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Acknowledged, agreed, and submitted by

Nominee's Signature ____________________ 6/24/20 Date

Nominee's Name (please print): **Mike Laidley**

Title (please print): **OMEGA Vice President and Program Director**

Company (please print): **Northrop Grumman Space Systems**

AVIATION WEEK NETWORK

2020 Program Excellence Awards

NOMINATION FORM

Name of Program: ________OMEGA Launch Vehicle____

Name of Program Leader: ___Mike Laidley ____

Phone Number: ___________(480)-814-6521____

Email: __________________Mike.Laidley@ngc.com ______________________________________

Postal Address: ___________1575 S. Price Rd., Chandler AZ, 85286 ____________________________

____

☐ Customer Approved (N/A)

- Date: Provided customer notification of our planned submission; due to program type and paper content, we did not believe approval was required. ______________________________________
- Contact (name/title/organization/phone): Maj Matthew Sanford/Deputy PM/USSF SMC/310-653-4349 ___

☐ Supplier Approved (if named in this nomination form)

- Date: ____
- Contact (name/title/organization/phone): ___________________________________

CATEGORY ENTERED

Refer to definitions in the document "2020 Program Excellence Directions." You must choose one category that most accurately reflects the work described in this application. **The Evaluation Team reserves the right to move this program to a different category if your program better fits a different category.**

☐ Special Projects

☒ OEM/Prime Contractor Systems Design and Development

☐ OEM/Prime Contractor Production

☐ OEM/Prime Contractor Sustainment

☐ Supplier System Design and Development

☐ Supplier System Production

☐ Supplier System Sustainment

Northrop Grumman OMEGA’s Agile Development with Model Based Systems Engineering and Virtual Reality

Abstract

Responsive to the nation’s need for a new EELV class heavy lift launch system to serve the National Security Space Launch (NSSL), NASA, and commercial customers, Northrop Grumman developed the OMEGA Launch System. Agile design with Rapid Learning Cycles using cutting edge Model Based Enterprise (MBE) and Virtual Reality (VR) practices early during the design and development of this system, greatly reduced development cycle times and interface risks. Vehicle level Model Based Systems Engineering (MBSE) implementation coordinating the functional architecture of multiple engineering disciplines for mission requirements verification is deemed a showcase of the DoD’s digital engineering strategy. MBE practices caught early design and manufacturing issues which were resolved at minimal costs before downstream design/operational impacts were realized. VR was instrumental in identifying and mitigating program risks including system/subsystem interfaces, product/tooling interfaces, design to production interfaces, and product to ground/launch facility interfaces. MBE and VR enabled new motor development to go from program start to static fire in only 16 months, half the time and cost of traditional methods.

Purpose

Heavy-Class Launch Services For The 21st Century

Northrop Grumman’s OMEGA Launch System is a family of expendable vehicles serving a broad range of missions for government and commercial customers. Designed for the 21st century, using state of the art technology, OMEGA replaces the aging fleet of 1990’s era Evolved Expendable Launch Vehicles (EELV). OMEGA combines low complexity solid boost stage propulsion with an efficient cryogenic upper stage to ensure reliability, high launch probability, enhanced responsiveness, and mission success. OMEGA can incrementally employ up to six Graphite Epoxy Motor (GEM) 63XLT thrust augmentation boosters, providing a wide array of performance capability. Using flight-proven technologies that have contributed to over 100 successful space launch missions, and conservative design margins in all elements of the vehicle, establishes OMEGA as a resilient and cost-efficient launch system. World class navigation and modular redundant avionics ensure highly accurate mission performance. OMEGA’s customizable payload accommodations and extensive mission capabilities provide customers with a launch system that consistently and efficiently meets or exceeds mission requirements and customer expectations. OMEGA is the new heavy lift workhorse for government and commercial customers.

