A Virtual Simulation Platform for the Design, Testing, and Verification of Unmanned Aerial Vehicle Designs

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Abstract*: The Aerospace Systems Design Laboratory (ASDL) at the Georgia Institute of Technology has an advanced virtual prototyping facility for small-scale UAVs and autonomous systems to conduct conceptual and preliminary design trade studies. The authors are using requirements inspired by a US Army UAV research project to develop a design process that will employ the Winning Program Experience (packaged DS software on the V6 platform). In order to analyze large UAV concept spaces, ASDL has developed a process called the Interactive Reconfigurable Matrix of Alternatives (IRMA). It provides a structured methodology based on morphological analysis for integrating objective and implicit information into the concept selection process. The IRMA enables functional decomposition of the problem to allow exploration and traceable reduction of the design space from an astronomical number of combinations to a manageable quantity. This paper presents an informative account of the approach and implementation of the V6 platform to a set of UAV requirements and mission scenarios that will enable designers to develop the necessary operational concepts and technologies. The process begins with a requirements and logical decomposition. A filtered morphological matrix is created and various alternative designs are evaluated next. Finally, a multi-attribute decision-making technique is used in conjunction with SIMULIA's Isight to perform trade studies and identify optimal solutions. The study will discuss how virtual test benches will be created for UAV systems, including simulation objects for SLM/Isight.*

Keywords*: Aircraft, Constitutive Model, Coupled Analysis, Design Optimization, Dynamics, Experimental Verification, Minimum-Weight Structures, Multi-Body Dynamics, Optimization, Probabilistic Design.*

1. Introduction

Modern aerospace systems are the pinnacle of complex technology integration. However, the cost of developing these systems in terms of design time, testing, and financial investment has grown significantly over the past half-decade. Furthermore, aerospace system complexity and the resulting cost of development has far outpaced the methodologies and techniques used in their design "(Briceno, 2013)." This discrepancy has resulted in the iterative design-build-test-redesign development cycle that is prevalent in complex systems design today.

The issue at hand requires a new approach to the design and manufacturability of complex aerospace systems – an approach that relies on virtual experimentation and verification in place of physical prototyping. Such an approach requires tool suites capable of – at minimum – defining transparent system requirements and enabling traceability, capturing sufficient component fidelity, modeling complex system interactions, fulfilling crucial verification and validation tasks, and infusing the impact of both manufacturability and procurement concerns early into the design process "(Briceno, 2013)."

A proponent of a similar methodology over the last few years has been the Defense Advanced Research Project Agency (DARPA) which has defined and managed a 300-million dollar effort to revolutionize American manufacturing and the design of military vehicles. This effort – known as Adaptive Vehicle Make (AVM) – is a portfolio of programs managed by DARPA that was established to define and execute a methodology capable of translating programmatic requirements into a full-scale, physical artifact that embodied those requirements while bypassing the need to initiate physical prototyping. At the time of writing this paper, the AVM program is entering into its testing phase where it will systematically analyze a powertrain – designed for an amphibious assault vehicle – against a program of record. However, the AVM program has already proven its capacity to expedite the design and manufacturing process by using state-of-the-art modeling and simulation tools coupled with the use of component-based, cyber-physical models. The powertrain system mentioned above was the product of the AVM methodology applied through an open-source design challenge called FANG (Fast Adaptable Next-Generation Ground Vehicle). The FANG challenge was a 3-month open-source design competition focused on developing the powertrain system of a next-generation amphibious assault vehicle. In 3 months, competitors across the United States formed multidisciplinary teams and worked with a common cyber-physical library of components to design a powertrain that exhibited superior performance, low cost, and increased manufacturability in comparison to an existing program. The FANG challenge acted as the first beta test for the AVM methodology at such a large scale, but proved quite successful as it demonstrated the potential to translate programmatic requirements into a manufacturable, cost-effective solution in a matter of months "(Adaptive Vehicle Make (AVM))".

The remainder of this paper will present a design methodology that supports virtual experimentation and verification in place of physical prototyping and testing. To accomplish this, the design methodology will advocate a series of enabling tools and techniques that are integrated in a virtual experimentation framework. These tools and techniques will be discussed throughout the remainder of this paper in the context of the virtual design of a UAV.

2. Motivation – Unmanned Aerial Systems

The Army Research Laboratory (ARL) is sponsoring ASDL on a project called Micro Autonomous Systems and Technologies (MAST) which is a consortium "(Mait, 2008)" of academic and industrial research organizations that collaborate on the development of technologies in the fields of micro-electronics, autonomy, micromechanics and integration "(MAST-CTA)". The purpose of developing these capabilities is to provide tactical situational awareness in complex terrain such as those found in urban areas. Unmanned systems are currently used in many war theaters to deliver real-time intelligence but none exist to provide similar capabilities at the squad level. The MAST program seeks to fulfill this intelligence-gathering need at the squad level by providing integrated heterogeneous platforms the work together autonomously and synergistically to perform the required operational functions. These systems will need to work together to provide reconnaissance and surveillance of complex environments such as building interiors. The systems will be equipped with instruments that can assess their situation by obtaining and interpreting data from optical, acoustic, or chemical sensors. Ultimately, the goal is to relay information that describes the enemy's position and activities.

