ISABE-2015-20286

A New Sizing and Synthesis Environment for the Design and Assessment of Advanced Hybrid and Electric Aircraft Propulsion Systems

Christopher A. Perullo, Jimmy Tai, Dimitri N. Mavris
Georgia Institute of Technology, USA

Abstract

Recent studies have shown great promise in transitioning the fields of hybrid and turbo-electric propulsion technology from the automotive field into commercial aerospace. While several high quality studies have been produced in recent years that shed light on both the potential benefits and challenges associated with hybrid electric aircraft propulsion technology, they are often performed using disparate tool sets and legacy tools that cannot adequately account for the highly coupled nature of hybrid electric propulsion systems. To take full advantage of the new design space afforded by hybrid propulsion systems, a new sizing and synthesis process is needed.

Researchers at Georgia Tech have developed a new toolset that carries the trust of existing design and analysis tools, such as the Numerical Propulsion System Simulation (NPSS), into the hybrid electric discipline. This new toolset, the Georgia Tech Hybrid Electric Analysis Tool (or GT-HEAT) contains public domain extensions to the basic NPSS propulsion modeling core. These transparent, easily shareable extensions include integrated airframe, power distribution, motor / generator, and energy storage models. GT-HEAT contains the ability to examine steady state, dynamic, and transient effects of the gas turbine, energy storage, and aircraft systems in an integrated manner to perform a more representative system design and assessment early in the design phase. This paper presents an overview of the tool's architecture, information on the public domain modeling methods, specific application examples, and current active areas of research.

Nomenclature

MDAO	*Multidisciplinary Design Analysis and Optimization*
TOGW	*Takeoff Gross Weight*
NPSS	*Numerical Propulsion System Simulation*
C.G.	*Center of Gravity*
TBW	*Truss Braced Wing*

Introduction

As traditional air-breathing engine technology matures, incremental improvements in efficiency and performance are becoming more costly. While great strides have been made in improving the traditional two/three spool separate flow turbofan in recent years with the advent of the geared turbofan and new lightweight, high temperature materials, there are limitations in improvements of the thermal efficiency due to aircraft installation constraints (Zimbrick, 1990).

To overcome some of the more familiar size, weight, and performance constraints, engineers have turned to adaptive technologies on both the airframe and engine. Such technologies open up an entirely new operational space by allowing the system, whether aircraft or engine, to be aware of its state and adjust accordingly. Adaptive technologies allow the airframe and engine systems and subsystems to adjust for changes in performance due to degradation and optimize their operation when away from their respective design points. Some examples of these technologies include adaptive trailing edges, integrated aircraft-engine flight management/control systems, and engine performance retention technologies (Urnes (2014), Rosenberg (1988), Yonke (1985)). More disruptive examples of adaptive technologies include hybrid electric and turbo-electric (distributed) propulsion (Bradley (2011), Kim (2013)). In essence such adaptive, or disruptive, technologies can be defined as *any feature of the engine or aircraft that contains one or more state dependent, independently controlled variable(s) that can be optimized throughout the mission*. This state dependency means that optimization is forced to become an activity that occurs inside the sizing / mission analysis process rather than an externally driven process, which is more noticeable when the conventional MDAO process for aircraft is illustrated in Figure 1.

The traditional MDAO sizing and synthesis process makes the implicit assumption that the various systems (i.e., engine and airframe) can be sized independently, or at least loosely joined, through the use of coupling variables such as design thrust and engine weight. In the traditional sizing and synthesis process initial guesses are used to set coupling and sizing variables such as takeoff gross weight (TOGW) and engine design thrust. The initial guesses are set from experience; the aircraft analysis module then predicts aerodynamics and weight distributions while the engine analysis module sizes the engine and produces engine performance tables across the flight envelope of Mach, altitude, and power setting. The vehicle is then 'flown' through a mission analysis with the assumption that lift must equal weight and thrust must equal drag (accounting for any changes in altitude). Using the predicted aerodynamics, the weight and flight conditions are used to estimate drag, which in turn provides the required thrust. The required thrust is then used with the pre-