Executive Summary: The Case for Excellence

21st Century Tools for 21st Century Technology

OMEGA's Agile Development with MBE and VR
• From program start to static fire in half the time and cost • Award winning MBSE implementation

Today's aerospace business climate requires rapid and cost effective development and certification of new launch vehicles and missile systems. To maintain program viability, budgets and schedules have to shrink markedly, while retaining the high levels of quality and safety mandated for use of these products. The launch vehicle industry, especially the rocket motor segment, has undergone a revolutionary shift during the past decade – including both customer needs and the competitive landscape. Among the key enablers for market place responsiveness, Model Based Enterprise (MBE) and Virtual Reality (VR) provide essential tools to enable agile development and sustainment of these modern complex aerospace products. Other changes include re-evaluating the standard serial approach of gated design development and testing, new processes, additive manufacturing of tooling, increased rigor for incremental milestone reviews, and analysis tool improvements. Recent demonstrations of new systems have indicated these revolutionary changes are well underway and fulfilling the new programmatic needs.

For launch systems, the main propulsion element design has significant impact on the agility of the development. Even with Solid Rocket Motor (SRM) propulsion systems, which historically have shorter development time and cost than liquid systems, a new motor using traditional methods would typically take 3 or 4 years to reach the static fire tests and qualification phase. With MBE and VR, Northrop Grumman has developed a solid rocket motor in approximately half the time (within 16 months) for half the cost without degrading the reliability of the system, which has a demonstrated success of 100% for comparable, flown systems over the past two decades.

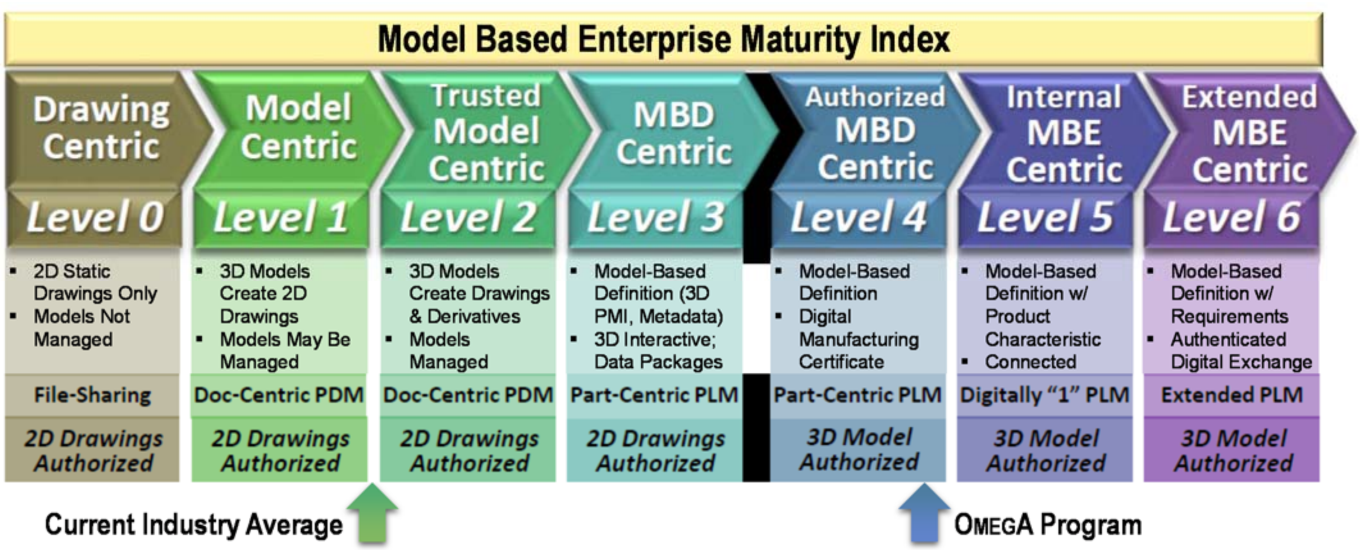
At the integrated vehicle level, the OMEGA Systems Engineering (SE) team developed a single modular functional analysis model in the Model Based Systems Engineering (MBSE) software Cameo Systems™ Modeler that is configurable for all OMEGA design reference missions and vehicle configurations. MBSE is a significant element of MBE. This effort, which garnered the 2019 Northrop Grumman Simon Ramo Award for systems engineering excellence, coordinates the functional architecture with the software, guidance, and electrical engineering requirements. This integrated requirements architecture supports a streamline software development process which leverages flight proven launch system avionics and software algorithms. The team utilized the MBSE model as the master requirements repository or "single source of truth" to capture all key performance parameters from released analyses, which form the basis for the validation of the design to meet the mission requirements. The use of the functional analysis modeling tools within MBSE created unambiguous decompositions of the needs, goals and objectives of the program's mission requirements. The modular model architecture defines the product realization process and completes the requirements verification process. OMEGA's MBSE is expected to lower sustainment costs over the life of the program as changes and obsolescence are easier to trace, manage, and address. The team recently received DoD customer endorsement for these efforts, with a recommendation that this methodology be a showcase for how Northrop Grumman is meeting the directive of the DoD 2018 Digital Engineering Strategy.

