INVENT Modeling, Simulation, Analysis and Optimization

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In this paper, a new subsystem-based approach to solve aerospace vehicle energy management issues is described. The goal of this approach is to create an “Energy Optimized Aircraft” that will maximize energy utilization for broad capabilities while minimizing complexity. To support this goal, an advanced modeling and simulation ICD process is established. This process addresses several of the current challenges facing modeling and simulation of large integrated systems.

Nomenclature

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<tr>
<td>APTMS</td>
<td>Adaptive Power and Thermal Management System</td>
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<td>Capability Efficiency Index</td>
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<td>DHS</td>
<td>Distributed Heterogeneous Simulation</td>
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<td>EOA</td>
<td>Energy Optimized Aircraft</td>
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<td>HPEAS</td>
<td>High Performance Electric Actuation System</td>
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<td>ICD</td>
<td>Interface Control and Specification Document</td>
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I. Introduction

The US Air Force Research Laboratory’s Propulsion Directorate initiated the Integrated Vehicle & Energy Technology (INVENT) Program in 2008. Leading up to the INVENT initiative there has been focused interest on the part of thermophysicists and thermal engineers to solve a “new set” of challenging aerospace vehicle thermal management problems. These problems are, for the most part, a result of inefficiencies stemming from a variety of components and systems such as electrical power systems, propulsion systems, and high-energy electronics devices. The idea that these are a “new set” of thermal management problems is a misnomer in that the relative inefficiencies have remained constant while the power and power densities that these devices are expected to consume and/or provide have continued to increase. This has ultimately resulted in the increase in total heat load combined with high-flux heat generating components. One would think this would not be a particularly challenging problem considering the evolution of a variety of thermal management concepts such as high-flux thermal management components developed over the last twenty years. But when one looks at additional constraints such as on-demand requirements driven by duty cycle, operating temperatures, isothermality, total heat load, the availability of suitable heat sinks, and poorly-defined environmental boundary conditions; these “new sets” of challenging thermal management problems can quickly become a costly thermal management nightmare. However, the implication that only better thermal management concepts and technologies need to be developed ignores the fact that, from an energy perspective, it is only a symptom resulting from the failure to properly take into account the need for improved system integration and optimization.

INVENT was established to address these thermal management challenges in modern survivable military aircraft, from a vehicle energy perspective, through new system integration and optimization approaches. These new aircraft have three to five times the heat load of legacy platforms while being limited in their ability to reject heat to the environment. Rejecting heat to the engine cycle through various flow paths has become the preferred approach. The added heat load is the result of modern avionics, advanced mission systems, fuel/thermal based vectored thrust control systems, increased use of composite structures, and larger more electric aircraft engine accessories such as generators, gear boxes, or environmental controls. The legacy approach to these systems has been to provide continuous infrastructure (hydraulics, fuel/thermal, pneumatics, electricity, cooling, etc.) even though many of the loads are used a small percentage of the mission (low duty cycle). INVENT is addressing the potential use of on-demand, duty cycle based systems that can greatly reduce these heat loads overall by “turning-down” their infrastructure demands during idle periods.

The ability to provide on-demand power and cooling may be the key to reducing infrastructure needs as well as reducing energy demand that decreases heat loads as a result. This concept is referred to as the Energy Optimized Aircraft (EOA) by the INVENT program. The main EOA infrastructure subsystems being addressed are the adaptive power and thermal management system (APTMS), robust electrical power system (REPS), and high performance electric actuation system (HPEAS), and their associated load suites as well as the engine system integration. The focus of the INVENT EOA is to make aircraft and vehicle systems more energy efficient by maximizing overall system energy efficiency in lieu of sub-optimized components and subsystems. The ability to solve the thermal challenges requires the knowledge and integration of complex systems to reduce the heat loads by addressing the “entire” vehicle energy picture. INVENT seeks to demonstrate the potential EOA technologies integration using modeling and simulation (M&S) followed by validation testing in the laboratories using systems integration facilities in conjunction with engine and vehicle test laboratories. The complexity of these highly integrated systems necessitates an effective M&S analytical approach to avoid the costs and risks associated with “cut & try” approaches to system integration. The purpose of this paper is to highlight the advancements in M&S that make a virtual approach to complex aircraft systems integration possible.

