L_\alpha & L_q + 1 & 0 \\ M_V & M_\alpha & M_q & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} \Delta V \\ \Delta\alpha \\ q \\ \Delta\theta \end{bmatrix} + \begin{bmatrix} D_{elv} & D_{thr} \\ L_{elv} & L_{thr} \\ M_{elv} & M_{thr} \\ 0 & 0 \end{bmatrix} \begin{bmatrix} \Delta\delta_{elv} \\ \Delta\delta_{thr} \end{bmatrix} \tag{3}$$

The dimensional stability and control derivatives are left in a general form and were constructed using numerical perturbations of the states and control inputs. We adopted a simplified model as a starting point for the control development. Besides the extension to full flight envelope controller synthesis, factoring in the rotor dynamics and the coupled rotor-fuselage dynamics is a crucial step towards the creation of a useful tool for conceptual eVTOL design.

For the longitudinal dynamics model, we first consider the open-loop characteristics. An analysis of the initial

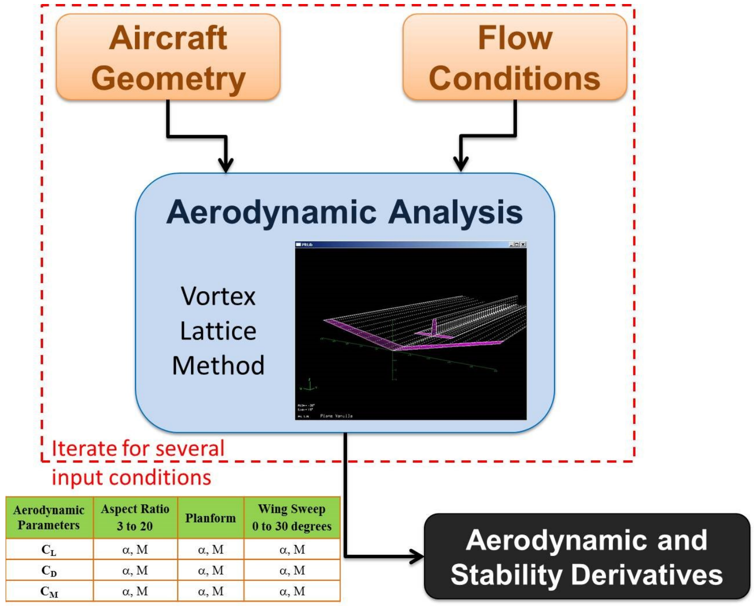


Fig. 12 Schematic of flight dynamic development based on aerodynamic analysis

aircraft configuration found that the open-loop dynamics are unstable. The poles of the open-loop system are listed in Table 2.

Table 2 Open-loop longitudinal model pole locations

#	Pole (rad/seconds)	Damping (seconds)	Frequency (Hz)
1,2	$1.57 \times 10^{-5} \pm 3.12 \times 10^{-3} i$	-5.04×10^{-3}	3.12×10^{-3}
3,4	$-0.768 \pm 2.29i$	0.318	2.41

In order to stabilize the system, we apply the Linear Quadratic Regulation (LQR) method – infinite horizon LQR for finding the control gains for the system. Once we find the controller, we consider the closed-loop step response of the system, as shown in Fig. 13 with the left column of figures corresponding to an elevator step input, and the right column corresponding to a throttle step input. The response is stable and demonstrates the ability of our method to develop reasonable controllers for the system. Currently, we applied the method to Lift+Cruise concept in a cruise condition, which uses a generic throttle command to the thrust propeller and traditional control surface deflections as inputs. In the future, this method can be applied to the hover and transition conditions with the multiple lift propellers as control inputs enabling implementation of novel control designs that leverage the increased control input degrees of freedom.

A variety of controller synthesis methods can be integrated in an automated fashion within the IDEA tool. For now, we investigated the application of LQR for use in the design loop. The LQR method has several parameters that are normally user-specified, such as the state, input, and cross weighting matrices Q, R, and N, respectively. The specification of these parameters and the open-loop system characteristics determine the closed-loop response. Initial implementation of the automated controller synthesis consisted of a fixed specification of the LQR weighting matrices (no cross-weighting matrix) and implemented the guideline provided by [23], which specifies diagonal elements based on the maximum allowable deviations for the state or input. The key to obtaining desired closed-loop behavior using LQR design techniques lies in selecting a suitable performance index and, consequently, the Q and R matrices.

