Coupled Aero-Structural-Propulsion Design of an Ultra-Light, Highly Flexible Aircraft

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The Fundamental Aeronautics Program has identified **Ultra Efficient Commercial Vehicles** as a key research thrust. A number of concepts have been proposed along those lines, such as the MIT D8 double-bubble and the Boeing SUGAR-High truss-braced wing. These aircraft rely on very high-aspect ratio wings to help achieve very low energy consumption. Ultra-light, long endurance, solar sensorcraft being proposed by companies such as General Atomics and Scaled Composites share a similar approach to meeting energy goals by leveraging highly flexible wings. This begs the question, **“"How does aircraft design change to take full advantage of highly flexible structures?”** The Vision 2030 CFD study also highlights the design of highly flexible wings as a modeling grand challenge problem. That study specifically highlights the need for highly multidisciplinary, tightly coupled design process with high fidelity tools to address this grand challenge.

Aero-Velo, the team that won the Sikorski Human Powered Helicopter Prize in 2013 and flew the a the first human powered ornithopter in 2010, is planning to build a new aircraft to attempt the Kremer Marathon Challenge; fly a human powered aircraft 26.1 miles in under 1 hour. Human powered aircraft demand the absolute minimum weight and maximum energy efficiency, so they invariably possess ultra-light highly flexible wings. To keep weight down structures are intentionally designed on the edge of failure. This provides an unparallelled opportunity to investigate the question, **“How can structural health monitoring technologies be used to enable lighter weight structures?”**, to address the **Real-Time System-Wide Safety Assurance** thrust**.**

NASA has been invited to participate in the design and flight testing of this aircraft. This proposal provides a summary of how NASA can contribute our expertise in multidisciplinary design to this unique opportunity.

Objectives and Technical Approach for Phase 1

The primary objective of this work is to design, test, and fly a human powered aircraft, capable of flying 26.1 miles in under 1 hour. Stanfords SU2 CFD tool, will be used for the aerodynamic analyses of both the wing and the propellers. SU2 has been successfully applied to the design of propellor systems[1]and has support for actuator disk boundary conditions that will be needed to implement the coupled wing-propellor design process. It has been demonstrated to work in the low Mach conditions that will be seen by this aircraft[2]. It also provides adjoint derivatives which are fundamental to the application of state-of-the-art gradient based design optimization methods.

The structural modeling will be performed with Toolkit for Analysis and of Composite Structures (TACS). TACS has the necessary advanced capabilities such as adjoint derivatives and efficient load and displacement transfer to enable coupled aero-structural design[3].

NASA Glenn Research Center will build the couple all the analysis tools using the OpenMDAO framework[4]. A design optimization will be performed to minimize the power required to fly the aircraft over the defined mission. A final report will be produced, and made publicly available via the NASA website and the Aero-Velo website, detailing the design process employed as well as the final design of the aircraft. The design will be completely open and disseminated publicly without any usage restrictions.

NASA Armstrong Flight Research Center will play a key role in the collaboration by both facilitating the actual flight testing of the aircraft and providing the Compact Fiber Optic Strain Sensors (CFOSS) that will be used to implement the real time health monitoring and to collect the vital structural validation data.

All work will be performed in close collaboration with the Aero-Velo team. They will be responsible for all construction as well as all flights associated with the marathon challenge attempt. After the attempt has been made, NASA will be given access to the aircraft to perform additional test flights to collect data. Aero-Velo has already committed to using OpenMDAO as their design platform for their marathon airplane effort and has been communicating with the PI for this effort, to deploy it inside their design team.

Innovative and Novel Aspects of Research

The nature of the highly flexible wing on this human powered aircraft will demand the use of non-linear structural models. A fully coupled non-linear structural, aerodynamic modeling method will represent a significant advancement in the state-of-the-art for aero-structural design. By including the aerodynamic design for the propellor as well, this work will demonstrate the benefits of more highly coupled convergent multidisciplinary design to overall aircraft performance.

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[1] Economon, Thomas D, Francisco Palacios, and Juan J Alonso. "A viscous continuous adjoint approach for the design of rotating engineering applications." *AIAA Paper* 2580 (2013): 24-27.
[2] Palacios, Francisco et al. "Stanford University Unstructured (SU2): An open-source integrated computational environment for multi-physics simulation and design." *AIAA Paper* 287 (2013): 2013.
[3] Kenway, Gaetan KW, Graeme J Kennedy, and Joaquim RRA Martins. "Scalable parallel approach for high-fidelity steady-state aeroelastic analysis and adjoint derivative computations." *AIAA Journal* 52.5 (2014): 935-951.
[4] Heath, Christopher, and Justin Gray. "OpenMDAO: Framework for flexible multidisciplinary design, analysis and optimization methods." *Proceedings of the 53rd AIAA Structures, Structural Dynamics and Materials Conference, Honolulu, HI* Apr. 2012.

In addition the Aero-Velo team will be building and testing their aircraft in the spring of 2015, with the goal of being ready to attempt the marathon challenge in July of 2015. This presents NASA with the unique opportunity to participate in an low-cost and extremely rapid design effort which culminates in actual test flights within a single year. The rapid design, build, test, re-design iteration cycle is an unparalleled opportunity to validate our design codes and methodology while applying them to an actual aircraft design effort.

Potential Impacts if Challenges are Met

The Kremer marathon aviation prize was established in 1959, and has remained unawarded for over 50 years. A successful challenge flight will represent a significant, high-visibility aviation achievement. NASA is uniquely suited to play a pivotal role in such a successful flight, and its success would raise significant awareness of the value of NASA's leadership in the field of cutting edge multidisciplinary aircraft design.

There is also tremendous value in the validation data that will be collected. Due to the extreme limitations on structural weight, it is common for structural failures to occur during the testing and development of human powered aircraft. This will provide the opportunity to apply real time health monitoring technologies in critical load scenarios during flight. The aerodynamic data collected will also be used to validate Stanfords SU2 code, which will enable its future application to the design of huge array of low-speed unmanned autonomous aircraft.

Work Plan Summary

- Develop parametric geometry model of airframe and propellor	11/2014
- Build structural model for airframe in TACS	12/2014
- Build aerodynamic models of propellor and airframe in SU2	01/2015
- Deliver 6 month progress report	03/2015
- Perform design optimization in OpenMDAO	02/2015 to 06/2015
- Perform test flights with airplane	05/2015 to 09/2015
- Deliver final design report	10/2015

Total proposed budget

1 FTE, Glenn Research Center	$175k
1 FTE, Armstrong Flight Research Center	$175k
Flight Testing	$50k
WYE Computer Science Support	$150k
GaTech TACS Support	$100k
Stanford SU2 Support	$100k
Total:	**$750k**