II. Background

Historically, aircraft were comprised of federated or independent mechanical, hydraulic, pneumatic and electrical subsystems. These subsystems were individually designed and optimized and were then integrated within the aircraft structure. A major obstacle for integrating these federated subsystems was ensuring the mass, volume, and associated pipe and wire routing could fit within the physical constraints of the aircraft. Initially this often required alteration of the component after hardware delivery. In the 1980’s when computer drawing packages began to emerge, the aerospace industry began to adopt the use of 3-D Computer Aided Design (CAD) as a way to address these physical integration issues. Specifically, all subsystem manufacturers were required to develop and deliver a CAD physical model of their subsystem to the system integrator to ensure form-fit early in the design process. This use of CAD physical models to support early design, thereby minimize costly hardware redesigns associated with
system integration, has proven to be very effective and is now a universally accepted practice that set a precedence for the utilization of computer models to address complex system integration issues.

Also, in the late 1980s, a shift toward More Electric Aircraft (MEA) was made to address the high maintenance costs, weight, and complexity associated with the federated systems [1]. As a result, MEA are now the baseline for most modern military and civil aircraft. Although the form-fit issue remains, the MEA initiative has led to other system integration challenges. Specifically, as a result of the limited heat sinking capabilities due to composite skins and survivability constraints, the increased power demands to support advanced radars, electrical actuation, and mission systems payloads are now directly coupled not only within the context of power and thermal integration but also within the mission profile that drives the on-demand systems (duty cycle based loads). To address this dynamic integration issue, computer models and simulations that characterize the subsystems performance and interactions with the other subsystems (engine, REPS, APTMS, HPEAS) are being developed and virtually integrated prior to hardware fabrication and testing.

Aircraft subsystem models are generally built individually against a static interface control and specification document (ICD). This ICD-based process is analogous to the 2-D blueprint-based process of installation relative to its ability to perform low risk integration. Dynamic subsystem integration requires a dynamic ICD process that can be achieved through M&S in the same manner that a 3-D CAD model is now used for installation design. The challenges of using a dynamic M&S-based ICD process are many and must be fully addressed in any successful program.

The first M&S challenge comes from the establishment of an integrated systems simulation involving integration of multiple company models. This challenge, or “M&S capabilities gap”, has become greater with the shift toward integrated systems or vehicle-level M&S and the trend of distributing design and analysis of various portions of the aircraft across multiple companies, as depicted in Figure 1. For example, one aircraft subsystem manufacturer may be responsible for the power and thermal management system requiring model development in a specific simulation environment, whereas another aircraft subsystem manufacturer may be responsible for the electrical system employing a different simulation environment. In fact, these simulation environments may be proprietary to each company, thereby prohibiting aircraft-level integration studies. In addition, most subsystem manufacturers have developed legacy computer codes and simulation environments that are used to support detailed subsystem design. Since intellectual property (IP) is contained within these legacy computer codes with respect to model verification, validation, and design methodologies, the manufacturers tend to resist transition of these models to other simulation environments or to the aircraft or vehicle systems integrators. With these different simulation approaches, integrating the subsystem models to support system-level studies and optimizations can be challenging, if not impossible.

To support this edict, some manufacturers have developed interfaces directly with selected commercial software packages. Others have maintained multiple versions of the models, one model for in-house detailed design developed in the legacy computer environment, the other model developed in the commercial software package to

Figure 1. System integration versus time.
support system integration studies and to serve as the contract deliverable. This lack of consistency between subsystem, system, and aircraft design and integration of models and model development approaches has led to discrepancies since the models reflect different versions of the hardware design or in the level of fidelity of each model. Since the first modeling priority for the subsystem manufacturer is subsystem design, the system integration models tend to lag and hinder the usefulness of these models in support of the system integration studies. An approach to address this issue that was developed by the Air Force Research Laboratory (AFRL) and others is Distributed Heterogeneous Simulation (DHS) [2]. This approach enables the subsystem models to remain in their native simulation environment and be integrated within the dynamic system simulation. To protect intellectual property with respect to the models or simulation environment, DHS supports model encryptions, model node locking, remote execution, and model time expiration.

