Title: Enabling Carbon-free Aviation through High-Fidelity Conceptual Design Phase I Final Report

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Introduction & Motivation

This research was undertaken to address the need for a robust conceptual design tool for unconventional or "next gen" aircraft. Of specific interest is the design of commercial aircraft to reduce or eliminate greenhouse gas emissions through aerodynamic design of the vehicle's shape and the design of hybrid or all-electric power and propulsion systems (which may be tightly integrated into the vehicle's structure). Existing conceptual design tools, which often rely heavily on correlations and fitted historical data, did not provide the flexibility or sufficiently general performance prediction capability to address arbitrary new designs. A fundamentally new software tool was required in order to rapidly evaluate such designs.

The need for new aircraft is readily evident from the cumulative environmental impact of the current global fleet. Commercial aviation is one of the fastest growing sources of greenhouse gas emissions and yet a critical component of the global economic infrastructure. A recent report[13], co-authored by the U.S. Department of Transportation, forecasts global CO_2 emissions due to commercial aviation of 1.5 billion tons per year by 2025, considerably worse than previous predictions of the International Panel on Climate Change[14]. By comparison the entire European Union, some 457 million people, currently emits about 3.1 billion tons of CO_2 annually. The same report found that growth of CO_2 emissions on this scale will comfortably outstrip any gains made by improved technology and ensure that commercial aviation is an even larger contributor to global warming by 2025 than previously thought. In addition to climate change, more than 30 million people will also be subjected to serious aircraft noise by 2025 (despite the anticipated introduction of quieter next-generation jet engines). In 2004 alone, the U.S. government spent roughly $0.5B on sound insulation and land purchases near airports for noise abatement purposes.[25]

Commercial aviation is already an industry economically driven by fuel efficiency. Growth is so rapid that the projections above exist in spite of a 70% increase in industry-wide fuel efficiency over the last four decades. A projected 1.4-3x growth in the number of flights by 2025[15] signals that fundamental technological change is needed to curb greenhouse gas emissions in a significant way without severe economic restrictions. The only path to long-term reductions in greenhouse gas emissions is to power commercial aircraft with a greenhouse-free fuel. By leveraging electricity and / or hydrogen as fuel sources, a sustainable future for the industry is possible. In addition, both the noise pollution and the total cost of operation of a commercial fleet may be considerably reduced, resulting in both economic and additional environmental drivers.

Previous efforts in electric or greenhouse-free aviation have focused on small aircraft with conventional configurations or on hybrid concepts (hydrocarbon-fueled turboelectric)[1,3,5,10,11,16]. This is due primarily to (a) the lack of any viable energy source of sufficient energy density for aviation, and (b) the lack of sufficiently high fidelity, integrated design approaches for fundamentally new concepts such as those planned for this study. Numerous previous studies have shown that a "clean sheet" design approach, in which the propulsion and aircraft systems are simultaneously optimized, yields considerable performance gains even for traditional fuels. Combustion-free propulsion systems widen this design space even further, opening the possibility for dramatic performance gains when high-fidelity tools are used in a multidisciplinary design optimization (MDO) framework. A "clean sheet" design, encompassing all aircraft systems including the performance metrics of unconventional energy sources, is necessary. Our work sought to evaluate not only performance but environmental impact and commercial viability of greenhouse-free aviation, establishing a blueprint for viable near-future energy sources for aviation.

With the fundamental goal enabling a sustainable future for aviation, the Phase I work focused on enabling this transformation in three key ways:

1. Build a conceptual design software environment in which the performance of hybrid and hydrocarbon-free aircraft concepts could be studied through realistic mission conditions.
2. Established realistic performance metrics for all-electric commercial aircraft through high-fidelity design and optimization. The Boeing 737-800 mission profile is chosen as the representative baseline for study (approximately 150 passengers transported a maximum of 3,000 nm). (Single-aisle aircraft will be responsible for a large portion of future aircraft fuel burn: Boeing projects 68% of all new aircraft deliveries through 2031 to be in the single aisle class[2].)
3. Provided a metric for both energy and power density required by an energy storage system to enable competitive operation of the concepts discovered.