Northrop Grumman's Systems Engineering Heritage and Model Based Evolution

Northrop Grumman has a strong history of applying systems engineering to the nation's most complex missions to achieve a system solution that balances cost, schedule, and technical performance objectives of the customer. Simon Ramo, the co-founder of one of Northrop Grumman 's heritage companies, TRW, invented systems engineering in the 1960s to help address the complexities associated with designing the nation's first Intercontinental Ballistic Missile (ICBM) System. Since that time, Northrop Grumman evolved and matured its systems engineering capabilities and applies the process across all of its programs to ensure mission success.

With six decades of demonstrated reliable, timely, and affordable development and production experience serving customers in the commercial, defense and civil government markets, Northrop Grumman is a leading developer and manufacturer of small, medium, and heavy class space launch systems. Northrop Grumman delivers a diverse range of space products, including satellites, space and strategic launch vehicles, missile defense interceptors, and sub-orbital target vehicles and sounding rockets. An ISO-9001/2015 certified company, Northrop Grumman is a domestic launch service provider that has pioneered new classes of rockets, satellites, and other space-based technologies that help make the benefits of space more affordable and accessible.

Over the past decade, Northrop Grumman (and OMEGA in particular) transformed its systems engineering processes to leverage the tools and capabilities associated with the digital enterprise, becoming an industry leader in the field. This transformation enabled a transition away from a document-centric process of maturing a system to a dynamic, efficient, and effective digital engineering process, and enabled the development of MBSE. 99% of the OMEGA design was released as 3D models rather than 2D drawings.

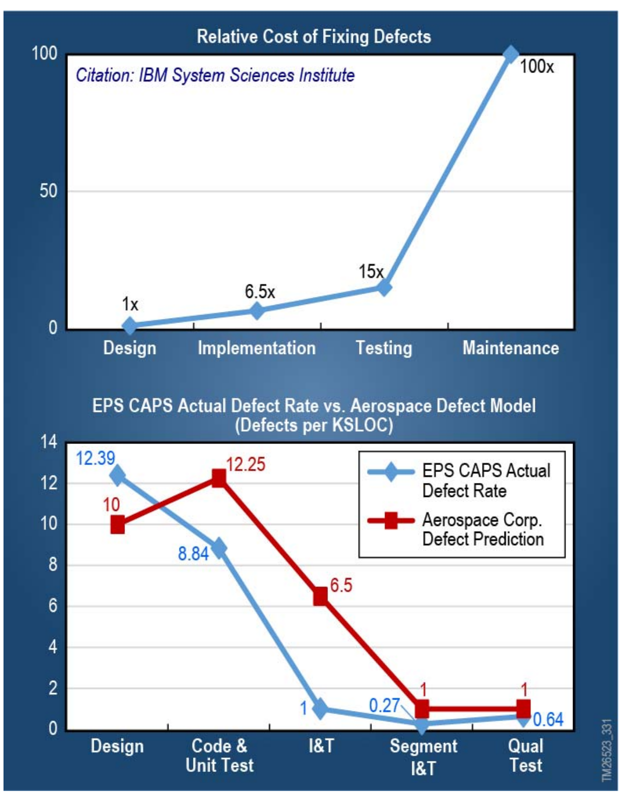


Northrop Grumman's holistic MBSE approach elevates models as the central piece of engineering information, building a cross-discipline digital thread that links these models to provide an Authoritative Source of Truth based on an internally consistent development and operational environment. This approach promotes communication between stakeholders, enhances knowledge capture, and manages complexity. The core of MBSE is the application of system models for system requirements analysis, design, performance analysis, verification, and validation throughout the system development life cycle.