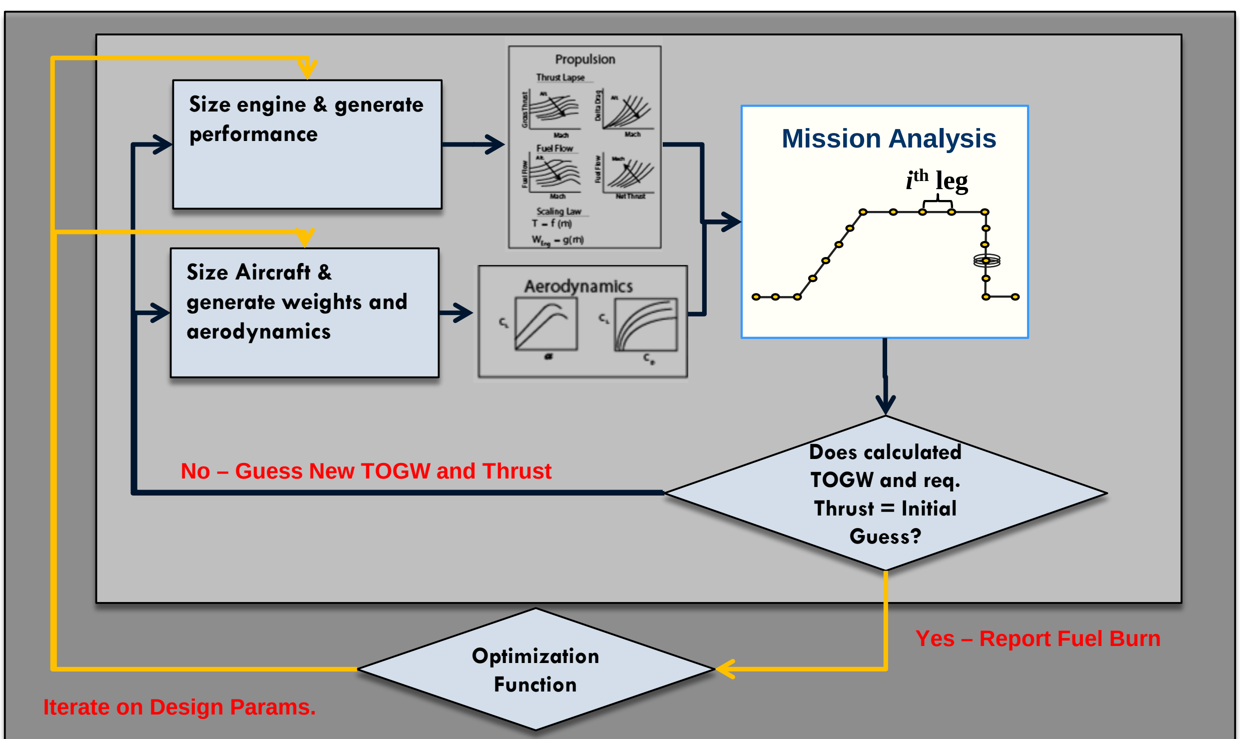

Figure 1: Traditional MDAO Process (Optimizer External to Analysis)

generated engine performance tables to estimate fuel burn for that point in the mission analysis. This continues for a discretized mission until total vehicle fuel burn is calculated. If the vehicle or engine is over-sized for the specified sizing mission, adjustments are made to TOGW or design thrust until a closed solution is found. This iterative process only finds a closed solution. In order to find an optimal one, an external optimizer is needed to iterate on design parameters such as aspect ratio or fan pressure ratio. This general MDAO arrangement has been used extensively and successfully for tens or even hundreds of coupling variables through the use of various distributed arrangements (Martins, 2013).

To demonstrate how the conventional, iterative process breaks down for adaptive or state dependent, consider the sizing scenario presented in Figure 1 for the case of a hybrid-electric propulsion system such as the hFan concept presented by GE and Boeing (Bradley, 2011). In such a system, a motor in the engine tail cone is attached to the low pressure (fan) shaft of a traditional separate flow turbofan engine. Fan propulsive power is provided through a combination of high temperature gas generated by the core and expanded through the low pressure turbine and torque applied through the electric motor. The motor is powered through battery storage present within the aircraft. There are an infinite number of combinations of core power and electrical power that will produce the same thrust; however, only one combination will result in optimal energy consumption over the course of the mission. As a result, the energy split between the gas turbine core and electric motor must be considered as an optimization variable *at every discretized mission point*, represented by the thick, blue arrow in Figure 2.

