GLOBAL INTEGRATION AND MANAGEMENT OF 21^{ST} CENTURY FIGHTERS

SIMULATION-BASED DEVELOPMENT OF FIGHTER AIRCRAFT

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Abstract

The competitive 21st century military business environment operates within the confines of decreased defense funding with increased customer expectations in reducing both the cycle times of product development and the total cost of ownership. Operating in these two confines will require a paradigm shift in the traditional ways of doing business. Revolutionary changes in management and military procurement will enable an effective integration of advanced technologies, lean manufacturing, acquisition reform, and motivated workforce. Managing the future global enterprise includes not only the prime contractor and the supply chain but also the international partners, teammates, alliances, the international and domestic customers, and innovative business arrangements.

Before a company can effectively implement revolutionary changes, it must first appreciate the ideas that worked in the past and will continue working in the future. Therefore, enhancing competitiveness includes the ability not only to benefit from legacy successes but also to implement continuous improvements. Much of what is required for success in the future is being implemented now at Lockheed Martin Aeronautics Company to enhance existing F-16 and F-22 programs and to ensure readiness for future aircraft programs.

This paper will present unique challenges of doing business in the defense aerospace industry of the future and how Lockheed Martin Aeronautics is poised to meet the country's defense needs within cost and schedule requirements.

1 Introduction: Evolution Revolution

Lockheed Martin Aeronautics Company is facing the challenges of defense acquisition in the 21st century to produce fighter aircraft that out-perform previous generation fighters *and* cost less to own and operate [1]. Defense budgets may be lower, but customer expectations are higher [1]. Moreover, the customer wants these fighters developed in a shorter cycle time. Through modeling and simulation, LM Aeronautics has perfected a 21st century process to design, develop, and manufacture the next generation fighter the customer rightly expects. Evolution of simulation-based development at LM Aeronautics began with our legacy successes through the F-16 fighter program and improved with the modern F-16 and the F-22 programs; it will be fully deployed on the Joint Strike Fighter (JSF) through the Virtual Product Development Initiative (VPDI). We validated the processes, methods, and software tools that comprise our VPDI through the Airframe Virtual Enterprise Pilot (AVEP) and the Airframe Affordability Demonstration (AAD).

2 Our Legacy: Continuous Improvement

Our legacy with successful fighter aircraft programs began with the F-16 aircraft, an innovative leap in technology (Figure 1). As F-16 production moved to the worldwide market, LM Aeronautics pioneered the use of digital data from replacing the drawing board to automating the production line. Through the F-22 program, we combined the development speed produced by digital data with streamlined processes and new teaming agreements to further reduce the development time and the associated costs.

Figure 1 - Legacy F-16 Meets 21st Century JSF

2.1 The F-16: The Fighter Standard

The F-16, widely recognized as the most cost-effective and most capable fighter on the market, sets a tough standard for any new fighter to beat. As the first electric jet, its fly-by-wire control system was considered daring. Although it was originally developed as an experimental lightweight day fighter, it has evolved into an all-weather fighter and precision strike aircraft. Its long, continuous production line testifies to its success (4000th delivered 28 April 2000). For the design and manufacturing engineers at Lockheed Martin Aeronautics, the F-16 presented an opportunity to consider the power of digital data to speed the product development cycle.

2.1.1 CADAM®

As the F-16 program prepared for production, LM Aeronautics worked to replace the tedious process of performing "on-the-board" aircraft drawings and changes through a 2½D Computer Aided Design (CAD) system, called Computer-Graphics Augmented Design and Manufacturing (CADAM®). CADAM provided the design engineer associativity among drawing views to speed drawing creation. CADAM also provided a "flange-angle spline" as a powerful attribute to associate an angle to spar and bulkhead flanges. Although the angle data added a slight burden to the design task, it more than paid for itself downstream by supplying the manufacturing engineer enough electronic information to define 5-axis numerical control (NC) machine paths.

2.1.2 ACAD

LM Aeronautics invented the proprietary Advanced Computer Aided Design System (ACAD) in the early 1980s to facilitate the rapid iteration process inherent in aerospace advanced conceptual design and analysis. ACAD, an associative CAD/CAM database, gives design engineers the tools necessary to create and modify geometry in two or three dimensions.