A second M&S challenge with respect to system integration pertains to limitations within some of the legacy simulation environments and, or with the legacy models. For example, some of these codes or models were developed to predict the steady-state or salient behavior of a mechanical or hydraulic subsystem. In addition, the fidelity of these models was limited to the bandwidth of the flight control computer or approximately (10-100 Hz). These same approaches may not be appropriate for capturing the electrical or thermal dynamics of integrated MEA subsystems. In such cases, higher fidelity analysis is only started once hardware integration issues arise leading to delays and solutions that are not optimal to the integrated system.

A third M&S challenge pertains to how proprietary information is protected within the subsystem models. Although IP protection and non-disclosure agreements are established between the subsystem manufacturers and the system integrator, a common practice is for the subsystem manufacturers to encrypt models into “black boxes” that only allow access to input/output variables at the top level. While protecting proprietary information is a foundation to a competitive market and must be adhered to by all parties, this practice can easily be abused, either intentionally or unintentionally, wherein methods and models found in open literature are also encrypted. By limiting access into a model, the usefulness of the model is questionable since the fidelity, assumptions, and validity cannot be investigated by the system integrator and modifications to the interfaces are not supported, thereby hindering system model integration. Although model verification documents may be delivered with the “black box” models, the models may not perform the same when integrated within the system. This limitation multiplied by every “black box” model can yield an integrated system simulation of limited to no value. This can especially be the case when analyzing off-design or growth capabilities of the aircraft. The subsystem manufacturers may not be privy to such studies and therefore the rapid assessment to determine such growth capabilities must be made by the system integrator with knowledge of the subsystem models.

A fourth challenge is that dynamic subsystem models typically represent a specific design and thereby limit the ability to support system-level trade and optimization studies. Such models are intended to address integration issues and potential control optimizations, wherein, the system-level optimization studies are performed using different simplified models. Although this approach of decoupling the dynamic (detailed) and design (simplified) models has historically had merit, the ability to design and analyze these on-demand power and cooling integrated systems requires that the dynamic interactions be accounted for earlier in the design process.

A fifth M&S challenge is the computational complexity of the integrated system simulation. Specifically, the integrated system simulation may execute too slowly to produce results in a reasonable amount of time to support analysis and optimization. This is driven by the types of system simulations being performed and the fidelity included within the subsystem models. For example, when analyzing aircraft-level thermal constraints the entire mission may need to be simulated, requiring system simulations that need to execute several times faster than real time to produce timely results. Conversely, if a temperature constraint for an individual solid-state device die is of interest, this may only require examination over the worst case flight segment. In this case, due to the increased fidelity and limited simulation time required, simulation speeds on the order of hundreds to thousands of times slower than real time may be sufficient. The challenge is in defining models of the appropriate fidelity and implementing a simulation environment that will accommodate large-scale systems in a computationally efficient manner [3].

A final M&S challenge is that although several programs have addressed common modeling architectures [4] and environments [5], modeling requirements for fidelity, boundary conditions and interfaces, verification, validation, and optimization of aerospace systems have previously been developed by individual programs. This lack of a standard for these aspects has limited the re-use of models, burdened programs to develop such requirements, and has decreased the potential benefits and understanding that is possible from the integrated system simulations.
III. Energy Optimized Aircraft

Current emphasis to maximize energy utilization and still provide a maximum Air Force capability has led to renewed interest in the optimization of aircraft systems. In doing so, there has been a significant shift in how aircraft subsystems such as thermal management, power generation, power distribution, and load management are being addressed in relation to the vehicle as a whole. Future power and thermal management systems will be highly interdependent and must be capable of operating in an on-demand mode in a highly dynamic environment. Traditionally, these systems evolve as a result of single-point engineering trade studies. However, the inherent coupling and interdependency of these systems to each other, the propulsion system, and the dynamic maneuverability of the vehicle airframe has spawned renewed interest in system integration and optimization from an energy perspective. This has resulted in the initiation of unique research efforts and facilities to investigate the effect of these highly-coupled, nonlinear system interactions and their non-equilibrium and unsteady nature on energy utilization. Due to the highly-dynamic or unsteady nature of these systems, new science and engineering concepts based on first principles are emerging with the idea that “Science of Integration” provides a rational and logical approach to energy management. This approach must take into account the “entire” energy picture that addresses all energy forms such as energy stored, converted, distributed, and dissipated.