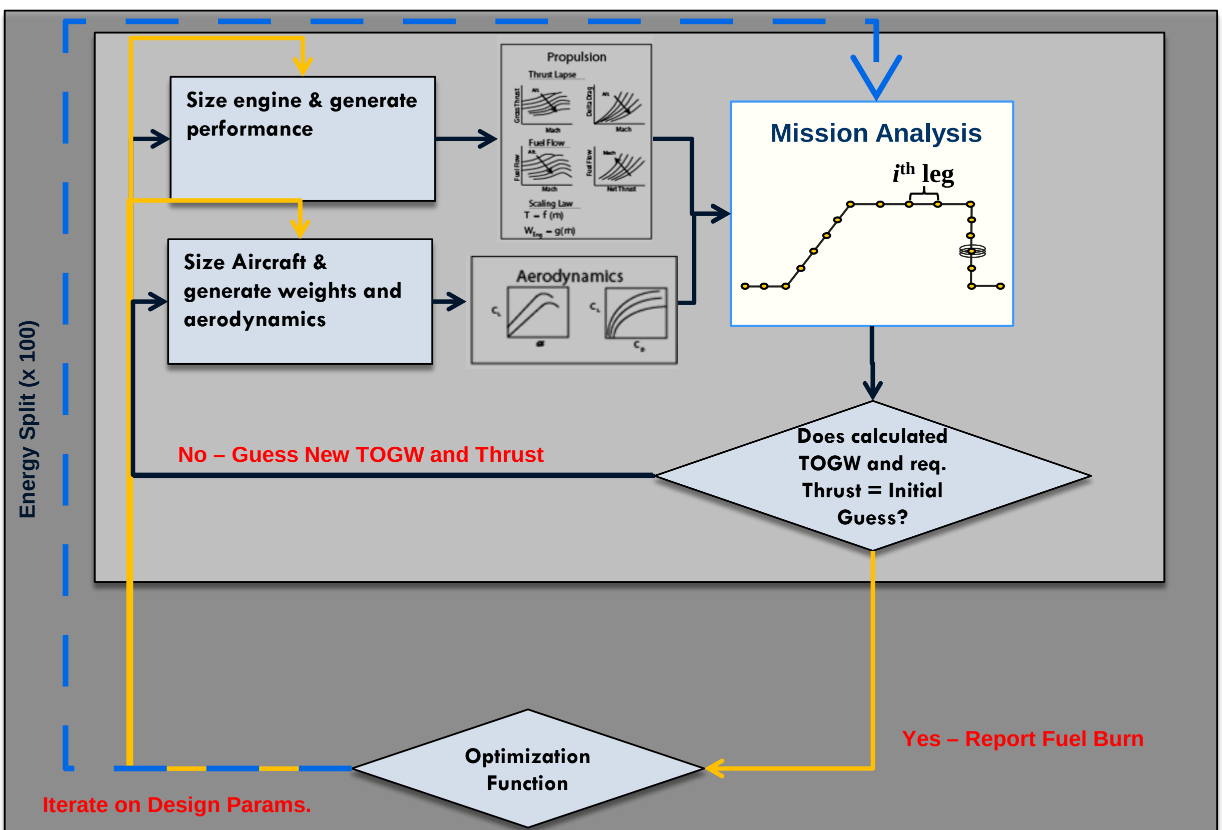

Figure 2: Traditional MDAO Process Applied to Adaptive Technology

If there are 100 discretized mission analysis points, then the optimizer in Figure 2 must now optimize the gas turbine / electrical energy usage for 100 additional variables including the additional design parameters. It is not hard to see how this problem becomes intractable as more adaptive, state-dependent technologies are added to the system. This issue is a likely occurrence as engineers use adaptive technology and more electric propulsion to extract every last bit of efficiency out of traditional architectures. While the numerical efficiency of the problem posed in Figure 2 could be improved through the use of a local mission optimizer or path-optimization techniques as proposed in (Perullo, 2014) the addition of adaptive technologies, when designed in the traditional MDAO framework, requires the engine performance or vehicle aerodynamics tables to include *a new dimension for every conceivable operating state of the technology*. This is a result of running analysis modules sequentially; the first module has no information on how it will be used by a subsequent one. Therefore, every possible usage scenario must be analyzed and passed to the subsequent analysis block in order to ensure convergence. As the number of technologies increases, so does the analysis time due to generation of a significant amount of additional, mostly unused data.