OMEGA's MBSE development leveraged Northrop Grumman's successful implementation of MBSE on other programs.

Northrop Grumman's application of MBSE played an integral role in the successful completion of static and flight tests on the Attitude Control Motor (ACM) development. The ACM sits atop the Orion Launch Abort System (LAS) to provide pitch and yaw trim control for reorientation of the crew module prior to LAS jettison. The application of MBSE from front end requirements definition through system test was applied to derive igniter and propellant mass flow rates required to meet simultaneous ignition rise time and thrust capability requirements. Northrop Grumman used the system performance model for requirements decomposition and continuous requirements verification and the model architecture to support design optimization. Software and firmware were generated directly from the model. Northrop Grumman used hardware-in-the-loop, static, and flight test results to anchor models allowing defects to be found early in the development process.

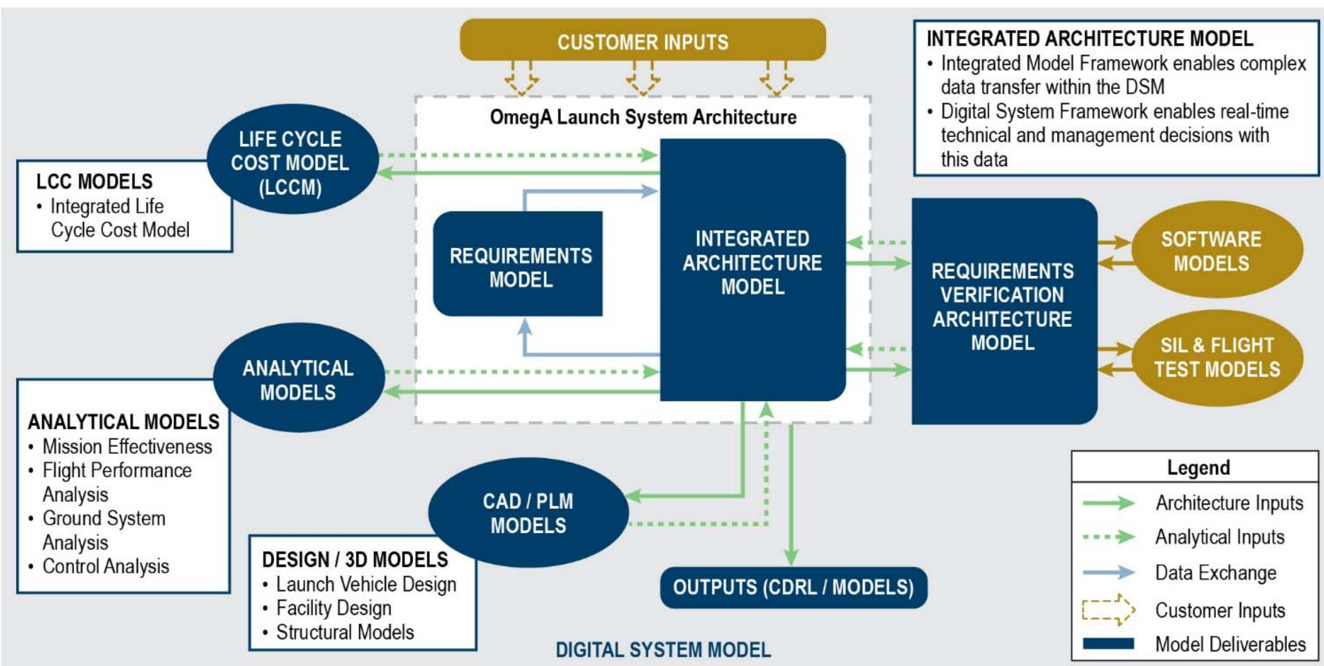
The MBSE approach enhances communications, design precision, system integration, and capability reuse, while creating an overall integrated system model (or view) that continues throughout development and operational lifecycle phases. Across Northrop Grumman there is history of using MBSE to drive designs of mission- and safety-critical systems. MBSE was applied to more than 50 programs spanning multiple domains including the Ground Based Strategic Deterrent (GBSD), the nation's next generation ICBM system, next generation aircraft including fighters, bombers, autonomous vehicles, cyber resilient command and control systems, missile defense systems, and secure network operations. On GBSD, Northrop Grumman applied descriptive and analytical models together using Multidisciplinary Design Analysis and Optimization (MDAO) to analyze tens of thousands of design cases to optimize the missile design and ensure the final product provided optimal performance while minimizing cost and risk. As another example, Northrop Grumman successfully applied MBSE techniques across the design, development, and test phases for the Enhanced Polar System Control & Planning Segment (EPS CAPS) program and demonstrated the MBSE methodology saved development, test, and certification costs and reduced the time to deliver products by 30%. These models and the integrated digital thread that forms their foundation allows errors and inconsistencies in the system to be detected much earlier in