Phase I Summary

Consistent with the goals above, the centerpiece of our Phase I efforts was a flexible, easily extensible software framework for the analysis and design of aerospace vehicles. In order to enable revolutionary new aircraft, including those that do not rely on hydrocarbon fuels, a method of conceptual design is required that can accept arbitrary aircraft configurations. Many current software tools for aircraft conceptual design rely upon empirical correlations and other low-fidelity approximations for the propulsion and power system (traditional jet fuel) as well as the architecture of the airframe (fuselage and wing or, in some cases, certain types of blended wing-body.) On the other hand, designing unconventional aircraft configurations featuring integrated, game-changing technologies, including but not limited to hydrocarbon-free concepts, will require the ability to perform conceptual design using both physics-based predictions (higher-fidelity) as well as relevant correlations (lower-fidelity) based on available historical trends. In short, a design tool is required that allows for an arbitrary aerospace vehicle to be designed with an arbitrary level of fidelity in its supporting data.

SUave, Stanford University Aerospace Vehicle Environment (see suave.stanford.edu), was developed in the Aerospace Design Laboratory (ADL) to fulfill this need. SUave is a Python module, a language chosen for its widespread support in the science and engineering communities as well as its exceptional ability to interface between various languages. It is designed as an easy-to-use application programming interface (API) with clearly-understandable syntax accessible to those with minimal Python experience. By design, SUave is intended to be driven by or interfaced with other tools, including numerical optimization frameworks such as NASA's OpenMDAO (also a Python tool.)

SUave's core is a modular set of components than can be assembled and analyzed without having to write any additional software. **Vehicles**, the top-level data structure, are assembled from **Components** that include Wings, Fuselages, Propulsors, etc. These components themselves can be specified at a level chosen by the user to match the fidelity of the available analysis methods. For instance, a component can be described by only the minimal information necessary for completing a low-fidelity approximation of its performance or directly with high-fidelity data and geometry.

Though green aviation is our immediate research application, Vehicles are not limited to aircraft: the class structure in SUave has been created with complete generality. For example, during the construction of the class structure, rotorcraft, UAVs, and even launch vehicles were considered and could, potentially, be analyzed in the same way.

Aerodynamic and mass property information can be generated from simple models within SUave or easily imported from external sources like CFD or wind tunnel results. Similarly, **Missions** are assembled from **Segments**, which consist of a variety of intrinsic types including trimmed cruise, climb, descent, glide, or launch vehicle trajectories. **Propulsors** (which include anything turning stored energy into a force on a Vehicle) are similarly constructed from Elements that include compressors, turbines, burners, motors, fans, and so on. This flexibility is key to our research's application of SUave: hybrid and combustion-free propulsion concepts embedded in a tightly integrated vehicle design. To accommodate high-lift devices and other in-flight changes experienced by a Vehicle, **Configurations** can be defined for the same Vehicle and assigned to appropriate Segments. The syntax sample shown below in Fig. 1 provides a highly abbreviated example of some of this functionality.

Vehicles and Missions are ultimately Python objects and can hence be used as indexable data types within arrays. In implementing SUave, care was taken to keep the Mission and Vehicle data orthogonal to one another. This allows a given Vehicle to be simulated in many different missions or many different Vehicles to fly the same Mission. This arrangement of the core data structures makes off-nominal mission performance and performance comparisons between different candidate designs as easy and as flexible as possible. Off-nominal performance is of particular importance in new and / or unconventional configurations without a history of accumulated data available for conceptual design.

Consistent with SUave's development philosophy regarding interfacing with design and optimization tools, sensitivity analysis via automatic differentiation (AD) has also been integrated. This functionality provides both internal and external advantages in performance and flexibility. Internally, AD provides a fast and accurate means for obtaining gradients required by SUave's core Mission solver (details below) that accelerates solution times. Externally, it provides an automatic method for users to obtain sensitivities of performance metrics of interest with respect to design parameters.