Through ACAD, new versions of the F-16 as well as innovative conceptual design shapes are quickly evaluated for aerodynamic viability. The system supports techniques that integrate wireframe, surface, solid modeling, and visualization making it ideal for rapid design iterations. ACAD interfaces with simulation systems for electromagnetic signature prediction, aerodynamic analysis, computational fluid dynamics, and structural analysis. If required, it can then produce stereolithography machine files for rapid prototyping and low cost scale model fabrication (Figure 2).

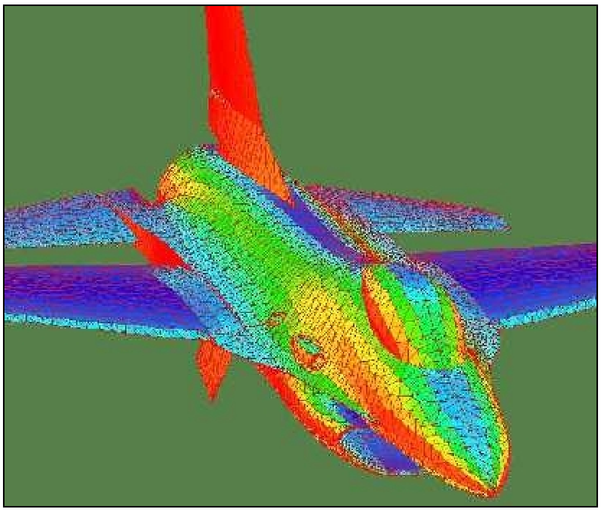

Figure 2 - ACAD Produces Meshed F-16 Model

2.1.3 CATIA®

To harness digital data, LM Aeronautics adopted Dassault Systemes Computer-Aided Three-dimensional Interactive Application (CATIA®) in the mid 1980s as a 3D modeling CAD/CAM system. CATIA® provided advanced 3D surfacing capabilities required for building fighter aircraft. CATIA® surface modeling increased our ability to reuse engineering data for downstream functions. With this major event, engineering data called the Master Dimension Data Base (MDDB) could now serve as the manufacturing master.

Aircraft that had historically been built from master forms could now be built directly from digital data in 3D CAD/CAM tools, like CATIA®. Together, with a shift in the aircraft development process, digital engineering data greatly improved the previously hand-made manufacturing master forms that really only estimated the mathematical representations of the engineering surfaces.

Two milestone projects provided validation of this new process. The Modular Common Inlet Duct (MCID) project provided an inlet design that could be used with two different jet engines. The plaster master form, which serves as the basis for the complete family of assembly tools, was machined directly from numerical control data derived from the CATIA® surface model in a fraction of the time required for the conventional method of hand finishing the master form. For a major F-16 block project, we bypassed fabricating a conventional tool family because we judged it too time consuming. Thus, we elected to machine the component master gage directly from the CATIA® MDDB surface data and eliminate the cost of several coordinated tools, including the master form and the time required to fabricate it. This project exceeded all expectations in reduced span-time and improved accuracy.

CATIA® functionality evolved from surface modeling to solid modeling. Solids were immediately recognized as the product Simulation Building Block.

2.1.4 COMOK

Solid modeling using CATIA® advanced further when COMOK (a proprietary visualization tool developed by LM Aero in the 1980s) was implemented on the F-16, FS-X, and F-22 programs as an electronic mockup simulation replacing expensive metal mockups in the factory (Figure 3). As a result, we generated digital solid mockups in a fraction of the time of the metal mockup. COMOK also facilitated the concurrent development of systems design for hydraulic/fuel tubing and wire harness routing. The electronic data from the 3D tubing solid models are used to create the tube bend data that drives the computer numerical control (CNC) benders. The 3D solid model data are used to develop wire harness fabrication boards. Other analyses made possible with the solid mockup are the kinematics models used to verify complex mechanical designs, including landing gear and actuated surfaces.