the development cycle and reduces cost and increases schedule certainty compared to the more traditional systems engineering approach.

OMEGA's Award Winning Model Based Systems Engineering

Northrop Grumman awarded the 2019 Simon Ramo Award for Systems Engineering Excellence to team members working on the OMEGA launch system in recognition of its application of MBSE to capture all key performance parameters and validate the design's ability to meet the requirements for early integration missions. For OMEGA, Northrop Grumman's approach to MBSE and establishing the digital system model as the single source of truth is illustrated below. The OMEGA modular functional analysis model is configured in MBSE for all design reference missions and all possible vehicle configurations. The project complexity encompasses all of the functional behavior and performance-based characterizations for the entire OMEGA product line. Northrop Grumman uses the customer-accessible model as the single source of truth to capture all key performance parameters and to validate the design meets all the mission requirements. This innovative approach combines Product Line Engineering (PLE) methods with classic systems engineering analysis tools in the MBSE environment, creating a single functional timeline model to manage the configuration uniqueness for every future mission while maximizing commonality and reuse to the fullest extent possible.



The OMEGA launch system MBSE capability provides improvements in configuration management, manifesting flexibility, and issue resolution. As an example, the implementation of these tools reduces change cycle analysis and approval duration by 25 to 50%, depending on change complexity. The system tools and models also provide independent verification of capability and risks.

The team's modular architecture approach meets the intent of the Defense Acquisition Guidance (DAG) Modular Open Systems Approach while combining this with the DAG Modeling and Simulation directive. The team also followed the guidance of DAG Engineering Resources directive to generate affordability goals, process improvements and coordinate with stakeholders and functional experts in program development. The use of modular MBSE building blocks to rapidly define vehicle configurations meets the guidance of DOD SD-24 "Value Engineering Best Practices and Tools" by using a single platform to manage a high-cost, multiple-product complex application on an accelerated development schedule.