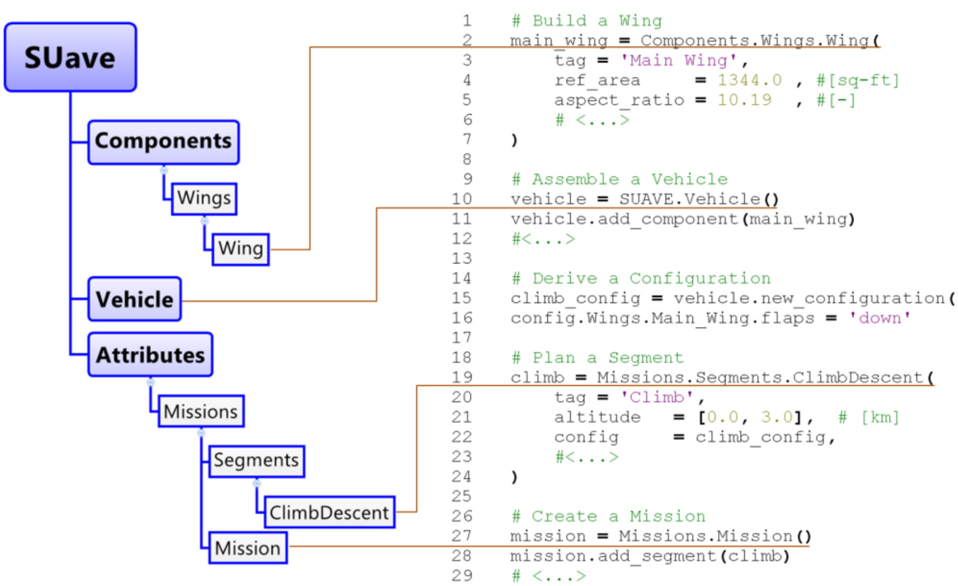

Figure 1. Abbreviated class diagram and sample syntax demonstrating SUave's modular construction and flexibility.

SUave's core functionality is the evaluation of the performance of a given Vehicle through a given Mission. In order to support arbitrary levels of fidelity, this is done by integrating the relevant equations of motion directly, making the simulation of a Mission independent of the level of fidelity of the supporting data. This is performed on a Segment-by-Segment basis via a pseudospectral collocation method and relies on the user-provided or internally calculated mass properties, aerodynamic, and propulsion system data. After a Mission solution is completed, the resulting state data is then post-processed into a wide variety of performance metrics of interest to the user or optimizer, including sensitivity information. These include, but are not limited to, total mass, range, specific fuel or energy consumption, specific range, etc. A sample of results from a SUave for the analysis of a nominal Boeing 737-800 mission is shown below in Fig. 2.

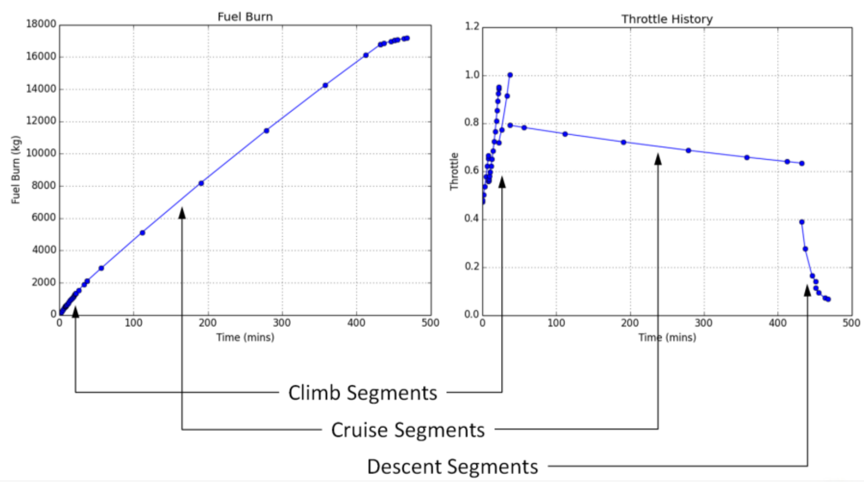

Figure 2. Sample results from a six-segment Boeing 737-800 Mission simulated in SUave, including three climb Segments, one trimmed cruise Segment, and two descent Segments. Total (integrated) fuel consumption and throttle history are plotted.