Performance objectives or metrics, based on the closed-loop characteristics and response, can then be calculated and passed as outputs to the aircraft design optimizer. The performance metric outputs can be treated as constraints in the optimization. There are a number of performance metrics that can be used to quantify the suitability of the synthesized controller: the gain and phase margins of the feedback loops, static aerodynamic effectiveness of the control surfaces, handling qualities, gust response, etc. Handling qualities evaluation usually requires a pilot to operate the system, however, there exist quantitative requirements and metrics that can be incorporated into the conceptual and

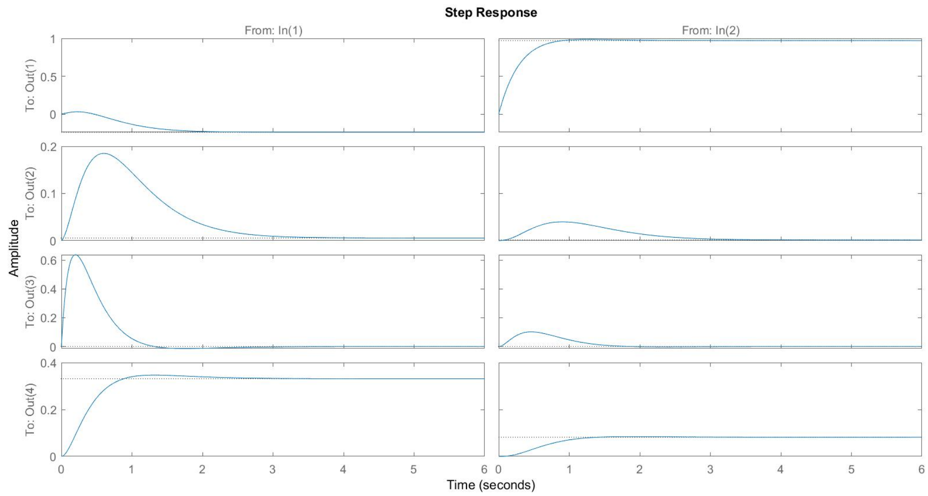


Fig. 13 Closed loop step response of the longitudinal dynamics system

control design processes. Generic handling qualities standards for novel concepts that undergo "conversion" (transition from hover to forward flight) do not currently exist. The standard metrics can be drawn from the aircraft and rotorcraft handling qualities specifications in Refs. [24, 25]. A collection metrics relevant to rotorcraft concepts have been compiled for use in NASA's SIMPLI-FLYD tool [2]. Depending on the aircraft design concept and application, the importance or relevance of these performance metrics can change.

VI. Multidisciplinary Design Architecture

The major focus of this effort is to enable multidisciplinary considerations in the eVTOL design process. The development of the various analyses was in support of this task and we are working towards the ability to incorporate controls, internal structure sizing, multi-fidelity analysis, and acoustics into the system level optimization framework. At this point we have integrated various conceptual level analyses, mainly consisting of the aerodynamics analyses, energy network modeling, and weight estimation, into the MDO architecture. The notional MDO architecture for the IDEA tool is shown in Fig. 14 with the analyses yet to be fully integrated into the architecture grayed out. The FEA-based internal structure sizing optimization and automated controller synthesis are currently standalone analyses.

The software framework for the implementation of the system level optimization was based primarily in Python. The IDEA tool implementation leverages that of the SUAVE software and takes advantage of the variety of optimizers available in Python. The modularity and flexibility of the codebase enables quick integration of tools such as OpenVSP and OpenMDAO, which can expand the capabilities of the IDEA tool. OpenMDAO, in concert with OpenVSP, provides a platform for seamlessly implementing different MDO architectures and enables the use of a wide variety of optimizers, higher fidelity disciplinary analyses (CFD, FEA, etc.), and other tools.

The various analyses discussed in this paper form the foundation of our IDEA tool for use in future MDO studies. The MDO implementation can be effectively understood through a demonstration of the first iteration. The first iteration of the optimizer requires specification of a baseline conceptual design, a mission profile, and the analyses to be performed for the defined mission.

