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Physics-Based Distributed Collaborative Design for Aerospace Vehicle Development and Technology Assessment

Raymond M. Kolonay[a]
[a]United States Air Force Research Laboratory, WPAFB, Ohio 45433

Abstract. One of the missions of the United States Air Force Research Lab (AFRL) is to develop and assess technologies for next generation aerospace systems. Currently, the assessment is achieved using empirical relationships and historical data associated with systems developed previously. The assessment is done in this fashion due to resource constraints on time, personnel, and funding. Performing technology assessment in such a fashion, although timely, is not necessarily accurate. This is due to the fact that many of the technologies and system configurations being evaluated have no historical or empirical information associated with them. Hence, traditional assessment techniques produce misleading results and subsequently ill-informed decisions by Air Force leadership associated with technology investment and potential future system capabilities. To address this issue the Multidisciplinary Science and Technology Center within AFRL's Aerospace Systems Directorate is developing physics-based design exploration and technology assessment methods and processes. The new methods and processes utilize physics-based analyses and a distributed collaborative computational environment to predict vehicle performance which in turn is used in mission level simulations to assess the impact of a given configuration or technology on the combat effectiveness of a system. The new methods and processes will be executable within the same time and resource constraints of the traditional process. This enables AFRL technology developers to have a quantifiable and traceable trail of the impact of their technologies on system performance parameters such as weight, lift, and drag into terms that Air Force leadership measures system effectiveness – lethality, survivability, sustainability, and affordability. This leads to well informed decisions concerning technology investment and achievable capabilities.

Keywords. multidisciplinary design optimization, collaborative design, network computing, physics-based design, Service ORiented Computing EnviRonment (SORCER)

Introduction

One of the missions of the United States Air Force Research Lab (AFRL) is to develop and assess technologies for next generation aerospace systems. Currently the majority of the assessments are achieved using empirical relationships and historical data associated with systems developed previously. The assessments are done in this fashion due to resource constraints on time, personnel, and funding. Performing technology assessment in such a fashion, although timely, is not necessarily accurate. This is attributed to the fact that many of the technologies and system configurations being evaluated have no historical or empirical information associated with them. Hence the traditional assessment techniques produce misleading results leading to ill-informed decisions by Air Force leadership associated with technology investment and potential future system capabilities. To address this issue the Multidisciplinary Science and Technology Center within AFRL's Aerospace Systems Directorate is developing physics-based design exploration and technology assessment methods and processes to support Air Force leadership decisions on potential system capabilities and technology investments. The new methods and processes utilize physics-based analysis methods and a distributed collaborative computational environment to predict vehicle performance which in turn is used in mission level simulations to assess the impact of a given configuration or technology on the combat effectiveness of the system. The new methods and processes will be executable within the same time and resource constraints of the traditional process. A high level representation of the desired technology assessment process is depicted in Figure 1. It consists of the following areas: strategic guidance, system specification and concept of operations, mission assessment/combat effectiveness, and physics-based system and technology performance. The primary differences in the proposed process compared to current practice occur in two significant ways. First the use of a physics-based system and technology performance instead of empirical or historical information and second the feed forward of this information to evaluate mission assessment and to influence the concept of operations and system specifications. What follows in this manuscript is a brief description of each of the areas in Figure 1 with a detailed discussion on what is contained in the Physics-based System & Technology Performance area, its relationship to Mission Assessment and Concept of Operations and System Specifications, and examples of its implementation and usage.

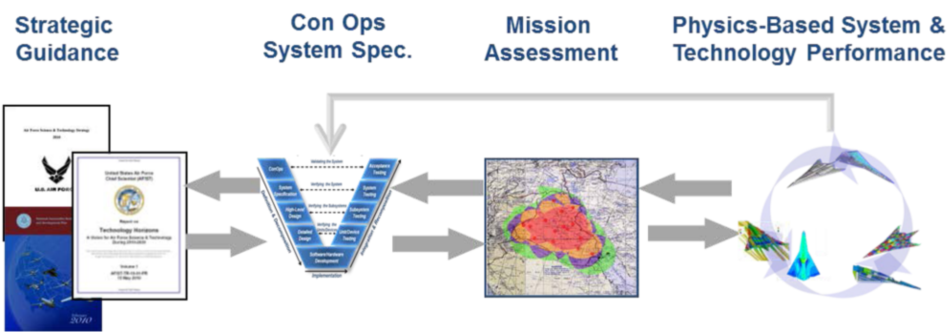

Figure 1. Technology Assessment Process

1. Strategic Guidance

To obtain an understanding of the area of strategic guidance it is best to take a brief look at the US DoDs acquisition process. This is depicted in Figure 2. AFRL's technology development and assessment role takes place primarily pre-milestone B (Concept Refinement and Technology Development). The following description of the interaction between the "customer", those giving strategic guidance, typically one of the Air Force's Major Commands such as Air Combat Command (ACC) or Air Mobility Command (AMC), and the acquisition community (Air Force Material Command) is summarized here from Reference 1. Once the warfighter(ACC, AMC etc..) has identified a need, the early Systems Engineering and JCIDS (Joint Capabilities Integration Development System) processes begin, where DoD strategic guidance, joint operating concepts, and joint functional concepts are considered as inputs to the DOTMLPF (Doctrine, Organization, Training, Materiel, Leadership & Education, Personnel, and Facilities) evaluation to determine if indeed a materiel solution is needed. A gap analysis is performed while considering user needs and technology opportunities. Operational requirements are then generated. This is the first decision point in the process. If it is determined that a material solution is required to meet the needs and required capability the formal acquisition process for the system(s) is kicked-off. Otherwise, the need is satisfied with existing capabilities within the DoD. If it is determined that a material solution is required this leads into the conceptual design phase of the system and eventually into an Analysis of Alternatives (AoA) process where the most promising solutions are compared in detail to select a preferred concept to move forward into technology development processes. There is/should be a continuous communication between the acquisition community and the customer (those providing the strategic guidance) to ensure that the customer capability requirements are well defined and for the acquisition community to convey to the customer if the desired capability is possible to deliver with existing technology, what the cost will be, and what is the risk associated with delivering that capability.