With the core functionality in place, SUave was verified via testing against two very different, well-known aircraft for which data is publicly available or for which our team has had considerable experience: the Cessna 172R and the Boeing 737-800. In the former case, the results produced by SUave were compared with data published by Cessna, including ceiling, maximum climb rate, and maximum cruise speed. In the latter case, results were compared to those obtained in previous studies that we have participated in with independent analysis tools. The results of the 737-800 comparison are summarized below in Table 1.

Parameter	EDS	PASS	TASOPT (no winglets)	SUave
Cruise Mach	0.78	0.78	0.78	0.78
Mission Range (nm)	2,950	2,950	2,950	2,950
R1 Range (nm)	2,092.4	2,124	2,230	2,124
Payload (lbs)	36,540	36,540	36,540	36,540
Block fuel (lbs)(mission)	38,180	38,422	41,238	39,556
Beginning Cruise Altitude (ft)	35,000	35,000	35,000	35,000
Climb fuel burn (lbs)	4,012	4,186	4,522	4,601
Cruise fuel burn (lbs)	32,280	33,160	35,912	32,352
Approach fuel burn (lbs)	1,194	1,076	804	890

Table 1. Verification and validation data for SUave, showing a comparison of results for a nominal Boeing 737-800 Mission against other conceptual design software tools.

The second major portion of our Phase I research involved utilizing SUave, in addition to ADL's computational fluid dynamics (CFD) and aerodynamic shape design software suite, SU^2, to evaluate two different carbon-free commercial aircraft designs. Given the existing knowledge base, the Boeing 737-800 was chosen as the baseline aircraft (and mission) for comparison. It was assumed that airline operations require that the cruise speed, cruise altitude, passenger capacity, and cargo capacity (mass and volume) not be changed. Numerous combinations of energy sources were considered, including many types of batteries and hydrogen fuel cells. Ultimately, the volume constraints of the aircraft geometry made liquid hydrogen the best source of primary energy storage with a smaller battery storage capability for backup, emergency, and potentially recharging purposes. Superconducting motors and ducted fans were used for propulsion, drawing from the synergy provided for superconducting materials by a cryogenic fuel. Aerodynamic data was provided by SU^2 and mass data was estimated via direct three-dimensional modeling in CAD and correlations where necessary. Propulsion modeling, in this case, was simple given the choice of a number of independent ducted fans. Both concepts meet the NASA N+3 noise, pollution, and equivalent fuel burn requirements per the technical objective of our Phase I proposal.

The first concept, shown in Fig. 3 below, is based on the 737-800's original shape. The fuselage has been lengthened to accommodate the extra volume required for hydrogen fuel tanks. The tail section was modified to place three fans between the tails and the wing was extended into a joined-wing design to accommodate the extra lift required with improved induced drag characteristics. Propellant is stored in both the wings and lower fuselage (below cabin seating area.) A total of nine superconducting motor + fan units were required to meet all the thrust requirements for liftoff and climb. In analyzing the mission it was assumed that all fans throttle evenly for simplicity, though it may be advantageous to simply deactivate some units in cruise or even brake (recharge) some units during descent and landing to provide additional drag and energy recovery.