VII. Lift+Cruise Concept Case Study

A. Initial Configuration

The candidate application used throughout the initial development of the IDEA tool is a Lift+Cruise DEP aircraft concept similar to the Wisk Cora design. The Lift+Cruise concept is also considered a 'stopped-rotor' concept, which signifies that the lift-rotors are stopped during certain mission segments, such as cruise. The initial design of this concept is shown in Fig. 15, and was based on publicly available information. Selected high-level design parameters are

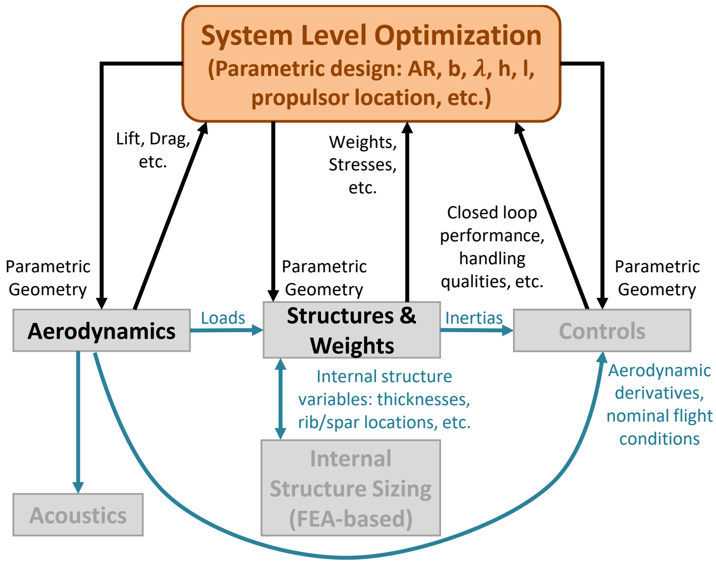


Fig. 14 Initial MDO architecture for IDEA

included in Table 3. The lift-rotors, of which there are twelve, were assumed to have two blades and identical radii, whereas the thrust propeller has three blades. The battery was assumed to be lithium-ion with a pack-level specific energy of 400 W-h/kg.

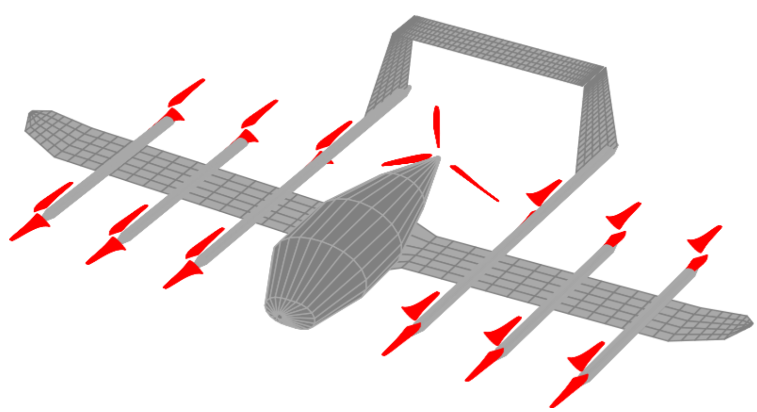


Fig. 15 First iteration of stopped-rotor eVTOL concept

Table 3 High-level design parameters of baseline concept

Design Parameter	Value	Unit
Wingspan, b	36	ft
Aspect Ratio, AR	12	-
Lift-rotor radii, r_{Lift}	2	ft
Thrust-propeller radius, $r_{forward}$	3	ft
Maximum Takeoff Weight	2700	lb
Battery Specific Energy	400	W-h/kg

The initial analyses of the baseline design effectively make up the first iteration of an MDO. Before we can conduct the mission level conceptual analyses, a few components must be designed and sized. An initial specification of the energy network, which includes the rotors, motors, and battery, is necessary for estimating the maximum takeoff weight. The critical design conditions for the lift rotors and thrust propeller are not known a priori. For this first iteration, the design conditions are estimated based on the hover condition and the cruise condition for the lift rotors and thrust propeller, respectively. Later iterations in the MDO can refine the rotor designs to account for the critical conditions of the mission. The electric motors are then designed to meet the expected conditions of their respective rotors. Once the components are designed, we can conduct the component weight build-up estimation process. Because the rotor designs, and other components (e.g. the landing gear mass estimation) are dependent on the maximum takeoff weight, this process must be performed iteratively until the weight estimation converges.

B. Mission Profile Definition

Another important aspect that affects the aircraft design is the mission profile. Sizing and analysis of eVTOL aircraft can greatly differ from that of traditional aircraft. Specification of the mission profile is necessary in order to conduct a complete sizing and analysis and determine the viability of a UAM aircraft concept within a certain domain. An optimal conceptual design is sensitive to the mission profile, and, therefore, the profile must be purposefully designed. In fact, an aircraft concept should be tested across several missions for a more complete and robust design. A number of scenarios and profiles exist in the literature, from those originally proposed by Uber [26] to those designed in a more research-oriented approach [27]. The initial mission profile for analyzing the baseline Lift+Cruise DEP configuration was adapted from a standard UAM mission [27]. The adaptations to the standard mission profile were primarily focused on reducing the requirements on the aircraft design, and included a reduction in the climb and descent rates, and the cruise altitude. The final adapted mission profile is shown in Fig. 16. The reserve cruise segment is commonly included as an additional safety factor that the aircraft design must meet in order to ensure mission success in potential emergency situations.