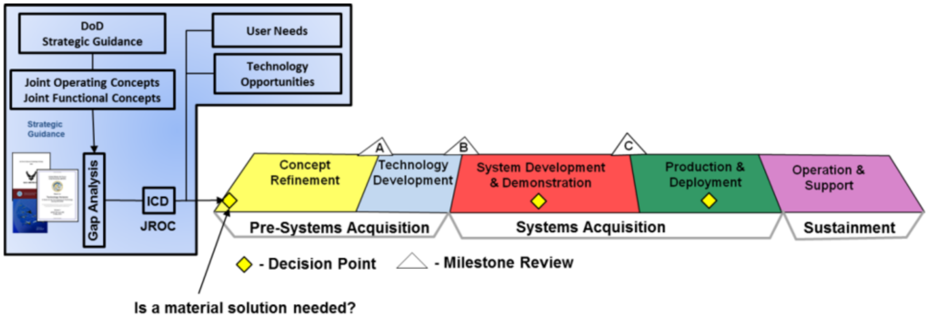

Figure 2. US DoD Acquisition Process

2. Concept of Operations and System Specifications

Returning to Figure 1 and focusing on the Concept of Operations and System Specifications, once it is determined that a material solution is required and the desired capability is identified the acquisition community begins to develop concept of operations and system specifications. At this point in the process a rigorous Systems Engineering Approach is employed (Figure 3).

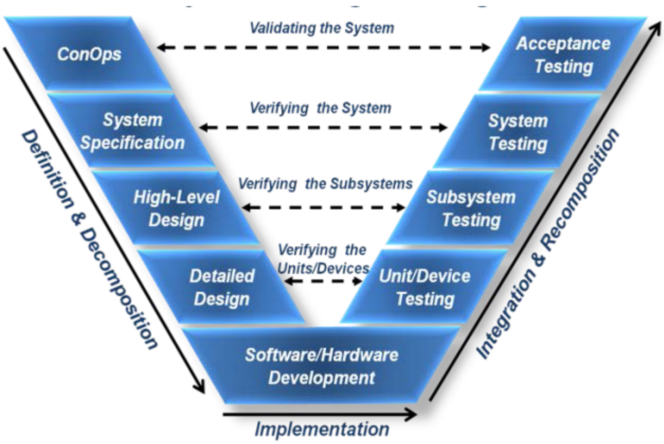

Figure 3. Acquisition Process Systems Engineering "V"

Shown in Figure 3 is the Systems Engineering "V" that represents the system throughout the acquisition process. In this particular phase the portion of the "V" that is being determined is "ConOps" or concepts of operation and system specifications. The goal is to use Systems Engineering to transform the operational needs identified by the strategic guidance into a description of system performance parameters and a system configuration through the use of an iterative process of definition, synthesis, analysis, and design. As Figure 1 indicates this takes place through an iterative process with the customer to identify/refine operational needs/desirements and the mission assessment team. To determine the concept of operations and systems specifications requires the consideration of multiple alternatives and architectures. These alternatives must be modeled and evaluated and scored based on customer needs. Currently, the modeling of the system is performed using traditional conceptual design information based on historical and or empirical information. A goal of the new process is to utilize physics-based models in this process. This is indicated by the feedback arrow between the "ConOps/System Specifications" block and the "Physics-based System & Technology Performance" block. At a minimum the physics-based models should be used to validate the conclusions made for concepts of operation and system specification before they are finalized.

3. Mission Performance/Assessment

Once a set of concept of operations and systems specifications are identified, the mission performance and combat effectiveness of a given system(s) is assessed. This is achieved using modeling and simulation (M&S) tools [2],[3],[4],[5]. These tools are typically capable of performing three levels of assessments: single-sortie analysis, mission-area analysis, and campaign analysis. A taxonomy for classifying M&S is live, virtual, and constructive. Live M&S implies a human operating a physical system. Virtual represents a human operating within a virtual environment, and constructive consists of a completely computer simulated environment (both user and system response). The M&S environment has representative models for both the friendly "blue" components and the adversary or "red" components for a given mission. As an example Reference [3] gives a use case for a penetrating intelligence, surveillance, and reconnaissance (PISR) mission. Models of blue components would consist of an air-breathing platform equipped with an electro-optical (EO) sensor that provides high-detail imagery for final target identification. Representative red components would consist of the integrated air defense system (IADS). This would include modeling commanders, weapons managers, surface to air (SAM) sites, sensor managers, and radar sites. For assessments carried out for such a single-sortie analysis or mission-area analysis the performance is usually measured in terms of war fighter/customer capability such as lethality, survivability, sustainability, availability, and affordability. These measures can be quantified by determining target kills per sortie, probability of target acquisition, probability of availability, probability of detection, and probability of survivability. In order for the M&S tools to perform the mission assessment they require inputs that describe the physical features and capabilities of the system. For example; vehicle speeds, turn rates, range, loiter time, specific excess power for a given maneuver, weapons load, weapons performance, vehicle radar signature, and sensor performance. This information is required throughout the entire mission profile. The fidelity of the air vehicle data cited above affects the accuracy of the performance assessments. The interest in this work is associated with the modeling of the vehicle performance such as speeds, turn rates, range etc.. and not of the representation of the sub-systems such as on board radar or weapons. Today's common practice is to model the vehicle performance using traditional conceptual design models that are based on empirical equations and historical databases for the vehicle capabilities throughout the mission. There is little or no physics-based analyses carried out to obtain this information. As mentioned previously, this is due to resource constraints on time, personnel, and funding associated with creating and executing the models. Unfortunately, performing vehicle capability and technology assessment in such a fashion, although timely, it is not necessarily accurate. This is due to the fact that many of the technologies and system being designed or evaluated have no historical or empirical information associated with them.