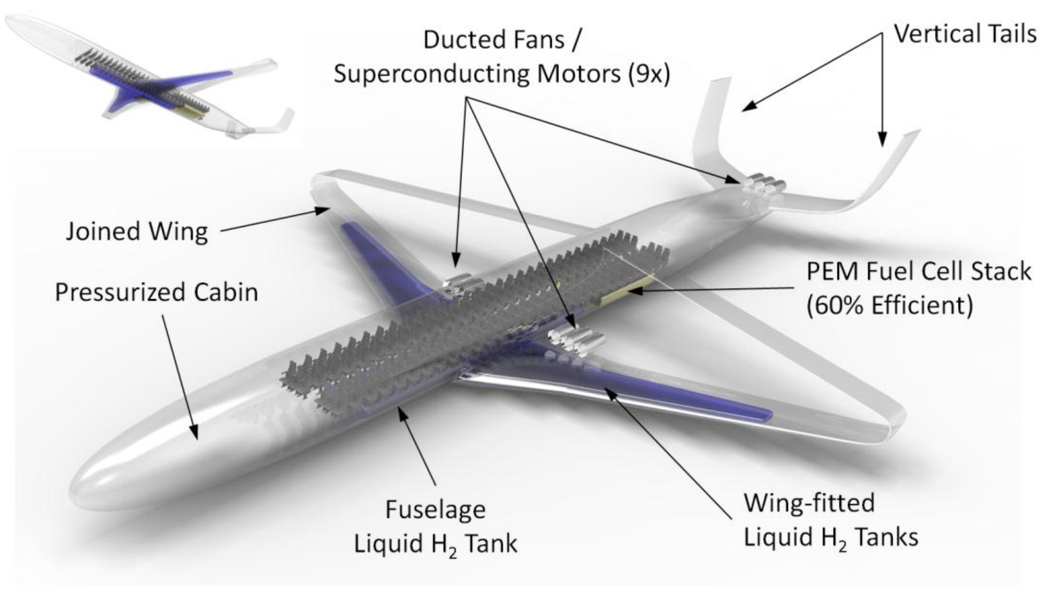

Figure 3. First aircraft concept based on liquid H_2 and PEM fuel cells showing major subsystems, key sources of mass, and single-aisle seating arrangement for 180 passengers. Lower view showing detail of fuselage-embedded propellant tank in upper right.

The second concept has a considerably different geometry with a blended wing-body (BWB) external shape enclosing a traditional pressurized cabin as shown in Fig. 4 below. The BWB geometry allows for greater internal volume that, in turn, allows for more efficient storage of the hydrogen propellant. All nine superconducting motor + fan Propulsors are located between the tails in order to utilize boundary layer ingestion (BLI) for improved propulsion system performance. Additionally, this concept increases the cargo volume available, but note that no detailed layout of internal structure was performed for the purposes of conceptual design. With the additional internal volume available, numerous different seating arrangements are available. The traditional single-aisle arrangement was chosen for consistency with the 737-800 in passenger comfort and to minimize the cabin pressurized volume. While the propellant, propellant tanks, fuels cells, batteries, and motors were modeled explicitly with data provided by our partners or from published, off-the-shelf technology, the primary structural mass was estimated from correlations. This is an area of fidelity we plan to improve considerably in Phase II.