These scenarios present the Army with a complex systems design problem. Each mission scenario is unique and these aerial systems must be able to quickly adapt to a host of situations. By introducing new technologies and integrated systems, the combinatorial design space of these systems becomes intractable as each scenario can be accomplished by a different combination of alternative concepts. For this reason a new approach is warranted to explore this design problem. The framework developed under the current MAST program enables designers to analyze the very large concept space for a variety of missions. The framework receives mission scenarios and requirements as inputs and using some advanced design methodologies, performs a series of concept down-selection and simulations to identify key technology gaps. The top performing UAV concepts are compared with current state-of-the-art systems to identify key technology metrics that provide guidance as to what level of capability is necessary for mission success. The framework integrates a series of multi-disciplinary tools for designing, simulating, analyzing, and predicting the behavior of one or more unmanned aerial systems.

One of the challenges in applying this MAST framework is executing it in an efficient manner and establishing traceability of requirements. This is due to having numerous modeling and simulation tools developed in different platforms. The framework has concept exploration capabilities that are driven by Microsoft Excel and Matlab. The modeling and simulation is performed using a combination of open-source gaming and robotics simulation software. The physical environment is virtually created in a different sketch editor.

Although the MAST program has had success in evaluating system and mission effectiveness using this framework Dassault Systèmes has provided an opportunity to enhance this framework with the latest in systems engineering software. Furthermore, the authors intend to complement the existing MAST process with methods and techniques developed under the DARPA AVM program.

2.1 Dassault Systèmes Winning Program

The Aerospace Systems Design Laboratory (ASDL) at the Georgia Institute of Technology is collaborating with Dassault Systèmes on a pilot project called the Winning Program Experience for Aerospace and Defense. This program is a 3D experience that provides a comprehensive solution for early program phases. The Winning Program consists of a dedicated process for proposal development that captures both the bidding process and provides a collaborative platform to integrate all key actors. Furthermore, it provides configuration definition where the user can architect the aircraft in semantics that have both physical definition and behavior. Trade studies are conducted to optimize the design for performance, for production, for operation, and for maintenance. Finally, the program provides the connectivity to adequately prove every aspect of the proposed solution.

3. Virtual Prototyping Framework

ASDL has developed a set of conceptual design decision-support methods and techniques for the development of Unmanned Aerial Vehicles (UAV). The integration of these methods with the Winning Program V6 tools and application of this framework to a UAV proof-of-concept is the focus of this paper. The framework in development is shown in Figure 1.

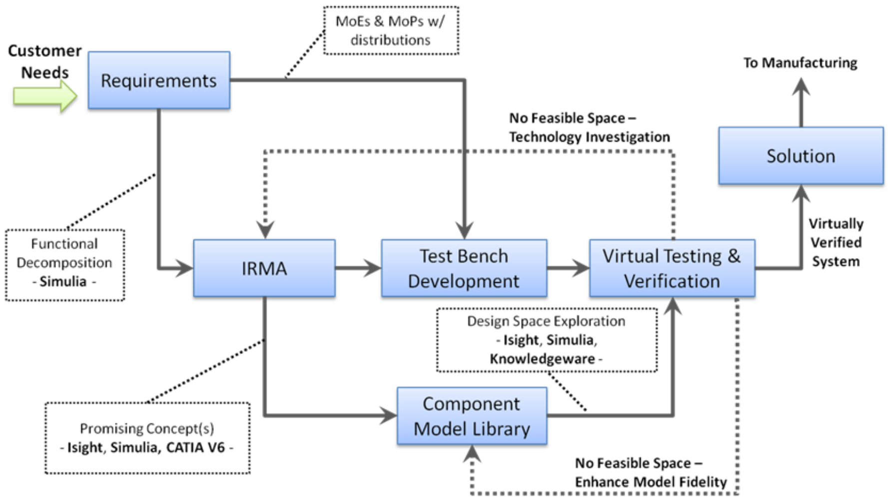

Figure 1. Winning Program Framework for Virtual Experimentation and Verification of Complex Systems Utilizing Interactive, Reconfigurable Matrix of Alternatives (IRMA)

The framework in Figure 1 is a high-level process that uses key enabling tools and techniques to support the notion of an integrated virtual experimentation and verification environment. Several key characteristics of the design framework are discussed below.

3.1 Requirements Definition

A critical step in the design process that precedes any mathematical formulation, concept exploration, or what engineers typically acknowledge as “design” involves a decomposition of programmatic requirements into manageable tasks and a transformation of those requirements into a vocabulary that engineers can understand. This process is illustrated in the data flow between the requirements and functional blocks in Figure 1**.** The goal of this process is to express programmatic requirements as a series of quantifiable engineering characteristics – where possible – that enable engineers to initiate the transition from “what we’re trying to do” to “how we’re going to do it”. The Winning Program utilized a subset of the requirements derived from the ARL MAST program. A subset of these requirements is provided below in Table 1.