As an example consider the calculation of cruise range using the Breguet range equation[6]

$$R = \frac{V}{C}\frac{L}{D}\ln\left(\frac{W_{i-1}}{W_i}\right) \qquad \text{Eq (1)}$$

R is the range, *C* the specific fuel consumption, *V* the velocity, *L/D* the lift-to-drag ratio, and W_{i-1} and W_i are weights of the vehicle at the beginning and end of the mission segment. Let's consider the vehicle weight. It will change during the mission segment due to fuel burn and potentially store release (external fuel tanks in the case of PISR) but the empty weight We will remain constant. In Reference [6], Raymer has a series of weight equations broken out into components and subsystems for the vehicle depending in the class of vehicle for We. Raymer identifies three classes of vehicles, Fighter/Attack, Cargo/Transport, or General Aviation. For the Fighter/Attack the wing weight sub-component is given as

$$W_{wing} = 0.0103 K_{dw} K_{vs} \left(W_{dg} N_z\right)^{0.5} S_w^{0.622} A^{0.785} \left({}^{t}/_{c}\right)_{root}^{-0.4} (1+\lambda)^{0.05} (cos\Lambda)^{-1.0} S_{csw}^{0.04} \quad \text{Eq (2)}$$

Where K_{dw} = .768 for delta wings, 1.0 otherwise, K_{vs} = 1.19 for variable swept wings, 1.0 otherwise, W_{dg} is the design gross weight, N_z the ultimate load factor, S_w the trapezoidal wing area, A – aspect ratio, t/c root – thickness to chord at the wing root, λ is taper ratio, Λ is the wing sweep at 25% chord, and S_{csw} is the control surface area. This is a parametric equation based on a curve fit derived from historical data from fighter/attack aircraft that Raymer had available data. It may or may not be applicable to the current configuration that one is designing. In addition if the designer is attempting to evaluate a new technology that has an effect on wing weight that has never been used on a previous aircraft it will not be accounted for in the above equation. One common approach is to estimate the impact of the technology under consideration on the wing weight using expert opinion and "k- factors". An expert will estimate that a given technology would reduce the wing weight by 10%. With that information the wing weight equation is just multiplied by a "k- factor" of 0.9 to indicate the impact of that technology. This type of approach more often than not compromises the mission effectiveness analysis and leads to erroneous conclusions concerning the impact of a given technology.

4. Physics-Based System Design & Technology Assessment

Examining the far right hand side of Figure 1 we now discuss the development of physics-based system design and technology assessment which is depicted in Figure 3. As discussed in sections 1 through 3, for the development of a new air vehicle, a compendium of complex requirements and objectives are set forth with the specification, among other items, of the aircraft performance, safety, reliability, maintainability, and the subsystems properties and performance. Once the high level set of requirements are established, the conceptual design of potential configurations that meet those requirements are explored. The results of these conceptual designs are used to feed the input requirements for the mission assessments described in section 3. As mentioned previously, in the conceptual phase, the vehicle and its performance are represented by a series of parametric equations and empirical relations such as the wing weight equation in Eq 2. Typically in this phase of the design process the number of design parameters is on the order of a few dozen. A representative set of design parameters in such a study are: wingspan, thickness to chord ratios, engine location, engine maximum thrust, and average cruising altitude. Examples of constraints on the design problem includes: maximum take-off distance, maximum landing distance, and minimum *Cl/Cd*. Two such programs that perform conceptual design of aircraft in this fashion are FLight Optimization System (FLOPS)[7] and AirCraft SYNThesis (ACSYNT)[8] program.