In conclusion, while external iteration may be appropriate for a few adaptive technologies, the problem becomes more unmanageable when multiple adaptive, state-dependent technologies are added to the system. In fact, any designs in which the engine and airframe are closely coupled require an integrated analysis in order to wholly quantify trades and performance benefits. As such a new modeling framework is needed that builds upon existing, trusted design and analysis tools while enabling coupling in an integrated, rather than iterative fashion. Challenges with using existing tools to attempt to assess adaptive technologies and integrated propulsion-airframe technologies include:

- Engine performance and boundary conditions must be assumed when engine is analyzed, before any vehicle sizing takes place;
- Adaptive technologies use strategy may change throughout a mission. This path dependency requires inline optimization with vehicle mission analysis;
- Legacy tools are often written in different languages and are not suitable for direct communication (i.e., they require external fixed point iteration to achieve a closed solution);
- Optimization is performed outside of the analysis portion of the design code.

New Modeling Framework

Modeling and Simulation Requirements

The aforementioned challenges establish that a new design framework is needed to evaluate adaptive and more electric propulsion technologies in a truly integrated manner within the conceptual design phase. First, one must establish the goals and objectives of such an environment. Since the aforementioned technologies represent a rapidly evolving field of study, several factors should be taken into consideration when creating a new conceptual design framework:

- Trust and availability of existing tools
- Flexibility of existing tools to model new, unforeseen technologies
- Ability to create both open-source and proprietary tool analysis modules

- Ease of integration with existing optimization frameworks
- Ability to interact with legacy tools of varying fidelity when required
- Ease of transfer between academic and industrial partners
- Ability to create open source modules to share with the community

The Numerical Propulsion System Simulation (NPSS) software has been selected as the backbone for this analysis (Evans, 1998). In addition to being the industry standard propulsion modeling tool (enabling common development and easy model transfer between propulsion and airframe OEMs), NPSS contains an advanced feature set including zooming ability and the ability to create both open source and compiled, proprietary analysis modules. Furthermore, advanced aircraft mission performance analysis features have already been created within NPSS (Kestner, 2012). This allows for the engine and airframe to 'talk' in real time as the mission is flown. While a seemingly simple feature, this ability allows for the tight level of integration required. However, the NPSS aircraft mission analysis toolset does not currently provide provisions for aircraft sizing or drag/weight prediction. These features can be integrated through the GT-HEAT, which is an open source extension to NPSS. GT-HEAT is a modular framework which can be customized on a per-user basis. While NPSS is itself a commercial tool, the GT-HEAT framework is built on top of it and can be modified in an open source manner for individual applications. The following section provides a more comprehensive overview of the modeling framework.

Development Roadmap

The primary goal of GT-HEAT is not to create new analysis codes from scratch, but rather to bring together existing, trusted tools (with augmentation) to allow for the design and assessment of advanced configurations while accounting for hybrid, electric, and adaptive technologies. This is achieved through the use of modular, open-source environment building upon the native NPSS toolset and extending the work of (Kestner, 2012). The GT-HEAT environment is built upon the integrated tracking of three main analysis groups throughout a mission: weight, available potential energy, and thermal energy. The use of modular elements allows the vehicle and engine to update their respective states in "real time" throughout the mission analysis. The phrase real time is placed in quotes as the authors are not referring to real time in the controls sense. "Real time" in this context is referring to that each analysis module can access full state information if they are exposed from all other analysis modules. Figure 3 provides a graphical description of the GT-HEAT functional framework. A vehicle is represented by a mission, airframe, and engine assembly. Each assembly, or object, is a self-contained analysis that contains multiple sub-analysis modules that may be activated and defined depending on the analysis being performed.