Table 1. UAV Concept Requirements List

Denomination	Attribute	Relation	Value	Units	Remarks
R1	Surface of floor explored	≥	90	%	Small building, decent light, benign environment
R2	Determine obstacle type and #	---	---	---	
R3	Mission time	≤	10	min	
R4	Reserve time	=	2	min	
R5	Noise at furthest point in room	≤	50	dB	
R6	Noise around vehicle	≤	70	dB	
R7	Number of operators	≤	2	---	For deployment
R8	Deployment time	≤	5	min	
R9	Size of the vehicle	≤	doorway	ft	Longest length ≤doorway for entering/exiting

3.2 Requirements Decomposition

Requirements decomposition leverages techniques such as Quality Function Deployment (QFD) to transform high-level programmatic requirements into quantifiable engineering characteristics in the form of Measures of Effectiveness (MoE) and Measures of Performance (MoP). The Army Handbook on Assessment and Measures of Effectiveness in Stability Ops "(US Army CALL)" defines MOP's and MOE's in the following fashion:

> MOP – *A criterion used to measure if a task is performed to a necessary standard. A MOP measures output, that is, were actions done correctly*.
>
> MOE – *A criterion used to assess changes in system behavior or capability that is tied to measuring the attainment of an end state, achieving of an objective, or creation of an effect.*

Thus, a single MOE may be comprised of a series of MOP's. This decomposition process is the first step involved with identifying the functions a product must perform in order to comply with programmatic requirements and offers useful information supporting the design of simulations that will capture a concept's ability to comply with those requirements.

3.3 Concept Exploration

Aerospace systems are complex in the level of integration, coupling, and sheer number of components used to develop a complete system. It is therefore necessary to advocate intelligent concept exploration techniques throughout the early stages of design as a means of capturing and understanding the full breadth of potential, unbiased solutions. This is especially important to perform in early stages of design when engineers are confronted with vast conceptual spaces coupled with the greatest amount of design freedom. Design decisions that are made in the conceptual phase have the potential to significantly contribute to the majority of the overall program costs (as illustrated in Figure 2) and effectively remove degrees of freedom that may foster revolutionary concepts.

Furthermore, design decisions made early on work to “lock in” a concept and will consequently make any future redesign decisions expensive. The significant influence that early design decisions have on the overall success and cost of a program motivates us to pay special attention to concept exploration and processes that maximize design freedom throughout the design process.

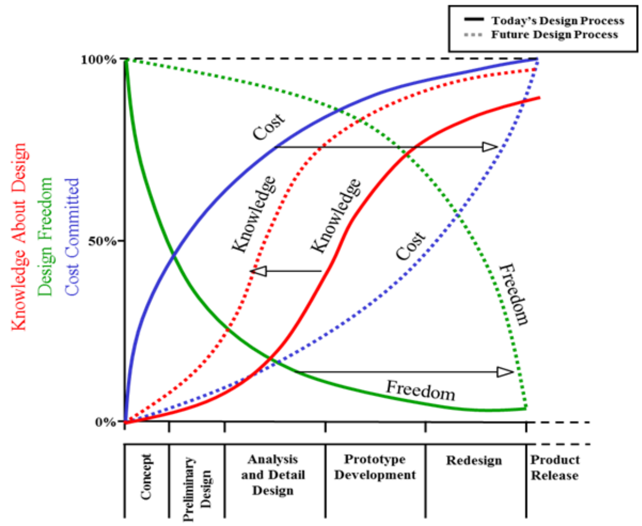

Figure 2. Design Freedom and Cost of Design Change

For this program, a technique pioneered by ASDL, called IRMA (Interactive, Reconfigurable, Matrix of Alternatives), was used to assist in the management and exploration of vast combinatorial spaces that are commonly experienced in early conceptual stages of design. The IRMA process organizes a functional decomposition of programmatic requirements and defines alternative mechanisms to carry out each function. A subset of the IRMA developed for this program is provided in Figure 3**.**

Interactive Reconfigurable Matrix of Alternatives - IRMA

	Option 1		Option 2		Option 3		Option 4		Option 5		Option 6	
Locomotion	Crawler		Multirotor	yes	Slither/Serpent		Hopper		Flapping Wing		Lighter than Air	
Communication	Wifi	yes	Bluetooth		Optical		Wired		Acoustic			
Power	Battery	yes	Capacitor		Fuel Cells							
Sensor - Mapping	Microphone		LIDAR	yes	Chemical Sensor		SONAR		RADAR		Stereo video	
Processing - Nav.	Panda Board	yes	PIC		Custom board		Offboard PC					
Processing - Movement	Ardupilot		Open Pilot	yes								
Sensor - Location	GPS		Gyros		Magnetometer		IMU	yes				

Figure 3. IRMA with Functional Alternatives Highlighted to Generate A Single Notional Concept.