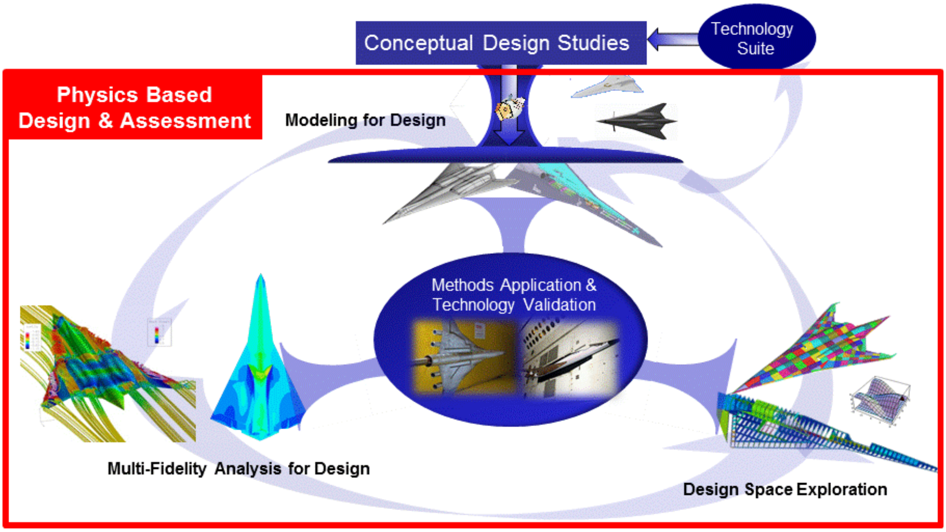

Figure 3. Physics-Based System Desing & Technology Assessment

During this phase of the development process a technology suite that will potentially be included in the system is identified. The set of technol¬ogies selected depends on the time frame that the capability is desired. In general technologies are classified as near term, mid term and far term. Although there are no standard times asso¬ciated with near, mid, and far term, typically near term is within 4 years, mid 5-10 years out, and far term is 10-20 years on the horizon. Hence the technology suite chosen is time dependent. As an example a set of technologies identified for the PISR for the mid term may be; active aeroelastic wing, advanced laminar flow - distributed roughness ele¬ments, dielectric barrier discharge actuation for separation control, and ultra-light multi-function airframe concepts - integrated structural antennas. Once the suite of technologies are identified a conceptual design study is carried out. In the conceptual design phase the vehicle and its performance is represented by a series of parametric equations and empir¬ical relations such as the wing weight equation (Eq. 2) (Top of Figure 3). This representation will be referred to as zeroth order fidelity. As cited earlier, examples of software applications that perform air vehicle conceptual design are FLOPS and ACSYNT. As stated in section 3 the current practice for representing a given technology in the conceptual design phase is a series of knock-down or knock-up factors ("k-factors"). For example active aeroelastic wing technology, based on expert opinion, is believed to enable a 10% reduction on GTOW for a PISR configuration. This factor is then applied to the appropriate weight equation (such as Eq. 2) in the concep¬tual analysis application. With the selected technologies and their associated effect factors a conceptual design is performed. Often the zeroth order application is connected to a formal optimization algorithm to produce a concept that has the minimum GTOW with the maximum range. Again, the number of design parameters in such a study is on the order of a few dozen(wingspan, chords, thickness to chord ratios, engine location, engine maximum thrust, and average cruising altitude) and any gradients required are determined analytically or by finite difference. During this phase of the design space exploration tens of thousands configurations of the sys¬tem are explored. This is possible due to the small computation cost(a few seconds on a desktop machine) of determining the vehicle performance using historical databases, parametric equations, and empirical relations.

Once the conceptual design study is completed, the performance and several attributes of the vehicle are obtained. Figure 4 illustrates the resulting output from a typical conceptual study. It is important to note that this information is output as a series of real and integer numbers. There is no physical geometry associated with the results. Hence, a great deal of effort is required before any physics-based analyses can be performed. From the conceptual design the necessary performance parameters (vehicle speeds, turn rates, range, loiter time, specific excess power for a given maneuver, and weapons load etc..) required for the mission M&S can be extracted.

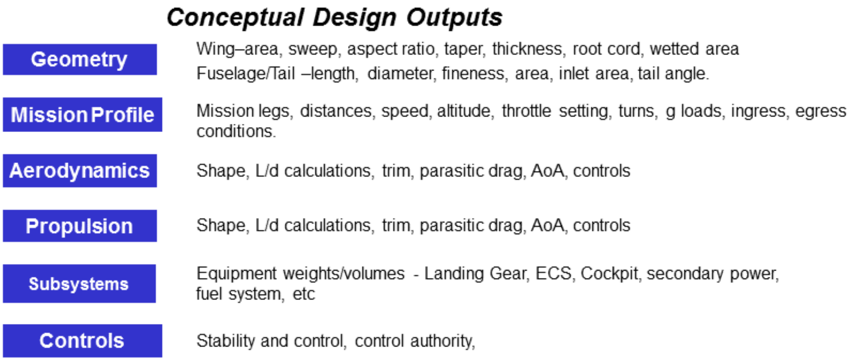

Figure 4. Conceptual Design Outputs

Standard industry practice is to primarily use the results obtained from this zeroth order analysis/design to evaluate the mission performance and technology assessment in the M&S phase of Figure 1. Little or none of the process shown boxed in labeled “Physics-Based Design & Assessment” of Figure 3 is used to impact the conceptual design or the M&S mission assessment. The purpose of this work is to propose and demonstrate a process that uses higher fidelity models based on physics to perform the conceptual design and compute the information required for the M&S analysis. The vision is to merge conceptual design with the following aspects of preliminary design:

- Increased fidelity of disciplines
- Increased number of disciplines considered
- Increase the chaining and couplings of disciplines
- Perform design optimization considering aerodynamic, structural, and control effector design variables simultaneously

The overall goal is to perform design studies and M&S mission assessments with physics-based models with the same resources and time that traditional conceptual design is achieved today. In addition it will enable the evaluation of and maturation of tens of design configurations at a high level of fidelity rather than the one or two that are typically done in a traditional process. If accomplished, three primary benefits can be obtained; data with less uncertainty associated with it for making decisions concerning system capabilities and technology assessment, reduction in the discovery of late defects within the system due to physics, and opening up the design space to enable novel concepts and otherwise unobtainable capability by leveraging the discipline couplings.

4.1. Merging Conceptual and Preliminary Design

Figure 5 illustrates a design process flow diagram or an N2 diagram for a traditional conceptual design process. The blocks on the diagonal represent engineering disciplines (with a level of fidelity) and lines on the upper right represent the feed forward of information or chaining of disciplines while lines on the lower left indicate the feedback or coupling of disciplines. Coupling is defined as the need to simultaneously solve disciplines such as aerodynamics and structures to perform an aeroelastic analysis. Coupling implies a bi-directional dependency. Chaining is defined as the need to sequentially chain analyses together to obtain the necessary result. Performing a pre-stressed structural analysis prior to executing an eigenvalue analysis is an example of chaining. This is a one way dependency. Finally, fidelity refers to the level of physics included in a specific domain.
The disciplines represented in this process are propulsion, weights/mass properties, aerodynamics, mission performance/range, and an optimizer. Each discipline has a level of fidelity of "0" indicating the use of empirical equations and historical information to represent the necessary information for the respective disciplines. Also, this process will be executed in a single location on a single compute resource, usually a desktop.