In the previous sections the goals in terms of reduced heat loads and improved efficiencies have been discussed. This section is dedicated to defining what an EOA is with respect to INVENT and what trades must be considered in achieving such an aircraft. For civilian aircraft wherein the mission is the transport of a payload over a certain distance at a certain speed, the EOA has been defined as the fulfillment of this mission in the most efficient manner [6]. Although this definition covers the essence of an EOA, it does not capture the added constraint imposed by a multi-role military aircraft. Furthermore, over the life of the aircraft, new capabilities and missions will need to be supported that are unknown to the original designers. Therefore, the INVENT EOA definition is an aircraft that is optimized for broad capabilities while maximizing energy utilization (aircraft and ground support) with the minimum complexity system architecture. This expanded definition allows for numerous trades such as minimum energy consumption versus flexibility (minimum complexity) at the airframe level. For example, without provisions for growth, an aircraft that may be optimized for energy consumption may not be capable of supporting a future-generation sensor suite. Therefore, either multiple aircraft are required to fulfill this mission or capabilities are compromised. Both do not satisfy the EOA requirement.

With such examples and unknowns around future requirements, how does one prove whether a design is an EOA or not? First, near-, mid-, and far-term aircraft-level goals must be established. These goals will translate to architecture and subsystem growth requirements, thereby guiding technology investment and preventing a single capability highly-complex (inflexible) solution. This vision toward growth and technology investment is depicted in Figure 2 wherein the INVENT EOA that meets the near-term goals may not be the architecture that has the lowest energy consumption or highest Capability Efficiency Index (CEI). CEI is defined as

\[
CEI = \frac{\text{Capability}}{\text{Energy Consumed}}
\]

where Capability can represent mission-level aspects such as range, low-altitude engagement time, payload weight, sensors / weaponry supported; program aspects such as availability or cost savings; or integrated system aspects such as thermal or power margins. Energy Consumed accounts for the aircraft and ground support energy required to perform the mission. Flexibility refers to the inverse of complexity where complexity is defined as the measure of how tightly integrated the design space is with respect to change. For tightly integrated design spaces, changes propagate quickly and widely throughout the system resulting in costly and time-consuming redesigns [7]. Such designs can also result in unanticipated interactions, multi-mode failure cascades, and unanticipated vulnerabilities [7]. Therefore, it is in this context that mid- and far-term goals must be accounted for in determining the design impacts to support such growth.

Within INVENT, wherein the primary focus is the design, analysis and optimization of the integrated system, growth is investigated with respect to thermal and power margins. The relevant physical phenomena of interest to address the INVENT goals can be divided into two time domains. The first is the mission-level wherein the impact of different technologies on the aircraft’s thermal margin can be quantified. This thermal margin or thermal balance is depicted in Figure 3 where the fuel tank temperature is the fulcrum. If a thermal margin exists, the fuel tank temperature will not increase as a result of fuel thermal cooling demands and may actually decrease for certain modes of operation. In this figure, the engine fuel demand (right side of balance) establishes the baseline thermal sink capacity at the various mission points. More specific, the required engine fuel flow, the feeder tank fuel temperature, and the maximum fuel temperature at the engine combustor determine the maximum amount of heat

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flux that can be added to the fuel without the addition of other cooling components. On the other side of this balance is the thermal fuel demand which is required to cool the aircraft fuel heat loads. These heat loads include the Full-Authority Digital Engine Control (FADEC), the Integrated Converter Controller (ICC), generator, Environmental Control System (ECS), and engine. Since the baseline thermal capacity is dependent upon the engine fuel flow and a goal of the aircraft is to increase range and decrease energy consumed, the aircraft-level impacts of decreasing fuel demand at the cost of adding cooling components to sustain thermal margins must be determined. Such additional components may include Return Fuel Air Coolers (RFAC), two-phase thermal energy storage, or forced air cooling components. Besides the addition of cooling components, another way to address this

Figure 2. INVENT EOA technology investment plan.