Working clockwise from the upper left hand corner of Figure 3, GT-HEAT contains a mission assembly that contains a user defined mission profile consisting of taxi out, takeoff, climb, cruise, loiter, descent, approach, and taxi-in phases as needed. The mission assembly is primarily responsible for providing ambient operating conditions to the vehicle assembly including rate of climb, velocity, temperature, pressure and in the case of a military vehicle information about release of payload or use of energy

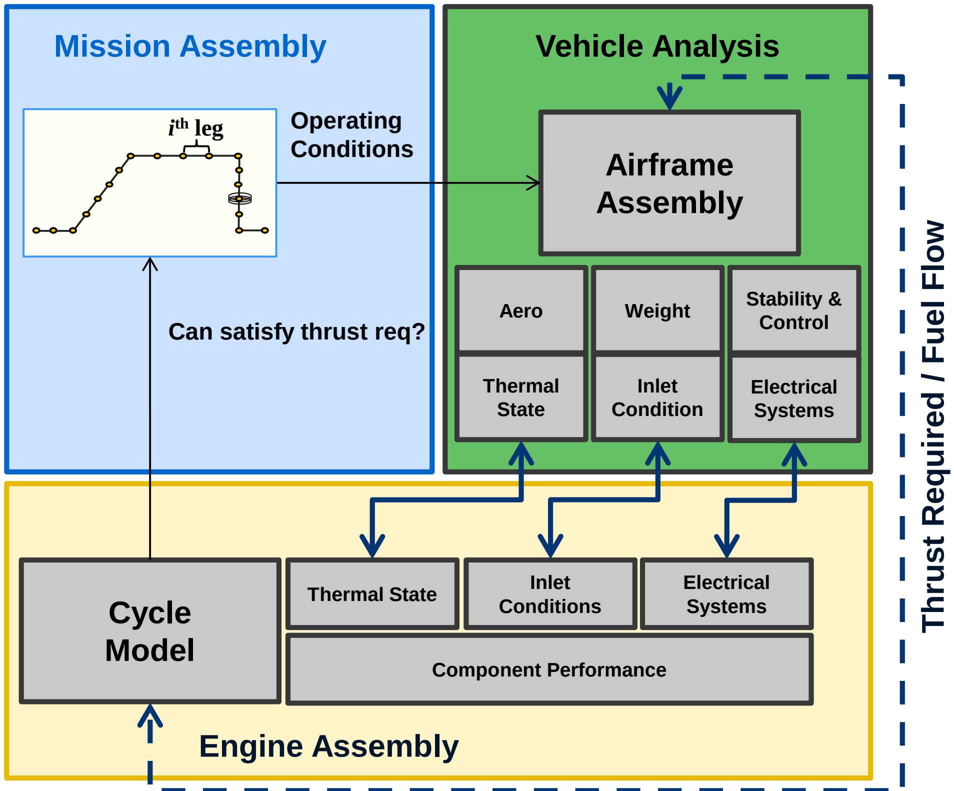

Figure 3: GT-HEAT Modular Framework

based weapons. The mission assembly does not perform any additional calculations. Its purpose is to provide boundary conditions to the vehicle and engine analyses.

Once ambient conditions are passed to the vehicle analysis, the airframe assembly is responsible for translating the current mission segments conditions into required thrust at a minimum. Additional calculations may be performed as necessary. Thrust calculation is done using developed aero and weight sub-elements. Leveraging NPSS' built-in scalability, the aero and weight sub-elements can be defined in a multitude of ways. The aero sub-element returns vehicle drag for a given weight (i.e. lift) and can be represented via pre-defined tables, empirical prediction routines, or zooming to a higher fidelity code such as CFD. The user may decide to further decompose the aero block into constituent parts such as lift dependent and independent drag, wave drag, and trim drag. The aero block also has access to the other subelements within the airframe assembly such as weight and angle of attack.

The weight subelement is designed to track vehicle empty weight, payload weight (which may change during the course of a mission, energy storage device weight, and liquid (i.e., jet A) fuel weight. The aero and weight blocks must be minimally defined for a basic analysis; however, the stability and control, thermal state, inlet condition, and electrical systems elements are likely to be used for the advanced, adaptive systems GT-HEAT is designed to assess.