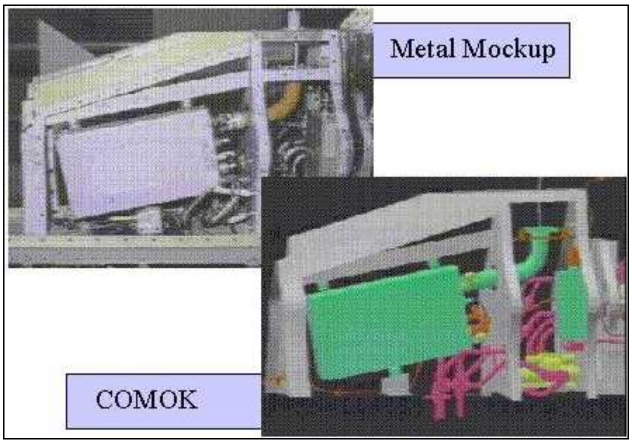

Figure 3 – COMOK Replaces Metal Mockup

To complement COMOK, LM Aeronautics developed COVIEW software derived from the VIEW analysis program. CATIA® solid models were transferred to COVIEW for visualization of large assembly models using the emerging graphics display capabilities of engineering workstations. Although the computer processing time was significant by today's standards, noteworthy productivity gains were clearly made in communicating the design intent using this tool for design reviews.

These individual success stories illustrate that LM Aeronautics moved quickly to take advantage of the cost and schedule savings associated with the downstream use of engineering digital data. Continual refinement of these methods and internal processes, when integrated with a fresh new business approach, led to streamlined production implementation of concurrent product development.

2.2 The F-22: The Air Superiority Fighter

The F-22 air superiority fighter raised the standard for higher performing fighter aircraft, becoming a balance of super-cruise speed and range, enhanced offensive and defensive avionics, and reduced observability (Figure 4). In winning the F-22 contract, LM Aeronautics realized the importance of organizing unique new teaming arrangements as well as automating the methods for product development. An organizational structure to support truly concurrent product development was deployed. Fully empowered program-based multifunctional product teams broke the bonds with the classical centralized organizational culture.

Figure 4 – F-22 Air Superiority Continues Legacies

2.2.1 IPTs: Organizational Efficiency

Although Secretary of Defense William J. Perry directed the "immediate implementation" [2] of a management process, called the Integrated Product and Process Development, "throughout the acquisition process to the maximum extent practicable [2]," LM Aeronautics had already implemented IPTs on the FS-X and the F-22 programs in the early 1990s. These IPTs pioneered the IPPD philosophy of the U.S. Department of Defense (DoD).

In the IPPD environment, co-located multifunctional teams were empowered to make decisions and coordinate tasks at the lowest possible level. As such, design engineers could talk to a structural analyst or to a manufacturing engineer and initiate tasks with either, without the burden of going through administrative layers. The IPTs considered each aspect of the build-to-package (BTP) at the earliest possible time in product development. This cultural change was embraced, as team members were more than willing to accept responsibility at the lowest levels. Results of a recent DoD survey show that, for an effectively implemented IPPD process, the acquisition timeline has been shortened, life-cycle costs have been reduced, and the teams continue to meet the warfighter's need [2].

3.0 VPDI: Future Readiness

The next major step in fighter simulation development is embodied in the JSF. As the DoD website explains, "The Joint Strike Fighter (JSF) is the United States Department of Defense's focal point for defining affordable next generation strike aircraft weapon systems for the Navy, Air Force, Marines, and our allies. The focus of the program is affordability – reducing the development cost, production cost, and cost of ownership of the JSF family of aircraft." [3]. The JSF Vision is to be the Model Acquisition Program for Joint Service and International Cooperation and To Develop and Produce an Affordable Next Generation Strike Fighter Weapon System and Sustain It Worldwide.

In anticipation of the JSF program, LM Aeronautics moved forward with investment in simulation-based product development to decrease life cycle costs. As a result, the VPDI was commissioned in 1996, chartered with creating capabilities that exhibit revolutionary productivity improvements in airframe development, manufacture, and support (Figure

5). VPDI manifests itself within the Virtual Development Environment (VDE). The VDE recipe contains three basic ingredients: the lean process, leading edge simulation software and technology, and enterprise data management.