Figure 3. Mission-level balance.
thermal balance is to minimize the thermal fuel demand. This can be accomplished by minimizing/eliminating the requirement for fuel cooling in some components (FADEC, ICC, ECS…) by increasing the component operating temperatures or by reducing the heat generated by these components through on-demand controls or by reduced losses. INVENT is exploring all of these possibilities and performing integrated system simulations to determine the aircraft-level impacts on thermal margin from these different technology sets.

The second time-domain being investigated is segment-level. Currently, the physical phenomena of interest at this level are the electrical and electro-mechanical interactions. However, in future spirals of INVENT, this analysis will be expanded to include device- or sub-device-level thermal transients. The segment-level balance or dynamic margin is depicted in Figure 4. In this case, the electrical power quality is the fulcrum and the generation / power absorption capability of the generator / regenerative resistance network establishes the baseline transient power capacity. On the other side of the balance (left side) are the critical loads. These loads can include time critical loads such as counter-measure weaponry, flight critical loads such as control surface actuators and vehicle management systems, and mission critical loads such as radars and weapons bay door actuators.

In order to achieve this segment-level balance which includes not only steady-state power but also peak and regenerative power, three different approaches can be taken. In the first approach, the generation / power absorption capabilities can be increased to meet the requirements. This can impact not only the size of the associated components, but can impact the size, performance, and/or mean-time-between-failure of other components such as the gearbox, engine, and thermal management system. A second approach is to decrease the steady-state and transient power requirements for the critical loads. However, such a decrease may result in increased weight and volume for these components. The final approach is to examine transient power assist paradigms that successfully supply the required power to the critical loads while reducing the transient power requirements for the generation / power absorption systems.

Examples of transient power assist paradigms include the Electrical Accumulator Unit (EAU) [8] wherein a controlled energy storage device is used to source peak power above the aircraft generation capability and sink regenerative power to maintain power quality. Other examples include the ability to rapidly reduce or shed non-critical loads to maintain transient power quality. For this paradigm, the non-critical loads would limit their control response based upon their functional requirements or based upon the sensed bus voltage. For example, a cooling-loop pump may not need to respond rapidly due to the thermal time constant of the components being cooled and therefore its power draw can be limited or interrupted without loss of functionality or impact to the thermal cooling system. Furthermore, the pump can be used as a limited energy storage device to assist with transient energy balance. In the first scenario, the pump could be used to absorb regenerative energy by sensing a rise in the bus voltage and momentarily increasing the pump speed.

Figure 4. Segment-level balance.
A final scenario would be to have bi-directional capabilities in the pumps electric drive and utilize the pump to not only increase the power draw on bus over-voltages but to also source power to the bus during under-voltage conditions utilizing the stored rotational energy in the pump. Although the added weight and complexity of having a high-bandwidth bi-directional drive probably does not make sense for most loads, an optimized integrated system may make use of bi-directional power flow in the generators and auxiliary power units. To obtain dynamic balance / margin, INVENT is currently investigating all of these techniques in conjunction with the thermal balance to determine the overall aircraft-level impacts of the candidate architectures and technologies. Descriptions of some of these initial studies along with the simulation tools being utilized are provided in [9, 10, 3].