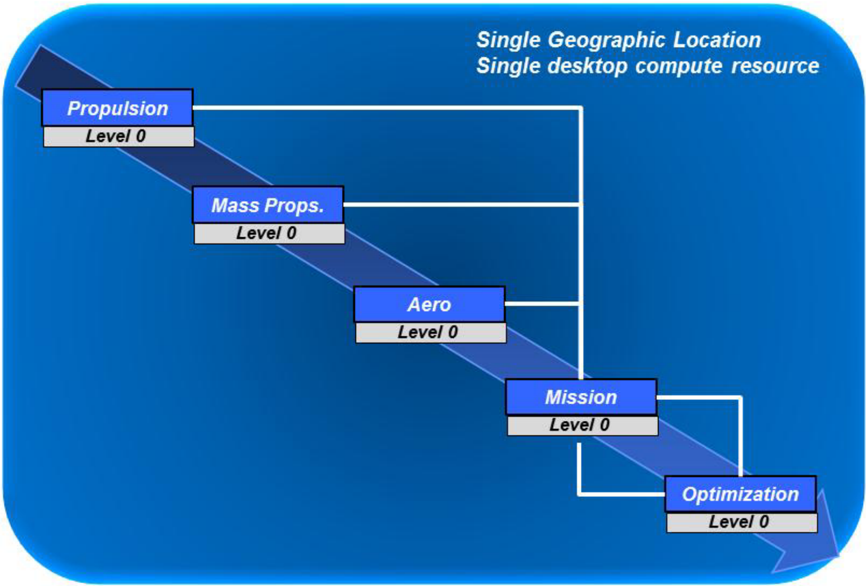

Figure 5. Traditional Conceptual Design Process

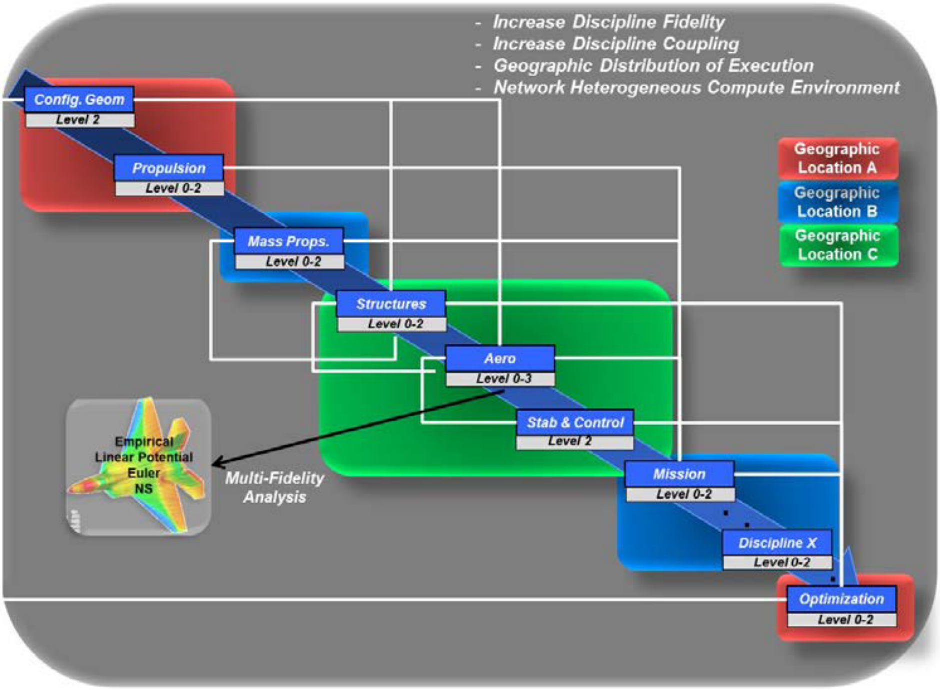

Figure 6. Multi-Fidelity Physics-Based Distributed Collaborative Design

Figure 6 depicts the desired process and is an expanded view of the boxed in area of Figure 4 with increased detail of the “Multi-Fidelity Analysis for Design” portion of Figure 4. Here, it can be seen that additional disciplines have been added, such as structures, stability and control, aeroelasticity (coupled structures and aerodynamics) and configuration and geometry when compared to Figure 5. Also, the concept of multi-fidelity analysis is introduced. Multi-fidelity for aerodynamics is indicated by Level 0-3. Where level 0 is the traditional empirical representation for aerodynamics, linear potential/panel methods are indicated by level 1, level 2 represents the Euler equations, and level 3 would employ the Reynolds Averaged Navier-Stokes (RANS) Equations for computing the aerodynamic quantities. The selection of the fidelity, coupling, and chaining is critical. The appropriate levels of fidelity, coupling, and chaining are those that are required to capture the phenomena that are critical in designing the specified configuration and to accurately assess the specified technology suite selected. This implies that the appropriate fidelity, coupling, and chaining are dependent on the configuration, the flight conditions, and the technology suite selected. Recall that for the PISR example that the technology suite selected consisted of active aeroelastic wing, advanced laminar flow - distributed roughness elements, dielectric barrier discharge actuation for separation control, and ultra-light multi-function airframe concepts - integrated structural antennas. Each of these technologies chosen requires a level of fidelity, coupling and chaining. For example active aeroelastic wing requires a nonlinear aeroservoelastic analysis capability where the transient coupled non-linear aeroelastic analysis will need to be able to capture structural geometric non-linearities and aerodynamic non-linearities possibly including viscous effects.