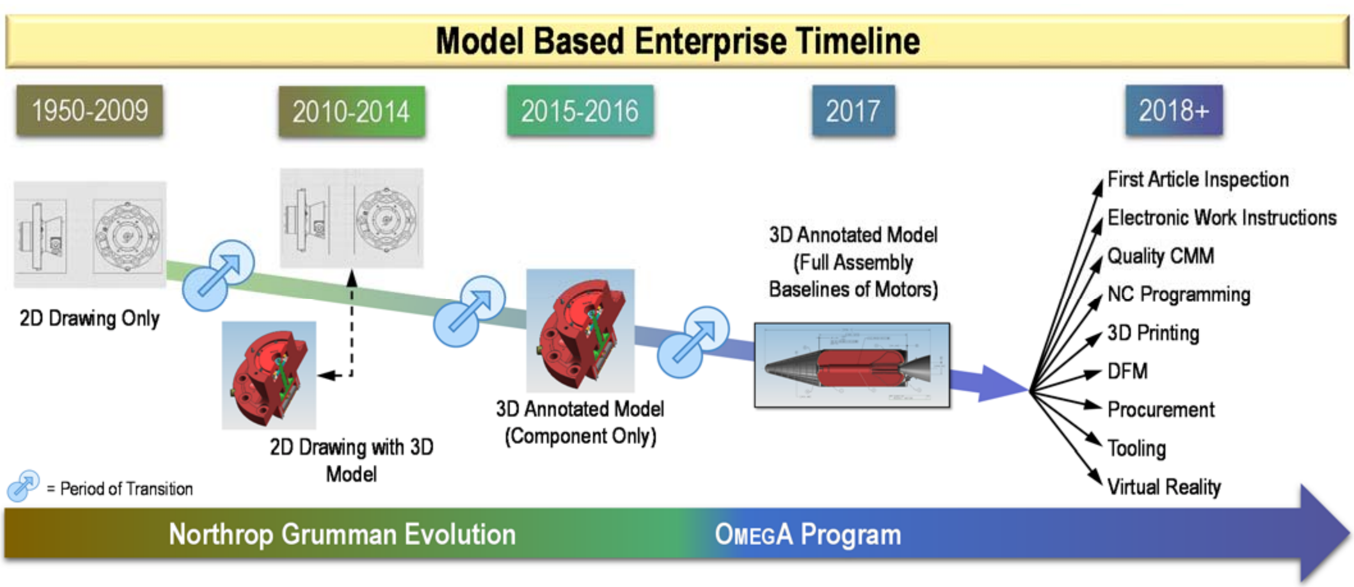
VALUE CREATION

Model-based engineering and VR capabilities are integral parts of the digital transformation that is occurring at Northrop Grumman. This transformation empowers our teams to deliver products and services to customers faster and more efficiently. It is a change in how we conceptualize, design, develop, deliver and sustain solutions and the tools and technologies we use. And OMEGA is a great example of digital transformation in use at Northrop Grumman.

OMEGA's MBE Benefits Northrop Grumman and Its Customers
• MBE and VR are revolutionizing the way Northrop Grumman does business • MBE teams spread the knowledge and benefits across groups within and outside the OMEGA program

The OMEGA MBSE development team is improving the culture at Northrop Grumman by increasing the value that the SE department provides to the organization. The team showed how SE could achieve difficult technical and cost objectives by combining the use of MBSE tools and PLE tools into a single solution that meets the needs of all program missions. Importantly, the team also educates their customers about the benefits that Northrop Grumman's use of these MBSE tools brings them. Team members participate in knowledge-sharing regularly by providing training sessions throughout the business unit to promote these techniques and share the knowledge gained on this program. The functional architecture and performance analysis defined by the MBSE Solutions team formed the basis of the OMEGA modular architecture approach. The methodology followed has been adopted by Northrop Grumman's corporate MBSE Community of Practice as the systems engineering modeling approach of choice. The team combined MBSE best practice modeling techniques with PLE methods to meet the needs of a multi-mission aerospace system. The sharing of these methods and tools on similar product lines throughout Northrop Grumman contribute to shaping the technical strategy of the corporation.

The transition to MBE and implementation of VR are revolutionizing the way Northrop Grumman does business. OMEGA's Common Boost Segment (CBS) has been a stellar example of a trusted model-based definition approach. There are no 2D mechanical drawings for manufacturing. Instead, embedded 3D model views are contained within the model-based definition. With a model that has been validated through release, the reuse opportunities present significant program savings versus recreating models for additional uses such as first article inspection, electronic work instructions, tooling, virtual reality, etc.



VR is being used throughout the design process, including: designs reviews, validation of manufacturing processes, human factors and physical clearance studies, cabling layout, facility design and tooling reviews, manufacturing and maintenance training, dry runs for operations, and augmented remove and replace activities. Significant investments in VR technology over the past three years have made it fast and easy to utilize the common digital master model directly in the VR system without the traditionally required days or weeks of VR model building.

The VR team reached out to non-engineering groups to show the value and insight that VR technology provides. For example, VR sessions with supply chain and procurement quality personnel are instrumental for those support organizations' increased awareness and understanding of the parts that they are actively procuring, which improves the accuracy, efficiency, and quality of the supply chain management.