IV. Integrated System-Level Modeling, Simulation, Analysis and Optimization

The primary goal of INVENT with respect to integrated modeling, simulation, analysis and optimization is to establish a virtual approach to complex aircraft M&S and hardware integration that can effectively address system integration issues, support platform-level energy optimization, and transition throughout the aerospace community as the standard practice for system modeling and simulation. To effectively accomplish this goal, the challenges described in the Background section will need to be addressed. The first steps were to: establish engineering and design issues to be addressed, create commonality between modeling philosophies across the many industry teams, determine modeling environments supported, define various modeling fidelities required, and establish boundary conditions and interfaces between component, subsystems, and systems. While INVENT is addressing a wide-range of general engineering and design issues associated with the various systems and aircraft integration and specific issues associated with three candidate aircraft, these issues are not the focus of this modeling and simulation paper. However, it should be stressed that prior to any M&S effort, the system integrator must understand the issues, trades, and optimizations being considered and that all supporting organizations comprehend the fidelity and access required from their models in order to support this objective.

With the engineering and design issues defined, a Modeling Requirements and Implementation Plan (MRIP) document was developed. The MRIP provides detailed descriptions of the modeling required to perform the integration and analysis of dynamic, on-demand systems and is designed to minimize the M&S capabilities gap by ensuring standardization of modeling practices across government and industry team members. The primary contributors to the M&S capabilities gap include modeling fidelity, modeling software, and input/output structure. The MRIP was developed to reduce the occurrence of many of these contributors and their contribution in significant program delays. A framework for system integration has been developed including clear definitions of all interface boundaries and exchange variables, design performance scaling within the subsystem models, and an optimization plan for determining the final EOA design. A model schematic of aircraft level interface boundaries between critical systems and subsystems is shown in Figure 5.

Each subsystem is comprised of a set of components that are modeled using physics-based time-domain behavioral models. To ensure the engineering goals are met, the MRIP provides descriptions of the components that include the behavioral aspects that must be captured. Achieving the INVENT goals requires modeling at various levels of fidelity and run-time performance. Specifically, two levels of modeling fidelity are utilized, segment and mission level. The models must be consistent across the levels of fidelity to support the seamless transition from detailed to reduced fidelity representations. Of significant interest is the detailed operating conditions of the electrical system wherein transients in the microsecond time frame can result in loss of an aircraft, and the sum of the transients can have significant impacts on the thermal constraints of a given component. The segment level models are intended to address these high bandwidth dynamics and are anticipated to run tens to hundreds of times slower than real-time and therefore will be limited to short duration (1-100s), worst case segments. Significant aspects of the EOA will need to be considered over entire missions to discern enhancements to mission capability including extended range, longer duration ground hold operational capability, and unrestricted flight envelopes. A reduction in fidelity is required to run entire missions within a reasonable time frame. These models are expected to run more than ten times faster than real time and focus on component temperatures varying as a function of the operating condition and ambient environment. The two levels of fidelity are essential to address the goals in developing an EOA.
Optimizing run-time performance is a significant hurdle to overcome in the development of higher fidelity models. The high degree of accuracy required in the models, in conjunction with the run-time performance expected, forces the model developer to focus not only on the physics modeled but also on the implementation of these physics in the simulation environment. Namely, appropriate selection of the numerical solution method must be considered and attention to how calculation methods within the simulation environment impact run-times must be paid. The MRIP provides guidelines for preferred modeling practices that will result in improved run-time performance, with the goal being run-time performance that is consistent with the fidelity of the model. Particular detail has been given to the aspects that drive the numerical solvers with respect to number of time steps required and appropriate use of discrete event detection methods.

Although consistency in run-times and fidelity are essential to system integration studies, inconsistent boundary conditions result in significant delays in system integration. The MRIP defines the interface variables that will be exchanged between models. In addition, directionality of the physical variables is also detailed to mitigate any additional delays. Behavioral characteristics such as mechanical motion, heat transfer, and current flow can be defined as positive or negative and if the directionality is consistent within the model, either definition will be mathematically correct, but when integrating models developed by various industry partners, a consistent definition is necessary. The physical signals exchanged, including current/voltage, position/velocity/force, etc., depend on the particular component. Modifications to a component model may be necessary to satisfy appropriate boundary interfaces. For instance, if the output of a component is a capacitor and connects to a component whose input is a capacitor, the two capacitors must be moved to a single model. Flexibility in a model to support these types of modifications reduces system integration delays, but this flexibility is atypical for many industry team members due to concerns over proprietary information.
While control algorithms are typically proprietary, most physical models are derived from textbook or publically available literature. The complexity of the INVENT program has resulted in a paradigm shift regarding encryption of models and requires that suppliers make available the underlying code to the system integration team. Although control algorithms can be encrypted, the ‘text book’ models must be made available to the integration team to minimize delays when debugging errors and ensure consistency in boundary interfaces. In addition, the competitive nature of the program across industry suppliers requires that models be examined from an accuracy standpoint to ensure fair competition across the team members. For instance, company A may be calculating a particular loss mechanism, whereas company B neglects this loss mechanism resulting in B’s model having higher efficiency than A.