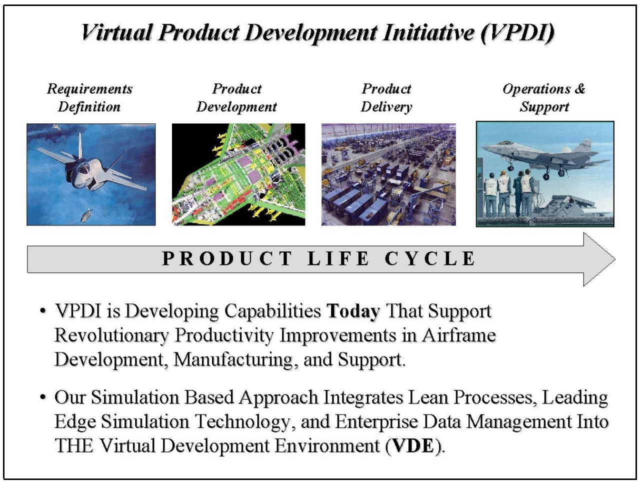

Figure 5 - VPDI Improves Product Path

3.1 Lean Processes: Best Practices

The lean process formalizes proprietary best practices in the areas of solid modeling methods, NC methods, and composite design, analysis, and manufacturing methods. The process is built around a fully attributed solid model or a model-centric environment using multi-discipline teams consisting of design, structure analysis, manufacturing, and simulation engineers as well as tool designers and manufacturing planners (Figure 6). Tools

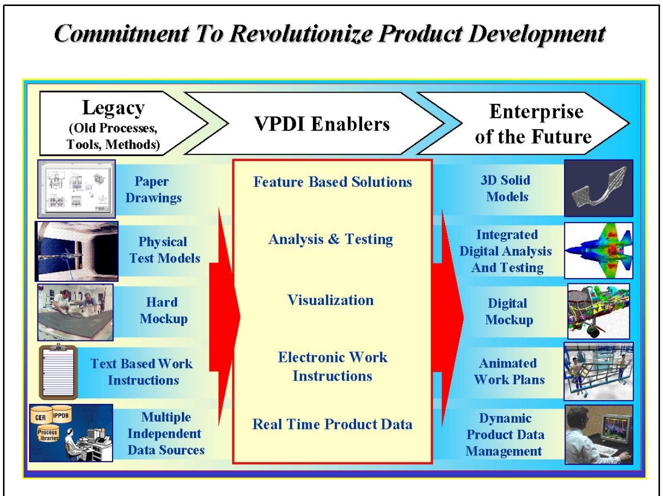

Figure 6 - VPDI Bridges Our Legacy to Our Future

are available to simulate the lean process for product trades and for early identification of testing requirements

3.2 Plug and Play: Flexible Tools and Processes

VPDI identified leading edge simulation software and technologies that are integral to the VDE. A "plug and play" philosophy emphasizes commercial off-the-shelf (COTS) best-in-class tools fused with the lean process. The software tools are deployed with an open architecture based on commercial information technology standards to facilitate integration with other COTS tools. As a consequence, fighter aircraft have typically not been designed and built as efficiently as today's technology allows. Even with the accuracy provided by wire-frame digital models, the process of the past called for duplicating much quantity of data as the design was passed from design to other disciplines. With every variation of the data, chances for confusion and error degraded the process. By comparison, today's software in accord with innovative processes can weave a digital thread from design through assembly—and beyond.

3.3 PDM: Enterprise Repository

A product data manager (PDM) was employed to provide a "smart" repository for enterprise data. Metaphase™, an object oriented PDM designed by Structural Dynamics Research Corporation (SDRC), orders and performs tasks in a consistent fashion controlled by a workflow built into the PDM. The PDM is accessible in a collaborative environment by multiple teaming partners in different areas of the globe. This global data management software emphasizes the product BTP to furnish the data necessary to build and maintain detail parts and assemblies. It performs this function by linking to the BTP concisely organized data, such as product requirements, CAD/CAM models, FEMs, stress analysis reports, manufacturing plans, tool orders, and product simulation files. The PDM also facilitates a product assembly structure relating detail parts to sub-assemblies, installations, and top assemblies.

4.0 AVEP: Global Environment

The VDE was verified with a pilot project we called the Airframe Virtual Enterprise Pilot (AVEP). A JSF typical airframe structure was developed in AVEP in a multinational collaborative environment using the tools and processes of the VDE. The AVEP, conducted in 1999, verified the virtual environment infrastructure (VEI) that is critical to successful global partnership, development processes, and tools.