Compatibilities between various functional alternatives are captured in a pairwise compatibility matrix that assists in enumerating concepts that are feasible in terms of functionality. The compatibility matrix is a mapping between all possible alternatives across the entire functional spectrum shown in Figure 3**.** Incorporating a compatibility matrix into the conceptual design phase ensures a first-order filtering mechanism for infeasible concept threads in the IRMA. It is important to point out here that a compatibility matrix like the one shown above only captures disabling combinations of functional alternatives. For example, selecting 'Flapping Wing' and 'Sonar' as alternatives to fulfill the functions of 'Locomotion' and 'Sensor-Mapping', respectively, may describe an incompatible pairing. If a new technology existed as a functional alternative in the IRMA that made it possible for these two alternatives to be combined into a feasible concept, its activation would not capture the transition of this pairing from infeasible to feasible. While we recognize this slight shortcoming, we accept it during this stage of the design process as the primary objective is to pare down the concept space to a set of promising concepts. Furthermore, identification and investigation of compatibility-enabling technologies is captured in a different phase of the design process laid out in Figure 1 and will be discussed in a subsequent section.

The IRMA is capable of leveraging various types of qualitative and quantitative data to provide first order comparisons between feasible concepts. However, if quantitative data is incorporated into the IRMA it typically exists as a knowledge database – gained from previous research – or is generated using "back of the envelope" calculations and input from subject matter experts. The IRMA generated approximately $1x10^{32}$ UAV concepts for the Winning Program. Activating compatibilities reduced that number to 17,280. Compatibilities clearly play a significant role in paring down the conceptual space during early stages of design, but even with this initial filter, it's quite obvious that detailed physics-based assessments for each concept is out of the question.

Each functional alternative was quantified and measured against operational and system-level MoE's and MoP's in order to establish a level playing field to compare radically different concepts. Table 2 provides a subset of the alternative rankings that revealed the most promising UAV concepts based on customer preferences which were captured as importance weightings on the high-level MoE's and MoP's generated as a result of requirements decomposition.

Table 2. Scoring Example - Top Two Alternatives

Rank	Locomotion	Communication	Power	Sensor-Mapping	Processing-Navigation	Processing-Movement	Sensor-Location
1	Flapping Wing	Wifi	Battery	LIDAR	Panda Board	Open Pilot	IMU
2	Multirotor	Wifi	Battery	LIDAR	Panda Board	Open Pilot	IMU

The most promising concepts were then examined more closely in an attempt to pare down the concept space to a single candidate to carry over into the next phase of design. After careful consideration, the multirotor concept (ranked #2 in Table 2**)** was identified as the most promising UAV candidate.

Integrating the IRMA into the design methodology illustrated in Figure 1 equips designers with a systematic process of down-selecting from a vast combinatorial concept space to a handful of promising concepts to bring forward into the next stage of design. This down-selection process is a critical element in the proposed framework as a means of managing the level of effort required in later stages of design that involve the development of multi-fidelity, multi-domain cyber physical components that enable virtual verification studies to be performed.

To recap, the methodology described in this paper thus far has provided a detailed account of translating requirements into quantifiable engineering characteristics that provide structure and guidance in terms of decomposing the functional architecture of potential design concepts. This functional decomposition is then coupled with a qualitative and quantitative assessment of functional alternatives to pare down the concept space to a handful of concept threads. These concept threads define a single design architecture that embodies all required functionalities of the product as dictated by the requirements. At this stage, the concept simply identifies an instantiated set of functional classes that it will utilize to perform required operations. It is still not understood what the final product will look like (although a rough idea may exist), how it will perform, or how it will be assembled. At this point, the design team begins to transform these vague functional concepts associated with the most promising concept threads into logical and physical artifacts that better define their associated physics, interfaces, and their intrinsic/extrinsic properties. The definition of these artifacts is an iterative process that depends on the required fidelity of the modeling efforts as dictated by the requirements. For example, requirements may be defined in terms of thresholds (e.g. vehicle much weigh less than 10 lbs to facilitate transportability by ground troops) and confidence intervals (e.g. +/- 0.5 lbs). Lower fidelity models that estimate component weight as a function of average density and approximate volume may not be capable of satisfying the required accuracy and precision of the weight requirement due to their simple formulation. Van der Velden "(Van der Velden, 2013)" discusses the use of model tolerances to capture this type of uncertainty in complex systems design. The key takeaway here is that the designer has limited knowledge at the onset of conceptual design to determine an appropriate level of model fidelity in an attempt to comply with programmatic requirements. However, Van der Velden describes a systematic process that leverages hierarchical model abstraction to identify models whose fidelity are key suspects for a system's inability to comply with programmatic requirements while maintaining an acceptable level of computational efficiency. These critical models are identified as candidates to undergo development in an attempt to increase fidelity and subsequently reduce error tolerance.