With the process in Figure 6 vehicle requirements associated with strength, stiffness, buckling, cruise performance, maneuver performance, static aeroelastic stability, dynamic aeroelastic stability, and controllability can be assessed for a given configuration. This is done by carrying out a 'loads' survey, based on the mission profile determined in the concept of operations, to identify the 'critical' set of flight conditions that drive the design of the specified configuration. This results in 100-200 critical conditions that must be considered, performing the design and evaluating technologies. These critical conditions are associated with different ground and air maneuvers throughout the mission and have a wide range of Mach number, altitude, dynamic pressure and control surface settings. In order to perform the design refinement at the critical set of flight conditions, higher fidelity, coupled, and/or chained analyses are required. Now the design parameters are not only the conceptual design variables cited earlier (wingspan, chords, thickness to chord ratios, engine location, engine maximum thrust, and average cruising altitude) but also structural sizing parameters (skin thicknesses, spar thicknesses, spar cap cross-sectional areas and moments of inertia) and control effector parameters (the number, size, and location of control effectors). This brings the total number of design parameters from a few dozen up to thousands. This produces a multidisciplinary, multi-fidelity, optimization problem that needs to be solved during the design space exploration.

A final distinction between Figures 5 and 6 is the fact that in Figure 5 the design is carried out in a single location on a single compute resource, usually a desktop machine. Figure 6 in contrast shows that different discipline blocks may reside at different geographic locations and execute on vastly different hardware. This enables distributed collaborative analysis and design space exploration. This will be covered in further detail later.

The last process component to discuss in Figure 3 is "Modeling for Design". This part of the process represents the bridge between the conceptual representation of the system and a representation that is required to perform physics-based analysis and design. As stated in Figure 4 the conceptual representation of the vehicle is a series of real and integer numbers. There is no physical geometry associated with this representation. In order to perform physics-based analysis and design it requires the solution to integral, ordinary, and, partial differential equations to obtain the necessary system responses. In addition to the responses (pressures, aerodynamic coefficients, structural deflections, structural stresses, etc.) the sensitivities of these responses with respect to the set of design parameters under consideration are also required for gradient based design space exploration and uncertainty quantification. These can be computed analytically, semi-analytically, finite-difference, automatic differentiation, direct methods, and adjoint methods. For complex geometries closed form solutions to the response and sensitivity equations do not exist, hence numerical procedures are used that require representation and discretization of the domain. Finite element and finite difference techniques are commonly used for computing the response quantities of interest. Currently, the process of moving from the conceptual representation to a representation that is necessary to further evaluate the vehicle at a higher level of fidelity is a "choke point". Indeed, the current state-of-the-art is extremely time consuming and hands-on intensive. It is typically accomplished by a designer and/or analyst taking the conceptual design information and using a CAD system to generate a parametric associative model. The model development is based on years of experience and company standards and practices. The parametric associative model must at a minimum have the following attributes: smooth water tight outer mold line, an internal structural layout, and subsystem volumes, locations, and mass properties.

Many in industry are pursuing a “single” parametric associative model referred to as a Master Model. The Master Model concept traditionally contained only geometric information but has now been extended to contain any critical information that may be needed throughout the life of a product. The “single” Master Model is a single logical representation of the product that may be distributed geographically or between several different databases or applications. The point being that there is a single representation of the product without any duplication of information. All users begin from and update a single representation of the product to insure consistency. A CAD system (UniGraphics, ProE, Catia etc.) along with a PDM (e-Matrix, Windchill etc.) system are typically combined to create a Master Model. Many companies are also coupling the Master Model with knowledge based engineering (KBE) systems resulting in what is called an “Intelligent Master Model” (IMM) [9],[10] or “Smart Product Model” (SPM) [11]. This allows design intent and rules to be maintained with the model along with the model representation itself. Typical KBE systems employed are AML [12], Intent [13] and UG Knowledge Fusion [14]. A few features that are desirable for the IMM are:

- Ability to quickly generate a representation of the product.
- Support parametric and topological changes.
- Ability to quickly generate the domain specific analysis & design models
- Capture the knowledge and design intent of the product.

Within the Multidisciplinary Science & Technology Center(MSTC) two approaches are being explored to address the first three items listed above. One approach is “CAD light” focused on high fidelity geometry, specifically Constructive Solid Geometry (CSG), based on the OpenCSM code that can be driven by the Electronic Geometry Aircraft Design System (EGADS)[15]. The work in Reference [15] currently focuses on the ability to quickly generate attributed, parametric, associative models of the system that can be used for higher fidelity analysis models (level 3 and 4 fidelity) and can eventually have a linkage to manufacturing. The second approach developed by Alayanak[16] called MSTC-GEOM is not CAD based and is focused on the generation of level 1 and level 2 fidelity models. Specifically, aerodynamic, structural, and mass property components for analysis and design models. The primary goal of MSTC-GEOM is to automate the creation of analysis models and structural design models for well accepted tools such as MSC Nastran [17], ASTROS[18], ZAERO[19] or ZEUS[20]. Figure 7 is a representative wing structural layout that can be generated by MSTC-GEOM.