The IDEA tool has a highly flexible mission solver that allows the user to specify various sequential segments that make up the mission profile. Different mission segments are constructed and may include climb, hover, transition, cruise, descent, and reserve segments. New segment types can easily be extended from these existing mission segments. The mission can be defined in several ways, including setting pre-determined sequential-segment missions in which the cruise distance is specified, or using a variable cruise mission with a fixed end state-of-charge for an electric aircraft mission.

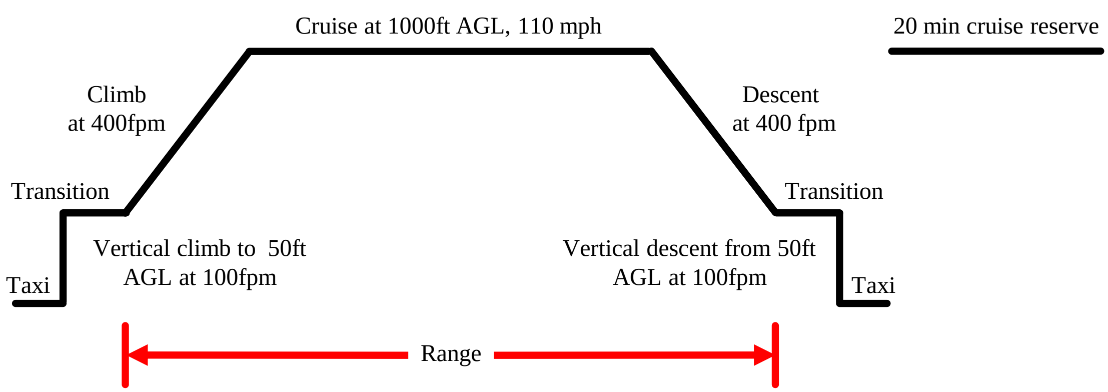
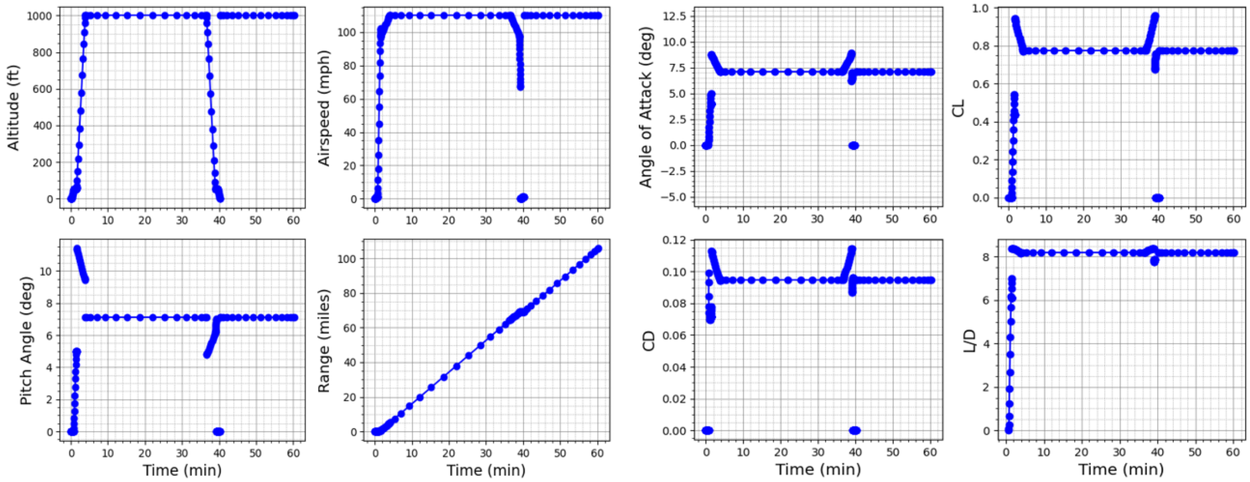


Fig. 16 Definition of UAM mission profile

C. Analysis of Baseline Concept

Once the baseline concept and mission have been fully defined and initialized, we can conduct the various disciplinary analyses and evaluate the performance. Completion of these initial analyses effectively comprise the first iteration of an MDO. Performance metrics can be extracted from these results and passed to the optimizer.