The VEI included an international wide area network (WAN) linking multiple teaming partners in Texas, California, and United Kingdom. UNIX based workstations, NT based personal computers (PCs), and standalone PCs were connected through this secure network. The global database was distributed, designed for maximum performance at the individual sites. Each site stored both local working data and configuration-controlled released data. All the data were synchronized between the site servers. Any of the teaming partners could view real-time the latest data from any other site.

4.1 AVEP: Systems Engineering Approach

The AVEP Lean Airframe Process applied was a top-down systems engineering approach composed of multiple phases. Each phase had entrance and exit criteria aligned with the JSF Program Milestones and applied to all teaming partners alike. This alignment ensured consistency of product data across the team and throughout the process. The systems engineering approach reduced change by making high-level decisions followed by progressively lower level decisions. Each phase added more detail to the previous phase until a fully developed BTP was available to fabricate and assemble the product.

The AVEP model-centric method was controlled by the PDM workflow. After the design engineer "submitted" to the workflow a BTP containing a solid model, the PDM notified other engineers of their required tasks via email. The workflow progressed as tasks were completed. Trade studies were conducted where necessary. At the end of the workflow, team consensus was reached with no surprises, and the BTP was "vaulted," or released. Team leads could follow the progress of their products with simple queries to the PDM. The AVEP team conducted joint design reviews everyday using a combination of telephone conferencing and networked computing. Various types of documents, including CATIA® and VAS models and MSOffice text data, were reviewed simultaneously by the team members. Control of the documents could be passed to any member in any location. These methods virtually eliminated miscommunication between members of the team and allowed interface control issues between the partner companies to be resolved online.

4.2 CATIA® Solids: Engineering Master Data

The product design for AVEP consisted of a solid based model-centric approach that emphasized downstream use (reuse) of the engineering solid dataset. CATIA® was used as the modeling tool. In the AVEP top-down approach, the final assembly was evaluated first to establish major interface control features. The assembly was then broken down into subassemblies, which were assigned to each of four sites around the globe. Simplified solids were quickly developed in the early phases to support trade studies. These trade studies used early concurrent finite modeling and manufacturing assembly sequence simulations.

The solids were also used for management to review the project utilizing visualization tools. Visualization Assembly System® (VAS), a visualization product developed by Engineering Animation, Inc. (EAI), was selected based on the software's demonstrated advantages for enterprise-wide product visualization, teamwork, and digital mockup capabilities. We used VAS for large model visualization and assembly analysis, including using it for interference resolution. As the CATIA® solids were released to the PDM, an automatic trigger translated and transferred the solid to VAS. The assembly structure, or bill of material (BOM), for the AVEP design was developed in the PDM. VAS provided an identical visual representation of the BOM by automatically extracting the assembly structure from the PDM. If the BOM changed in PDM, it automatically changed in VAS.

Drawings are used in a diminishing capacity in the LM Aeronautics solids-based environment. For the AVEP, drawings were created in CATIA® only where necessary to convey crucial data, mainly annotation regarding part or assembly processes. Generative drafting techniques are expected to replace the need for drawings altogether within the next few years. Much of the information, such as material and process specifications and procedures historically called out on the face of drawings or in the parts list attached to a drawing, is now stored as objects associated to parts and assemblies in the PDM. The rest of the data will be added as attributes to the solid model.

4.3 Process Verification: Productivity Gains

Many new processes and tools verified in the AVEP proved large productivity gains, among them composite part development, assembly process modeling, and tolerance analysis. Classical approaches to composite part development were labor intensive in design, analysis, manufacturing, and shop floor processes.

The LM Aeronautics streamlined composites process provides a single thread of data from design through fabrication. In the inherently complex, iterative environment of laminated composite design, strength and weight efficient laminates are developed quickly with an integrated set of tools centering around the Composite Design Technologies FiberSIM™ product. With FiberSIM™, attributed CATIA® geometry organizes the laminate into ply data sets, which are used for strength analysis, flat pattern generation, laser placement data generation, and mass properties extraction.

Stress analysis is another historically labor and schedule intensive task. AVEP utilized LM Aero proprietary software tools, which improved productivity by providing standard methods for analysis. One such tool set, called Structural Analysis Methods (SAM), performs general composite and metallic detail structural analysis. Another tool called VIEW, a Finite Element Analysis (FEA) post-processing tool, used rapid visualization and interpretation of finite element data. The structural sizing cycle time was significantly reduced with these tools.