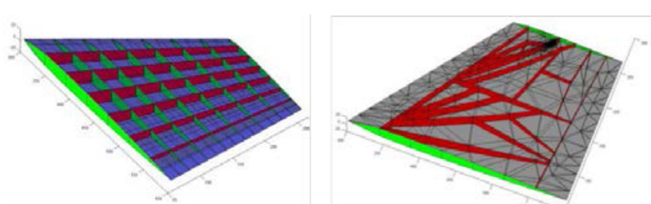

Figure 7. MSTC-GEOM Wing Structural Layout[15]

To summarize, the goals associated with merging conceptual and preliminary design is to enable the following:

1. Use an appropriate level of fidelity, coupling, and chaining that is necessary to capture the phenomena that are driving the design of a specified configuration.
2. Use an appropriate level of fidelity, coupling, and chaining that is necessary to capture the physics associated with the technology suite that is being evaluated.
3. Increase the number of configurations that can be prototyped. That is the number of configurations that can be carried beyond the conceptual level of design.
4. Use physics-based models to perform M&S

With the results of #1 and #2 a designer can evaluate and refine the configuration and determine if the selected configuration and the selected technology suite has the performance predicted in the conceptual design phase. The designer can confirm/update the knock-down/knock-up factors used in the conceptual design phase and rerun the conceptual studies and determine if the same configuration is produced. The designer can also identify any phenomena that may be systemic to the configuration chosen and make a decision if a new configuration should be chosen or if the systemic phenomena should be addressed in the design. Also, the use of #1 should help eliminate the discovery of late defects. These should now be predicted and accounted for earlier in the design process with the use of the appropriate fidelity, coupling, and chaining. The use of #2 should help reduce the risk of new technology, again by evaluating it with a higher level of fidelity earlier in the process giving the designer a more accurate representation of its requirements and performance.

4.2. Distributed Collaborative Design

To identify the computational framework requirements, refer to Figures 5 and 6. In Figure 5, for the traditional conceptual design process, it can be seen that the design is carried out in a single location on a single compute resource, usually a desktop machine. Figure 6 in contrast shows that different engineering discipline blocks may reside at different geographic locations and execute on vastly different hardware. This enables distributed collaborative analysis and design space exploration. This is a key enabler for performing physics-based design of tens of configurations with the same amount of resources that are allocated for traditional conceptual design. Such a process as identified in Reference [21] produces the following requirements for the computational framework:

- Seamless access to varying fidelity best in class tools to evaluate/modify the design.
- Process Representation with secure communication between all tools, data, and vested parties involved in the product development process regardless of their geographic location.
- Modularity that enables high level of reuse when moving from one study to the next.

These requirements are illustrated in Figure 8. The multi-colored ellipses represent engineering methods, data, and applications that are modular and can be reused depending on the study being conducted. They are distributed across a heterogeneous computing network depending on the computational needs of a given piece of software along with the corporate security requirements of the owner of the application, model, or data. The interconnecting lines indicate that a process is being executed to perform analysis or design computations such as those found in the N^2 diagram in Figure 6. Although Figure 6 shows only nine blocks in the N^2 diagram it is felt that to perform a fully physics-based design the number of blocks in the resulting N^2 will be on the order of a hundred(s). The run times of a given block will be from seconds to days or even weeks with data sets ranging from kilobytes to terabytes. The computational framework will have to accommodate such scales.

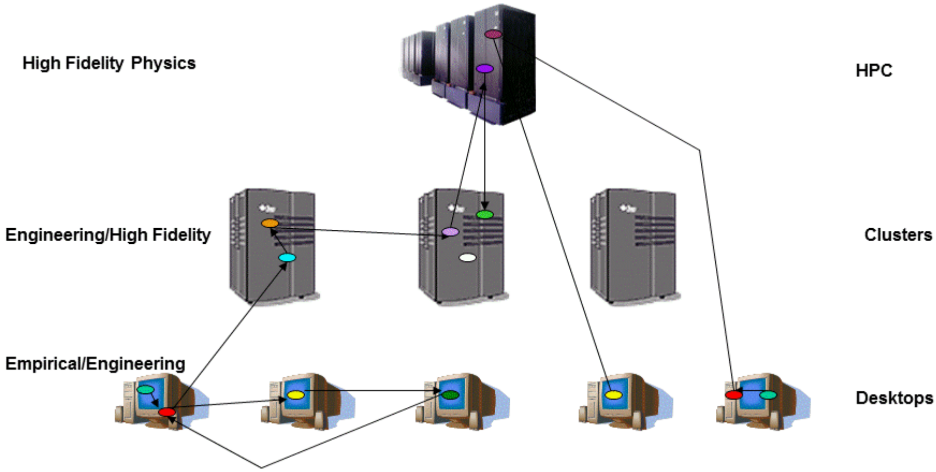

Figure 8. Seamless Access to All Methods, Models, and Compute Resources across the Network

The Multidisciplinary Science and Technology Center is using and developing the Service ORiented Computing EnviRonment (SORCER)[22],[23] to address the aforementioned computational framework requirements for distributed collaborative design. SORCER is a Java-based, network-centric computing platform that enables engineers to perform analyses and design studies in a very flexible, robust, secure, and distributed computing environment. SORCER federates distributed services in real time and orchestrates the communication between the services (engineering methods and models) based on a control strategy algorithm. It provides a common way to model analysis and design processes in conjunction with the system/product data.

5. Example: Physics-Based Distributed Collaborative Design

Recent studies[24],[25],[26] performed within the Multidisciplinary Science & Technology Center will be cited as examples of the impact of doing physics-based conceptual design and the usage of the SORCER framework to perform distributed collaborative computing. These studies focus on the same vehicle class, an efficient supersonic air vehicle (ESAV). The configuration studied is a single engine fighter with a gross take-off weight approximately 30,000 pounds.

5.1. Physics-Based Design

In references [24] and [25] Alyanak demonstrates the impact of increasing the fidelity in the vehicle weights computations and including static and dynamic aeroelastic analysis in the conceptual design phase to evaluate two technologies using physics-based analysis; active aeroelastic wing technology[27] and active flutter suppression. Figure 9 summarizes Alyanak's findings.