3.3.1 Transformation of Functional Concepts to Physical Artifacts

At the conclusion of this stage in the design process, the team has identified a promising functional concept utilizing the IRMA tool that consists of a multirotor system with a suite of sensor and communication devices necessary to perform the operations laid out in the requirements. In order to transform the functional concept into an artifact that could eventually be manufactured, a series of transformations are initiated that help define the parameters, properties, and characteristics that uniquely define the behavioral aspects of each functional mechanism. The product of this transformation process is a physical description of each functional concept. In other words, the multirotor concept that was chosen to provide locomotion is decomposed physically into its constituent parts, and each part is characterized in terms of its unique parameters, properties, and behavior. It is important to note that at this point in the design process, the designer has limited knowledge in terms of how specific characteristics of each component will impact the system's overall capacity to meet requirements. Therefore, it is in the designer's best interest to initiate the physics-based analysis stage with low-fidelity models for a few reasons: (1) Using low-fidelity models may be sufficient to meet programmatic requirements (2) the design process illustrated in Figure 1 supports iteration on model fidelity based on compliance with requirements and (3) at this stage, low-fidelity models will shift the focus from model development to gaining a better understanding of the system behavior. The following section will describe this process and how tools such as ENOVIA and Isight made it possible to conduct physics-based simulations.

3.4 Concept Sizing Utilizing ENOVIA and Isight

With the most promising concept identified, the next step involves sizing the candidate design to the mission. Composing the requirements and logical portions of the design is made possible within the ENOVIA environment. ENOVIA provides an organized and traceable way to link requirements to the system design. Once a promising concept is identified from the IRMA, a library of first-order models is developed that describes the behavior of each component. The library typically consists of low-fidelity behavioral models that identify the parameters and properties of each component that are required for sizing and synthesis analyses. Isight enables designers to define appropriate ranges for each parameter that can be changed in a parametric fashion during sizing and synthesis. Isight can then sample these ranges in order to efficiently explore the design space.

3.4.1 Isight implementation

The goal of utilizing Isight is to provide a tool to determine the size of the multirotor concept; more specifically, the size of the rotors, the pitch of the rotors, and the required RPM of the motors. With this information, the overall size of the platform can be determined. With the weight build up from ENOVIA, the amount of thrust required is calculated with a goal of thrust equal to weight at half power. This provides extra power for actual maneuvering the vehicle and is a common rule-of-thumb for thrust requirement. For this problem, both a design of experiment (DoE) and a built-in optimizer setup are considered in determining the most appropriate method for sizing the multirotor concept. The DoE approach uses discrete settings of inputs as shown in Table 3. The Matlab code is then executed with variations on input parameters as dictated by a Latin Hypercube DoE to determine the thrust of the multirotor concept. Figure 4 illustrates the optimization layout in Isight. The results of the runs are collected in a table and human judgment is used to select the best design from the feasible set. However, this approach omits potential optimal designs that might exist in the continuous design space. Therefore, the DoE was then replaced with an optimizer function to identify the optimal design. Isight optimizes the parametric properties of the rotor design as outlined below to determine the rotor design that provides the best performance while adhering to constraints as dictated by programmatic requirements and UAV best design practices.

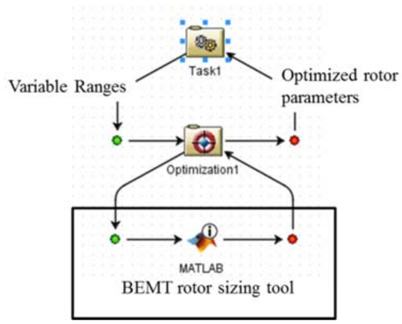

Figure 4. Isight Environment Block Diagram

The Isight environment optimizes rotor parameters that aim to:

Minimize rotor radius - The parameter to optimize is the rotor radius. Because the vehicle flies indoors and must be transported prior to its mission, the rotors must be as small as possible. Furthermore, minimizing the rotor radius will consequently reduce the size of the required UAV frame which will greatly reduce the overall size of the design.

Generate a required thrust value - The rotor must be capable of generating sufficient thrust to lift the UAV off the ground. Estimating weight for each of the subsystems identified in the IRMA will establish a payload weight that will be used to quantify the required thrust. A rule-of-thumb for UAV design is lift-off capability at half-power.

Adhere to design guidelines established by subject matter experts - Design variables were selected based on available components characteristics as well as from subject matter expert opinion. The main rotor design parameter ranges are shown in Table 3.

Table 3. Design Parameter Ranges

Parameter	Lower Bound	Upper Bound	Unit
Chord	0.01	0.03	meter
Pitch	1	6	degrees
Angular Velocity	15,000	20,000	RPM

3.4.2 BEMT rotor sizing code

The optimizer was using an external rotor sizing code to perform its optimization process. This code is an in-house, Matlab-based Blade Element Momentum Theory (BEMT) code that evaluates the performance of a rotor in hover mode. Given rotor characteristics and angular velocity, it returns the thrust and the power required by the rotor.

3.4.3 Optimized design

The characteristics of each rotor that accomplish sufficient lift while simultaneously minimizing rotor diameter are shown in **Table 4**. Assuming that each rotor would operate in the same fashion, the total thrust of a multirotor concept could be calculated using the results in Table 2by multiplying the thrust data by the number of rotors used. For example, Table 2 assumes a quadrotor concept that would generate a total thrust of 1,720 grams. This thrust value is very close to the goal of establishing liftoff capabilities at half-power.