Assembly process modeling on AVEP consisted of both discrete and physics-based simulations using Deneb Robotics Inc.'s software suite and CATIA® solid models.

Discrete simulations are high level dynamic, stochastic mathematical models of a manufacturing system that provide verification of the assembly sequence to schedule, span, and resource constraints. This simulation is dependent upon validated industrial engineering data input.

Physics-based simulations provided verification of the assembly sequence to the physical constraints of the factory, tooling, and human factors. The data from this simulation was used to ensure producibility, to refine the manufacturing plan requirements, and to integrate the resulting manufacturing requirements in the design. The results were also used for tool designs and shop floor planning. One unexpected result of the AVEP simulation was the detection of a collision of the automated drilling robot head with the fixture, proving that problems can be identified and eliminated before the expense of parts or tooling fabrication.

Variation Management Simulations predicted the effect of tolerances in the assembly process. Performing this dimensional management analysis concurrent to the design task ensured that tolerances were correctly specified in the design; full compatibility is then conferred to the manufacturing and assembly process plan.

5.0 AAD: Cost Reduction Innovations

The F-16 does indeed set a tough cost standard for future fighter aircraft projects. Lockheed Martin has maintained the cost of the F-16 even with vast improvements in capability and reductions in production rate (from 165 aircraft in 1993 to twenty-seven aircraft in 2002). The future requires us to stretch far beyond the cost reduction achievements demonstrated on the F-16. The AAD project gave us that opportunity.

The AVEP pilot project was completed concurrently with the JSF AAD program that fabricated parts and assemblies to prove revolutionary changes in fabrication and assembly techniques. Where the AVEP exercised the lean design process, the AAD investigated innovative ways to reduce manufacturing costs for JSF. For the JSF AAD, teams of engineers and technicians demonstrated a combination of manufacturing advancements, best practices in industry, and unique approaches to representative JSF structures. The results from AAD quieted vocal skeptics and even surprised AAD team members themselves. One assembly process that normally takes days to complete was reduced to minutes.

5.1 3D Solid Models: Design Harmony

AAD used 3D solid models of every part and every tool. In this model-centric environment, entire tool families were built around the actual design solids. Then physics based simulations of the assembly sequence were conducted. The parts and tools were designed in harmony to provide the most efficient balance between tooling and part self-locating features (parts are configured to assemble one way and one way only: the key to determinant assembly) (Figure 7). The features, which were part of the solid model and included small tabs, pre-drilled pilot holes, and raised locating surfaces, do away with most of the tooling normally used to position and hold structural pieces before they can be drilled and fastened together. In essence, the tooling becomes part of the structure itself.

This “design for assembly” method brings the tool designer and the design engineer together at the earliest stages of the product development cycle. The AAD team applied this solid model-based design-for-assembly method across the entire assembly process for the airframe structure, eliminating approximately 90 percent of the conventional tooling normally required.

Figure 7 – AAD Simulation Mirrors Reality

5.2 Automated Drilling System: Consistent Fabrication

Assembly span time accounts for much of the costs of manufacturing fighter aircraft. Lean manufacturing approaches can address everything from how a part moves through a production line to how the tools used for assembling an airframe are organized and located. Lean processes, such as automated drilling, can significantly reduce scrap, increase precision, and, consequently, reduce costs. The automated drilling system used in AAD drilled holes at a rate of six per minute. A computer-controlled laser-positioning system drilled, reamed, and countersunk fastening holes precisely according to locations prescribed by the digital description of the design. This one step replaces four steps in the conventional process. Holes are more consistently drilled so that fasteners fit every time with fewer drill bits required.

5.3 Advanced Fabrication: New Masters

The AAD project targeted several advanced fabrication methods for out-sourcing, conveying the design to the suppliers electronically. The solid model served as the master for part fabrication and quality assurance. Through this fabrication method, the AAD team demonstrated significant cost savings, validating complex manufacturing processes.