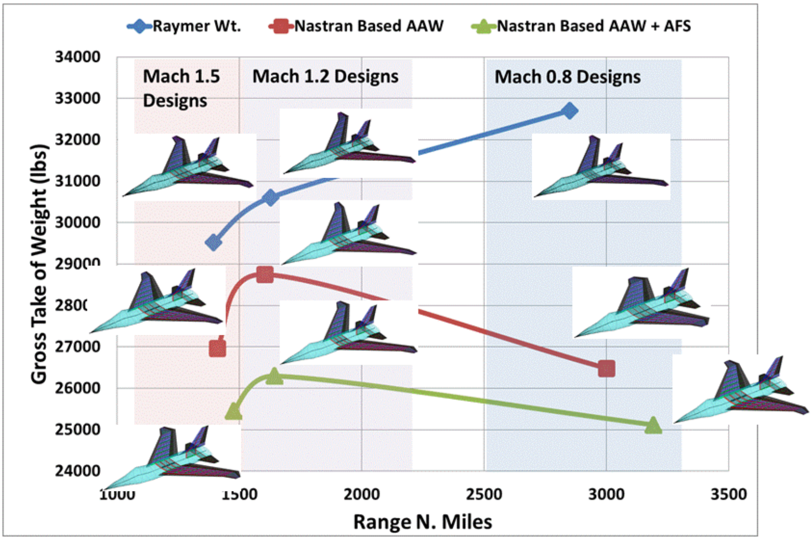

Figure 9. Physics-Based Design & Technology Assessment Results

Figure 9 illustrates nine different designs. They are identified by Mach number and by technology suite. For a selected cruise Mach number a multi-objective bi-level optimization problem is constructed and solved. The objectives are to minimize gross take-off weight while maximizing vehicle range. The design variables are a combination of conceptual design variables and preliminary design variables. The conceptual design variables are aspect ratio, inboard and outboard sweep angle, inboard and outboard taper ratio, wing break location, and thickness over chord ratio. The preliminary design variables are wing skin, spar, and ribs thicknesses. For a given cruise Mach number three separate optimizations are carried out to evaluate the impact of active aeroelastic wing technology and active flutter suppression on vehicle range and weight. The blue diamond labeled "Raymer wt" uses the vehicle weight equations found in Reference [6]. These weight equations are based on historical data and do not have any vehicles that use either active aeroelastic wing technology or active flutter suppression. Essentially, with those equations there is really no way to evaluate the technologies selected with a traditional conceptual design approach. What has been done in similar studies to account for active flutter suppression is to develop a "k" factor based on the weight report of a similar class of aircraft. In the report the designer identified the amount of structural weight that was added to eliminate flutter. In one study with a similar class of vehicle this was found to be 0.5% of the gross take-off weight (GTOW) of the vehicle. This "k" factor was used on the empirical weight equation. But as one can see from Figure 9 that if physics-based analysis is used to evaluate the impact of the technology the actual weight savings for the active flutter suppression technology ranges from 7% to 10% depending on the cruise Mach number. Decision makers would make drastically different investments based on these numbers. At 0.5% GTOW savings there would be no sense in considering or investing in active flutter suppression for this vehicle. But at 7%-10% GTOW savings this technology would have a significant impact on the vehicle performance.

5.2. Distributed Design

In Reference [25] Burton performs design studies of and ESAV configuration utilizing SORCER in conjunction with a mix of Linux-based cluster computers, desktop Linux-based PCs, Windows PCs, and Macintosh PCs. The ability of SORCER to leverage these resources is significant to MDO applications in two ways: 1) it supports platform-specific executables that may be required by an MDA; and 2) it enables a variety of computing resources to be used as one entity (including stand-alone PCs, computing clusters, and high-performance computing facilities). SORCER also supports load balancing across computational resources via the JavaSpaces technology, making the evaluation of objective and constraint functions in parallel a simple and a dynamically scalable process. In [25] a GTOW minimization is performed while a range constraint is enforced. A bi-level optimization procedure is carried out with the outer loop design variables being wing area, taper ratio and aspect ratio, while the inner loop design variables are wing skin thicknesses. A sequential linear programming (SLP) algorithm is employed which requires sensitivity calculations. The SLP method used is tailored for taking advantage of SORCER's parallel computing capability on a large number of CPU cores such that gradient and line search calculations are executed in parallel. This resulted in significant computational savings. In this case it reduced the computational time to perform the optimization from 24 hours to approximately 2 hours. An order of magnitude reduction in time due to using the SORCER computational framework. This enables a conceptual designer to use physics-based models when performing their design space exploration within the same time frame and resources (assuming the computational resources are available) as the traditional conceptual design process.

6. Concluding Remarks

A physics-based distributed collaborative design for aerospace vehicle development and technology assessment has been presented. The new methods and processes utilize physics-based analyses and a distributed collaborative computational environment to predict vehicle performance which in turn is used in mission level simulations to assess the impact of a given configuration or technology on the combat effectiveness of a system. This enables AFRL technology developers to have a quantifiable and traceable trail of the impact of their technologies on system performance parameters such as weight, lift, and drag into terms that Air Force leadership measures system effectiveness – lethality, survivability, sustainability, and affordability. The overall goal is to perform design studies and M&S mission assessments with physics-based models with the same resources and time that traditional conceptual design is achieved today and evaluate tens of configurations at the preliminary level of fidelity rather than the current practice of one or two. Three primary benefits can be obtained from the new process; generation of information with less uncertainty associated with it for making decisions concerning system capabilities, technology assessment, and technology risk reduction, reduction in the discovery of late defects within the system due to physics, and opening up the design space to enable novel concepts and otherwise unobtainable capability by leveraging the discipline couplings.

The process utilizes the SORCER computing infrastructure to enable collaborative design across organizational boundaries and full usage of all compute resource on the network ranging from desktops to high performance computing machines. This is the key to executing the process within the same amount of time and resources as a traditional conceptual design process.

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