Table 4. Optimized Design Parameters

Parameter	Lower Bound
Chord	0.03 m
Pitch	4.1 degrees
Angular velocity	15,000 RPM
Thrust	4.2N
Power required	75W
TOTAL THRUST	~1720 grams
TOTAL WEIGHT	~900 grams

Table 4 outlines the results from a first-order sizing and synthesis simulation that highlighted an optimized rotor design for the concept under study. These results represent a first measure of the multirotor concept feasibility with regards to programmatic requirements. Obviously, this type of analysis is not sufficient for accomplishing the objectives of virtual experimentation and verification as outlined throughout this paper; however, it is critical first-step in assuring the existence of feasible space (at least from a behavioral perspective). In order to facilitate virtual experimentation and verification that encompasses behavioral and manufacturability concerns, the team will iterate on the component models that they have developed thus far to incorporate the appropriate model features. These features may include aspects such as structural definitions, 3-D physical representations (CAD), higher fidelity behavioral models, manufacturability and/or procurement data for each component, and most importantly, the integration of these different modeling aspects into a single component artifact. This type of multi-aspect, multi-fidelity modeling effort will eventually establish a cyber-physical component model library that will enable virtual experimentation and verification for UAVs in the Winning Program. A discussion of cyber physical component modeling and virtual verification follows.

3.5 Developing a Cyber Physical Model Library

Cyber physical components embody the integration of computational and physical processes within a system and act as the building blocks of larger, more complex systems. In the context of this paper, a cyber physical component is a virtual representation of a real-world system that captures sufficient detail regarding its physical features (dimensions, shape, interfaces), behavior, and when available, manufacturing and procurement information (e.g. cost, lead time, shipping weight, etc.). Capturing this information in a single artifact provides users with sufficient data to make intelligent design decisions in a "plug and play" fashion and enables more sophisticated analyses to be performed.

The definition and management of cyber physical components within a complex system can be handled by a series of systematic physical decompositions until the desired granularity is met. Oftentimes, programmatic requirements and goals will dictate the required granularity. For example, the DARPA AVM program aimed to reduce the design timeline of complex military vehicles by a factor of 5 which, for the FANG 1 challenge, resulted in a physical decomposition of an amphibious assault vehicle powertrain that included components such as engines, transmissions, waterjets, and drive shafts "(Adaptive Vehicle Make (AVM))". The combination of programmatic requirements and the complex nature of the vehicle under study led to the realization that redesigning engines or transmissions from the inside-out – which are highly specialized for this class of vehicle – was outside the scope of the AVM program.

Figure 5 provides a notional cyber physical representation of an engine to illustrate the various aspects that make up these complex building blocks.

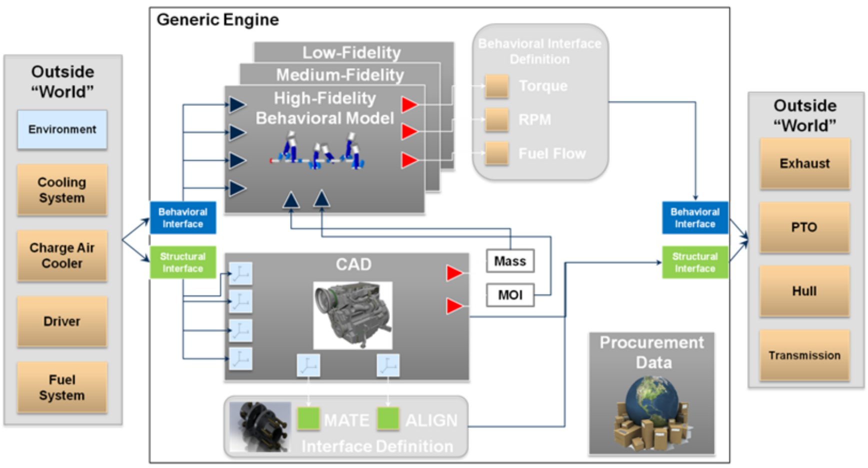

Figure 5. Cyber Physical Engine Component

The diesel engine component shown in Figure 5 illustrates the multi-aspect, multi-disciplinary nature of cyber physical components discussed throughout this paper. As shown in Figure 5**,** a component interacts with the "outside" world through structural and behavioral interfaces. Inside the component, the information relayed through the structural and behavioral interfaces is routed to different aspects of the component such as CAD and Modelica models. A critical aspect of this component is the connectivity between the multiple component aspects. In particular, this definition of a component promotes a dynamic link between CAD and behavioral models (shown in Figure 5 with Mass and MOI). Parametric components that provide designers with one or more degrees-of-freedom (DoF) are managed by exposing the DoF's at the top-level of the component and linking that parameter to the appropriate aspects. Defining the DoF's at this level ensures that there is no discrepancy between the physical and behavioral aspects of the component.