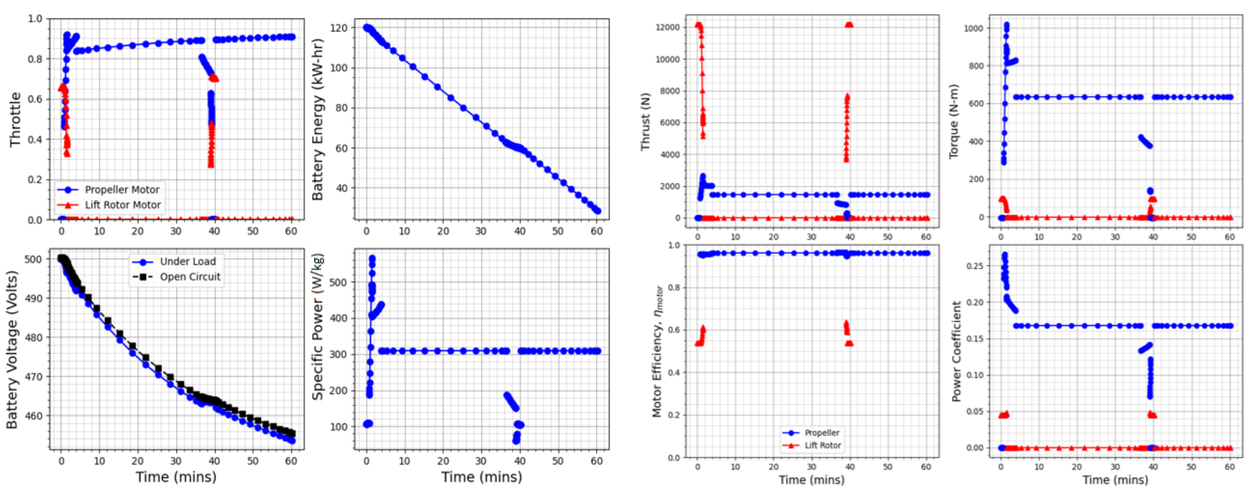
The implementation of the prescribed mission profile is shown in Fig. 17a. The altitude, airspeed, and range follow directly from the specification of the mission. The pitch angle, unless specifically prescribed, is dependent on the aerodynamic performance of the aircraft. Parameters related to the aircraft aerodynamic analysis and performance are shown in Fig. 17b for the provided mission profile. Note that the angle of attack time history was cropped to remove the ±90 degrees for vertical ascent and descent to better visualize the variation during all other mission segments.



(a) (b)

Fig. 17 Time history of (a) the mission profile and (b) the aerodynamic performance

Sample results of the energy network modeling are depicted in Fig. 18a. These results can be evaluated to help refine the design of the components in the energy network, such as the battery, the motors, the electronic speed controllers, etc. Several of the energy network states may be included as constraints in the setup of an MDO. For example, the battery energy should not be completely discharged at the end of the mission and should retain a reserve capacity to both extend the battery life and account for any emergency operations. We can similarly view the results from the propulsor network modeling and evaluate the designs of the lift rotors and thrust propellers, as shown in Fig. 18b.



(a) (b)

Fig. 18 Time history of (a) the energy network and (b) the rotor networks

This initial mission analysis effectively encompasses the first iteration of a multidisciplinary design optimization procedure. A few of the initial sizing procedures were used to bootstrap the aircraft design. The lift rotors and thrust propeller were sized based on assumed critical conditions. After running a mission analysis, the critical design conditions can be identified and drive the rotor design for the next iteration. Based on the results of this initial iteration, there are clear deficiencies that may be improved through an MDO, most notably the lift-rotor design. Detailed evaluation of transition segments, which incorporate aerodynamic modeling to capture the aero-propulsive interactions, within the optimization is an important avenue for further study.

VIII. Conclusion

Conceptual design of eVTOL aircraft must take into account aspects across multiple disciplines. The multi-disciplinary interactions, often left for evaluation after an initial conceptual design, may lead to significant benefits for eVTOL aircraft. In this work we have developed and integrated a number of analyses essential for the design and evaluation of novel concepts. Integration of higher fidelity disciplines through multi-fidelity combination can enable improved designs at lower computational cost. An important consideration, especially within the eVTOL design family, that we have incorporated at the conceptual design stage is the controller synthesis. Incorporating the controller in the design loop can prevent costly redesigns in the later design stages but also bring about novel configurations that take advantage of the new control avenues with distributed electric propulsion. The collection of capabilities we have developed form the foundation for the MDO architecture of our IDEA tool and future MDO studies.

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