The stability and control subelement allows the airframe assembly to track angle of attack, trim drag, and C.G. throughout a mission; this allows for the assessment of advanced flight management systems and control algorithms. The thermal state allows for tracking of any aspect of the vehicle thermal state including fuel tank temperature, cabin heat load, and any other user defined thermal system. The airframe thermal system allows for constant communication, via the NPSS solver, with the engine thermal systems. Fuel temperature and any other coolant loops can be constantly updated as the thermal state of the engine or aircraft change. Similar connection pathways exist between the inlet conditions, representing the boundary conditions to the engine inlet, and the electrical systems, which can be used to represent both secondary subsystems and energy storage devices as used in hybrid electric configurations.

The engine assembly contains an NPSS cycle module that is already extendable. The component performance is commonly represented through the use of performance maps; however, NPSS has been used with higher fidelity meanline and zooming codes (Sampath, 2004). The flexibility of NPSS' cycle analysis and design capability and recent extension with open-source hybrid electric elements allows for easy simulation of a wide range of hybrid electric propulsion systems (Perullo, 2014).

When necessary, the new connection pathways can be easily created between the subelements. For example, the stability and control (pitch), aero, and inlet conditions subelements may need to communicate with each other to determine the impact of boundary layer ingestion on the engine in the case of a hybrid wing body configuration. The decomposition within GT-HEAT is flexible enough to handle any advanced concept, propulsion system, or suite of adaptive technologies. New connection pathways can be user defined.

Once executed, the engine assembly communicates back to the mission assembly whether the required thrust to complete that mission segment is available. The user can place constraints within the framework to handle cases where thrust, thermal, or other constraints are violated. Flexibility allows the constraints to be customized to the system at hand.

The customizable, open-source nature of the developed GT-HEAT components allows for the user to create flexible rules and optimization strategies allowing for the optimization of any technology. The interactive nature of the assemblies also allows for path based optimization such as model predictive control to optimize the adaptive technology usage and capture the impact on sizing.

Sample Cases

While the framework has been formulated, analysis modules are needed to populate the environment to perform useful studies. Georgia Tech has been developing open source GT-HEAT elements aimed at enhancing the ability of the environment to handle hybrid electric and advanced thermal management applications. Figure 4 provides a development roadmap that details open source module development. In 2012 GT-HEAT elements were made that allow for inline simulation of electrical drive components with the thermodynamic NPSS model. Additional components and sub-modules were constructed to enable simulation of cryogenic thermodynamic systems for use with superconducting motors and power transmission systems. All of the elements were initially constructed for steady state simulation. In 2013 the elements were assembled into a parallel, hybrid electric turbofan architecture to demonstrate integration of the electrical elements with the conventional cycle tool (Perullo, 2014).

Realizing that highly integrated more electric propulsion systems require detailed thermal management work was undertaken in 2013 to demonstrate a transient integrated power and thermal management system for high electrical demand, pulsed energy applications. The developed models included transient shaft dynamics, energy storage effects, thermal storage systems, vapor cycle heat rejection, and parametric sequential and continuous logic control. Recent work has focused on implementing creating an integrated, parallel, hybrid electric architecture integrated with a Truss-Braced-Wing (TBW) aircraft which tracks thermal system performance across the flight envelope and allows for trades between energy usage scenarios including use of hybrid technology for takeoff only, takeoff only with charging during climb-out, takeoff and climb-out, only for cruise, or for all phases of flight. By integrating the airframe and engine analysis with GT-HEAT, the non-linear effects of thermal and energy management can be accounted for in an integrated fashion.