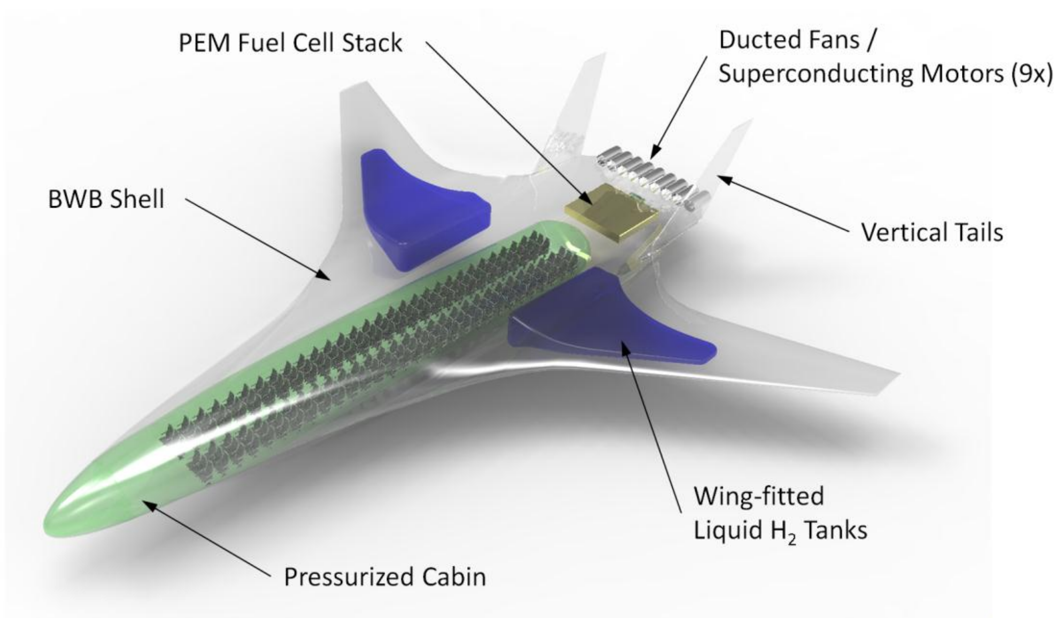

Figure 4. Second aircraft concept based on liquid H_2 and PEM fuel cells showing major subsystems, key sources of mass, and single-aisle seating arrangement for 180 passengers. (Internal primary structure not shown.)

The final portion of Phase I efforts included documenting and packaging SUave as an open-source Python module for use by NASA and the aerospace community at large. This involved online (wiki style, hosted by Stanford) and PDF (downloadable) documentation, including a user's guide, technical reference, and example models with tutorials. The SUave module utilizes the standard Python deployment already used by a large number of existing Python packages. Pre-built installers are available for Windows platforms in addition to standard distutils (command line) setup tools for Linux and Mac platforms. Currently, SUave version 1.0.2 and corresponding documentation (which is still being authored and edited) at suave.stanford.edu. Conditioned on available funding for this research, we plan to continue active support, development, and documentation of SUave with an annual major version release cycle and quarterly minor version release cycle.

Corporate Partners

Our Phase I corporate partners included:

- ✓ Winfried Wilcke, Senior Manager, **IBM Battery 500 Project** focusing on lithium-air battery technology (returning),
- ✓ Bruce Gamble and Glenn Driscoll, **American Superconductor**, focusing on superconducting materials and machinery (returning),
- ✓ Tarik Orra, Carlos Ilario, and J. Coura, **Embraer**, focusing on conceptual design of next-gen aircraft and collaborating on SUave software development.

Technical Impacts & Integration into NASA / ARMD Research Efforts

A significant portion of NASA ARMD programs is devoted to the development of future aircraft concepts that integrate advanced technologies into novel/revolutionary configurations in order to assess the potential impact of such technologies and guide future research investments. However, given the nature of the targeted configurations and technologies, when we continue to use existing conceptual design tools based on historical correlations derived from tube-and-wing aircraft we lack the fidelity required to ascertain the true potential of the technologies and configurations considered. The SUave environment is intended to incorporate the most relevant physics for these future designs (weight estimation, advanced aerodynamics, propulsion/airframe integration, etc.), enabling us to draw design conclusions with a much higher degree of certainty. Such capabilities offer the possibility of better understanding the realizability of NASA's future goals (for N+X designs) and of guiding future research efforts. Because of the open-source philosophy followed in the development of SUave, the environment can readily be integrated into NASA's internal research processes. Moreover, since SUave has been built from the ground up (in the Python language) so that seamless integration with the OpenMDAO framework is possible (currently being explored), and OpenMDAO is a program developed at NASA, we believe the integration could be carried out more easily. Finally, initial discussions have suggested that portions of existing NASA sizing / design tools (such as FLOPS, ANOPP, NPSS and others) could be made compatible with the SUave infrastructure, enabling the use of our tool without the need for costly validation of new predictive strategies.

Dissemination & Distribution

We disseminate our research in two ways: publishing SUave as an open-source tool and publishing scientific papers discussing SUave's capabilities, the design / sizing process and the results of our conceptual, carbon-free designs. Based on our experience with SU^2 (an open-source CFD and shape design suite) we have found that a well-supported, well-documented, open-source software tool is a very effective way to both engage the aerospace community and disseminate research – in many cases more effective than technical papers. In addition to aerospace researchers and professionals, SUave should be accessible to students in undergraduate and graduate aircraft design courses. If funding is available to refine SUave and its documentation, we plan on conducting a workshop at an AIAA conference to provide a hands-on demonstration of the software in conjunction with some technical papers on optimized carbon-free aircraft designs produced with SUave. It is our hope this open-source approach fosters a community that contributes to SUave's continued development in the future. A short article on this research has been published in the Stanford Energy Journal which can be read here.

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