3.6 Virtual Experimentation and Verification

This paper aims to present a revolutionary approach to the design of a UAV by presenting a methodology that focuses on eliminating, or at least minimizing, the iterative design-build-test-redesign cycle that plagues many complex engineering projects. This goal requires that the majority of subsystem- and system-level analyses exist only in a virtual context (i.e. absent of physical prototyping). In order to accomplish this, state-of-the-art methods and computational resources must be leveraged to sufficiently analyze designs in virtual environments, representative of those in which the real-world system will operate. To manage this effort, this paper will introduce the concept of a test bench, a term rooted in the testing of electrical hardware where an engineer would sit at a bench and verify the operation of a device-under-test. A test bench can be used to verify the operation of a cyber physical system at any hierarchical level. For example, a test bench can be designed to analyze the thrust-curve of a UAV powerplant or to assess the take-off distance of a full UAV. Regardless of the context, every test bench developed for a particular system should exhibit some amount of traceability to programmatic requirements.

The design methodology presented in this paper supports continuous, transparent, and traceable threads that will establish a dynamic link between program requirements and simulation test benches. This will enable simulation results to be directly compared to program requirements to assess compliance. The V6 ENOVIA platform is used to perform the requirements decomposition and supports the generation of alternative concepts. It also serves as the backbone to the overall framework and allows designers to identify the link back to requirements from any point in the process. This dynamic link between requirements and simulation testbeds will assist designers in managing evolving requirements. As requirements are altered throughout the design process, designers will be able to trace how those changes impact the system and will identify testbeds that need to be re-simulated for requirements compliance. This practice will result in a mapping between programmatic requirements and specific simulations (test benches) – enabling a structured framework for verifying a systems compliance with requirements. Figure 6 provides a notional test bench for a UAV and offers an example of how the simulation output can be directly mapped to programmatic requirements.

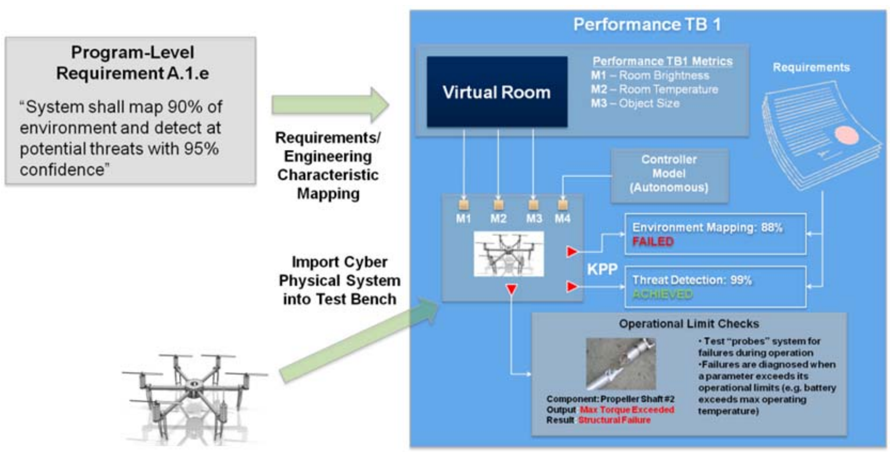

Figure 6. Notional Test Bench Illustrating Mapping between Requirements and Virtual Simulations

Every test bench is a virtual representation of the real-world environment that the system will operate in. In order to support the methodology proposed in this paper – specifically, the notion of replacing physical prototyping with virtual experimentation – each test bench must be capable of sufficiently representing those real-world environments. As such, a critical aspect of each test bench will be its capacity to capture uncertainty in the operational environment.

In order to accomplish this, each test bench will be parameterized to capture uncertainty in the operational environment by allowing users to define operational characteristics as inputs. In this manner, sampling techniques – such as Monte Carlo Simulation – can be applied to the test bench in order to assess the feasibility of the system to meet operational requirements under uncertainty. In addition to the uncertainty of operational environment parameters, the user may define component parameter tolerances based on model fidelity to capture epistemic uncertainty in the virtual experimentation framework. Capturing the uncertainty of operational and system characteristics will be a critical element of enabling virtual verification of complex systems as a replacement for physical prototyping studies. Figure 7 provides an illustration of capturing uncertainty in a test bench.