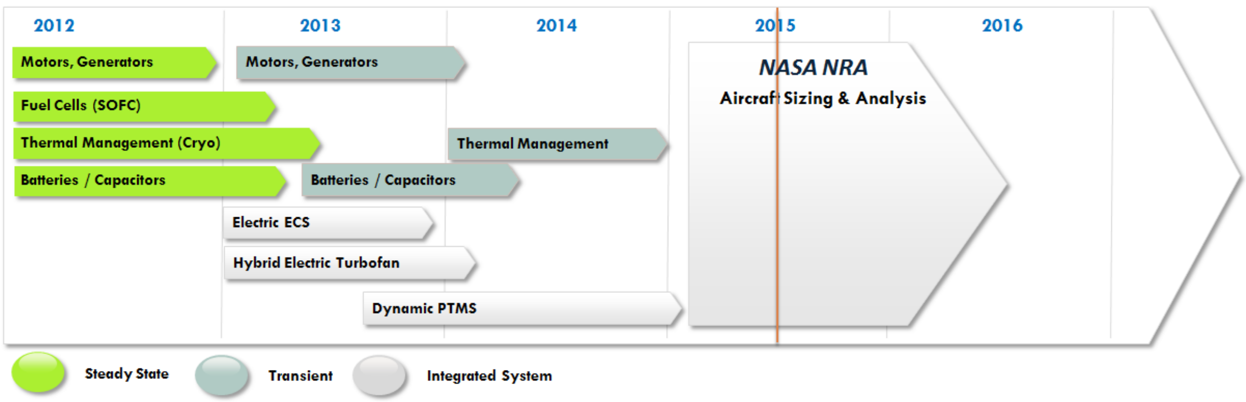

Figure 1: Past Development and Future Applications

Future Applications

Future plans for GT-HEAT are to implement aircraft sizing logic into the tightly coupled framework and to include more subsystems models for both the engine and airframe. This will enable assessment and trades between various subsystem and more electric technologies while accounting for integrated vehicle impacts.

References

Bradley, M., Droney, C., "Subsonic Ultra Green Aircraft Research: Phase I Final Report," NASA/CR-2011-216847.

Evans, A., Follen, G., Naiman, C., Lopez, I., "Numerical Propulsion System Simulation's National Cycle Program," 34th AIA/ASME/SAE/ASEE Joint Propulsion Conference, June 1998, AIAA 1998-3113.

Kestner, B., Nam., T., Flett, A., Wilson, J., Mavris, D., "Integrated Engine and Aircraft Mission Performance Analysis Using NPSS," 50th AIAA Aerospace Sciences Meeting, January 2012, AIAA 2012-0841.

Kim, H., Felder, J., Tong, M., Armstrong, M., "Revolutionary Aeropropulsion Concept for Sustainable Aviation: Turboelectric Distributed Propulsion," ISABE-2013-1719.

Martins, J., Lambe, A., "Multidisciplinary Design Optimization: A Survey of Architectures," AIAA Journal, Vol. 51, No. 9, pp. 2049,2075.

Perullo, C., Mavris, D., "A Review of Hybrid-Electric Energy Management and Its Inclusion in Vehicle Sizing," Aircraft Engineering and Aerospace Technology, Vol. 86, No. 6, pp. 550-557.

Perullo, C., Mavris, D., "Assessment of Vehicle Performance Using Integrated NPSS Hybrid Electric Propulsion Models," 50th AIAA/ASME/SAE/ASEE Joint Propulsion Conference, 2014.

Perullo, C., Trawick, D., Clifton, W., Tai, J., Mavris, D., "Development of a Suite of Hybrid Electric Propulsion Modeling Elements Using NPSS," Turbo Expo 2014, GT2014-27137.

Rosenberg, K., "Energy Management for Integrated Flight and Propulsion Control Systems," Digital Avionics Systems Conference, 1988, 88-3873-CP.

Sampath, R., Irani, R., Balasubramaniam, M., Plybon, R., Meyers, C., "High Fidelity System Simulation of Aerospace Vehicles Using NPSS," 42nd AIAA Aerospace Sciences Meeting, January 2004, AIAA 2004-371.

Urnes, J., Morris, C., Sheahan, J., Dykman, J., Clingman, D., "Control System Design for a Variable Camber Continuous Trailing Edge Flap System on an Elastic Wing," AIAA SciTech, January 2014, AIAA 2014-0835.

Yonke, W.A., Terrell, L.A., Meyers, L.P., "Integrated Flight/Propulsion Control: Adaptive Engine Control System Mode," AIAA/SAE/ASME/ASEE 21st Joint Propulsion Conference, July 1985, AIAA-85-1425.

Zimbrick, R.A., Colehour, J.L., "Investigation of Very High Bypass Ratio Engines for Subsonic Transports," J. Propulsion and Power, Vol. 6, No 4, pp. 490-496.