Although the MRIP attempts to minimize the M&S capabilities gap via consistent definition for common variability among industry partners, a model satisfying all expectations remains difficult to produce. Therefore, detailed reviews of the models must be conducted to ensure consistency with the MRIP, operability of the model (i.e. capability of model running many test cases without run-time failures), and that the models produce expected results. The system integration team for the INVENT program has developed scripts that exercise the models to test for model operability and verify that the design performance predicted is within specifications defined by military standards and/or the Systems Requirements Document (SRD) developed specifically for the INVENT program. Run-time errors can halt system integration as they are difficult to debug when complete systems are assembled. In the test scripts, as many as two hundred simulation cases are run on a single model and reports are automatically generated that display model design performance results and flag any run-time errors and sub-specification test points. This information can be fed back to an industry supplier who can debug the model to eliminate any issues observed. The automated aspect of this process allows for rapid evaluation of many models with little time cost to the system integrator. These testing procedures are essential in the development of robust models with verified design performance predictions and operability through a wide range of input conditions. In addition, the use of the test scripts across industry teams has the potential to lead to a standardized method for testing models before delivery to system integrators.

V. Conclusion

The INVENT Program was established to solve the challenging aerospace vehicle thermal management problems. These challenging thermal management problems are, for the most part, a result of inefficiencies stemming from a variety of components and systems such as power systems, propulsion systems, and high-energy electronics devices. Current emphasis to maximize energy utilization and still provide a maximum Air Force capability has led to renewed interest in the optimization of aircraft systems, known as the ‘Energy Optimized Aircraft’. Due to the highly-dynamic or unsteady nature of these systems, new science and engineering concepts based on first principles are emerging with the idea that “Science of Integration” provides a rational and logical approach to energy management. To effectively accomplish this goal, addressing engineering and design issues, creating commonality between modeling philosophies across the many industry teams, determining modeling environments supported, defining various modeling fidelities required, and establishing boundary conditions and interfaces between component, subsystems, and systems are underway.

Industry and the government are pursuing the primary goal of integrated modeling, simulation, analysis and optimization, which is to establish a virtual approach to complex aircraft M&S and hardware integration that can effectively address system integration issues, support platform-level energy optimization, and transition throughout the aerospace community as the standard practice for system modeling and simulation. A Modeling Requirements and Implementation Plan (MRIP) document was developed that provides detailed descriptions of the models required to perform the integration and analysis of dynamic, on-demand systems and is designed to minimize the M&S capabilities gap by ensuring standardization of modeling practices across government and industry team members.

Overcoming the significant M&S challenges is the current focus of on-going efforts. The challenges are integrating multiple companies’ complex models; development of higher order, dynamical M&S toolsets as compared to legacy simulation environments and models; overcoming the competitive nature and difficulty of IP and proprietary models’ distribution across multiple companies; subsystem models limiting the ability to support system-level trade and optimization studies; computational complexity of integrated systems simulations and resulting run-times; and overcoming the challenge of limited standardization of models and common M&S practices.

Future effort is concentrating on continued development of steady-state and dynamical models with the appropriate fidelity and run-time performance. Efforts are planned for maturation of designs and architectures for
energy efficient on-demand, duty cycle systems for EOA. This necessitates integration of the models and combining them with representative hardware for demonstration test in existing and planned systems integration facilities.

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References