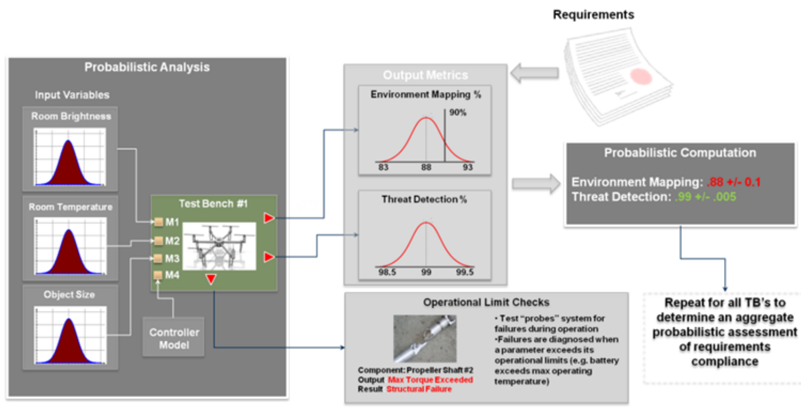

Figure 7. Capturing Uncertainty in Test benches

3.7 Design Space Exploration

The user now has an extensible library of cyber physical components that embody physical, behavioral, manufacturing, and procurement aspects into a single package or "lego block" that enable a plug-and-play functionality. The information contained within each component artifact is used to assist the designer to make intelligent decisions while considering the various aspects of design and to gain an appreciation for the impact of their decisions on the overall variability of the product regarding requirements compliance. However, at this point the user has only been provided with a library of components (this of this like a new box of legos), a set of goals (requirements), and a relatively vague design concept ("build a UAV utilizing a LIDAR sensor"). With this limited set of information and guidance, the user is still confronted with a combinatorial problem.

The management of the decisions that need to be made at this stage of the design process is supported by two enabling tools: (1) virtual test benches and (2) CATIA Knowledgeware. As described previously, a test bench is a simulation artifact that ensures design compliance with programmatic requirements by identifying the appropriate simulation environment and any metrics of interest (e.g. key performance parameters or KPPs) that are to be used to "probe" the results of physics-based simulations. The test benches provide the user with guidelines in terms of the functions the design must perform and any important metrics associated with the successful execution of that function. For example, a requirement may state that the system under design must be capable of hovering at a specified height for a minimum of three minutes. A test bench that examines the system compliance to this requirement must – at a minimum – quantify the definition of hover (perhaps as a ground clearance), identify the means of propulsion (some force that counters weight), describe any environmental specifications, and include a timer. A series of similar test benches will provide the user with a set of goals that the system must achieve in order to comply with the programmatic requirements. In this manner, the user can define a manageable set of tasks to carry out the system design. However, it is important to note that at this point, the user still has complete design freedom as to how the system will carry out the function prescribed by each test bench. In other words, the user will recognize the need for the system to hover, but the mechanism by which hovering is accomplished by the system is still up to the user and is constrained by the set of components contained in the component model library.

The second tool that helps to manage design decisions does so in a very different way than test benches. The tool is CATIA Knowledgeware expertise, corporate IP, and industry design standards in a systematic process and its primary role in complex systems design is to shift the engineers design focus from mundane, repetitive tasks to "high-value" work. It accomplishes this by capturing that supplies engineers with design templates that act as starting points for innovation. These templates automatically carry out routine (but necessary) tasks by leveraging automated flow structured defined in BKT/BK2. However, it's important to note that while these templates automate the repetitive, "low-value" design processes, they also capture the degrees of freedom in the system under study. It's these degrees of freedom that appeal to engineers as "high-value" work because they allow designers to channel innovation.

CATIA Knowledgeware will be used to automate the process of developing seed designs from the component model library by adhering to proven UAV workflows as established by ASDL's Design Build Fly (DBF) and MAST teams. The goal of this effort is to leverage CATIA Knowledgware to diversify the seed architectures composed from the cyber physical models contained in the component model library while adhering to UAV best practices in manufacturing and design. These seed architectures establish the system templates that enable designers to utilize "plug and play" functionality and leverage efficient sampling techniques (e.g. design of experiments) to explore the parametric design space.

4. Conclusion and Future Work

This paper has focused on providing a detailed account of a design framework developed by the ASDL to enable virtual experimentation and verification of cyber physical models with special focus on the UAV work being conducted as part of the Winning Program with Dassault Systèmes. The framework emphasizes the importance of decision-making in the early stages of design and leverages tools like IRMA and Knowledgeware to help manage vast combinatorial spaces, pare down concept spaces to the most promising alternatives, and remove mundane engineering tasks from the typical design process to enable engineers to focus on innovation through "high-value" work. At the time of writing this paper, the team has successfully developed a first-order, integrated modeling and simulation environment leveraging in-house physics-based formulations to size the most promising concepts according to the specified mission (captured in the programmatic requirements). Mapping requirements to high-level system characteristics and performing physics-based simulations were made possible by the use of ENOVIA and Isight. Future efforts will involve the use of the integrated CATIA V6 platform to develop and compose a library of cyber physical models that capture the functional, logical, and physical elements of the UAV system under study. The development of these components is guided by the IRMA results and each component will continue to evolve throughout the design process as necessary – in terms of the amount of information they capture and model fidelity – based on the results of the virtual verification studies. The final product will be a robust cyber physical system that complies with all programmatic requirements and is readily manufacturable as a result of (1) capturing manufacturing aspects in each component and (2) embedding best practices in manufacturing and assembly into the design process through CATIA Knowledgeware. The Winning Program team will develop a physical prototype of the UAV concept that results from the design process described in this paper. The team plans to examine the behavior of the physical prototype and compare it to the results of the virtual tests in an effort to identify areas of improvement. The design framework and processes that makeup the illustration in Figure 1 will continue to evolve as new methods and techniques are developed and knowledge is gained through physical prototyping with the end goal of establishing a virtual experimentation and verification framework that accurately depicts real-world behavior.

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