- High cutter speeds allow high-speed machining to form metal parts faster, with higher quality and more accuracy than standard machining techniques.
- Resin transfer molding presents a fast process for making small laminated composite parts to very precise dimensions. With this process, resin is injected under pressure into a two-part mold that contains carbon fiber material.
- Fiber placement uses computer control to automate the production of complex composite parts that conventionally require extensive hand lay-up. The AAD team used the process to create complex skin structures, such as ducts, wing skins, and larger doors.
- The more traditional method of hand lay-up was improved with modern technology. Instead of following paper-based work instructions and large templates, the AAD shop mechanics hand-placed the carbon fiber material that was located by laser-projected three-dimensional images of the proper size and ply direction.

Savings were also realized with other advanced fabrication processes. For example, large composite parts, such as wing skins, that were trimmed using a computer-controlled router driven by a digital model of the design reduced the amount of specialized tooling and improved accuracy. Quality assurance performed with a newly developed laser-based ultrasonic non-destructive testing technique inspected the internal laminate of composite parts. This technique uses pulsed lasers to generate ultrasonic vibration in the part and a laser interferometer to measure the resulting surface vibration.

With laser ultrasonic testing, AAD reduced inspection times by ninety percent. This optical inspection method requires no specialized holding fixtures and sets up in a fraction of the time required for water-based testing. Dimensional inspection was accomplished with a Metronor, a portable inspection device using infrared-sensitive digital cameras and a hand-held light-emitting diode pointer. The system can be used to check hole positions after drilling, any thickness of any material, and the proper placement of design features, like webs and flanges. Besides being fully portable, the Metronor is about one-fourth the cost of a large coordinate measuring machine. The AAD team could take the Metronor to the part and set it up in minutes.

5.4 Support and Operation Simulations: Early Evaluations Perfection

LM Aeronautics' commitment to simulation-based design has proven beneficial not only in design for manufacturing but also in design for operation and support. With modern simulation tools, the operation and support design requirements can influence the actual design process early in product development. These simulations can realistically consider multiple conditional variables.

Support simulations enable personnel to develop and evaluate the exact sequences for maintenance events, such as engine removal and store load procedures (Figure 8).

Operational simulations allow the evaluation of many different aircraft configurations with various operational conditions (Figure 9).

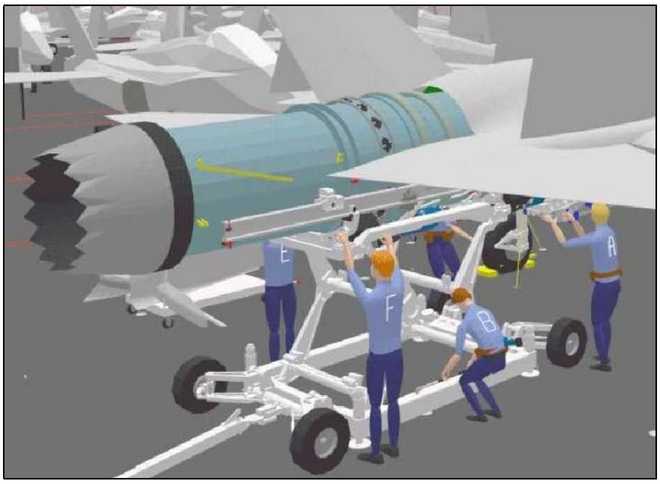

Figure 8 - Support Simulation Influences Design

Figure 9 - Operation Simulation Influences Design

6.0 Conclusion: The Virtual 21st Century

LM Aeronautics has invested in the future. Our process provides a high payoff, fully integrated modeling and simulation solution to meet the demands of global competition. Through legacy projects, we proved the value of digitizing data from surfaces to solids. We forged innovative teaming arrangements to provide efficient concurrent product development. We standardized simulation-based product development through high priority groundbreaking initiatives. We validated our tools, processes, and infrastructure through a hands-on approach. We have accurately emulated the environment for new fighter development. LM Aeronautics has aggressively embraced the principles of global simulation-based acquisition to ensure the best-in-class, most affordable fighter technology for the 21st century.

References:

[1] Johnson Lt. Col. Michael V. R, McKeon Lt. Col Mark F., Szanto Lt. Col. Terence R. *Simulation Based Acquisition: A New Approach*. Defense Systems Management College Press, 1998.

[2] *DoD Guide to Integrated Product and Process Development* (Version 1.0). Office of the Under Secretary of Defense (Acquisition and Technology), 5 February 1996.

[3] Department of Defense's JSF Internet Homepage http://www.jast.mil/html/aboutjsf.htm