Significant development process improvements with the evolution to MBSE and VR enable technological advancement of aerospace and defense products to be achieved much more efficiently, creating lower costs for commercial customers and a reduced burden on tax payers to provide for our nation's security.

METRICS

Metrics Provide Valuable Insight for OMEGA Program Management
• Reduction in design errors with cost and schedule benefits • Increased responsiveness to mission unique requirements • Reduction in labor and time to produce engineering artifacts

OMEGA launch system development included on an evolving metric-based analysis of performance focused on critical measurement criteria. Launch service requirements as they flow from the customer community provide only the very top level expectations regarding orbit insertion requirements, environments expectations, and mechanical and electrical interfaces. The launch system developers were tasked with developing very detailed system, subsystem, and component level specifications from these very broad sets of overall performance objectives. Measuring and tracking the development of detailed designs, specifications, analyses, and interfaces is a critical part of the program management necessary to forecast manpower, budget, and schedule requirements over the life of such a complex development program.

The program developed and maintained technical, schedule and cost review metrics to track the progress of the team through the design objectives. These metrics provided the dashboard necessary to plot the progress of the program along the roadmap outlined at project inception. Northrop Grumman provides an extensive toolbox of measurement processes for programs to implement during all phases of the project.

At both the system level and motor assembly level, the benefits of MBSE and VR are seen in tracking the reduced number of design errors, the time/labor to respond to mission unique requests, and the time/labor to produce the SE deliverables. For example, during CBS and GEM motor development, issues identified with model-based methods and VR were tracked with data including when and where (assembly level) in the development process they were found. For each issue, the metrics also included a projection of where in the flow the issue would have been discovered without MBSE and VR, what type of recovery action would have been required, and what the recovery cost would have been. In this way, Northrop Grumman estimates that the cost savings for just the design repairs alone would have been $150k, with significant additional operational and programmatic costs to react in a timely manner for several of the issues that were projected to only come to light at the launch site.

DEALING WITH PROGRAM CHALLENGES (VOLATILITY, UNCERTAINTY, COMPLEXITY, AMBIGUITY)

Transforming the Workplace Culture and Environment

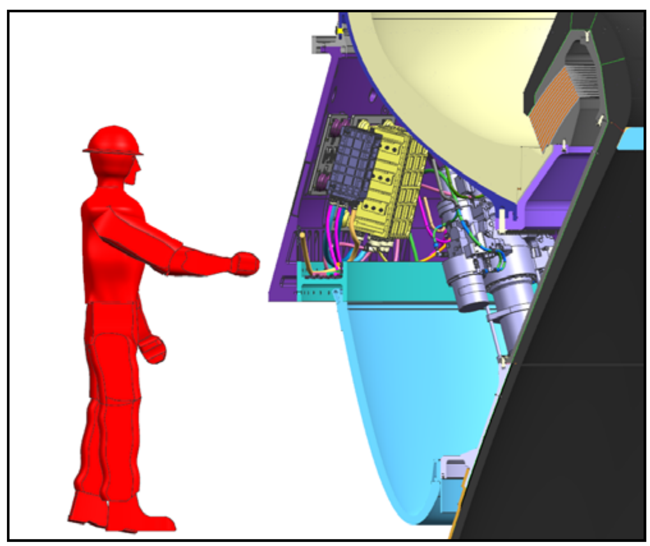
Change Can Be Difficult, But Highly Beneficial

- MBE adoption is not easy; nor is VR implementation
- If a picture is worth a thousand words, MBE with VR is priceless

While MBE with Product and Manufacturing Information (PMI) has been used as the design definition for new programs within Northrop Grumman, (e.g., CBS and GEM), there has also been a push to implement it across several functions inside and outside the company (manufacturing, operations, quality, supply chain, etc.) This is where most companies struggle or fail with their implementation of MBE. Northrop Grumman's leading role in adopting fully annotated model-based definition for all new product development and flowing this across functions was made possible by many team members working long hours to revise processes, trainings, and tools. The overall heritage processes and tools required additional rigor in specific areas to allow the design teams to be agile enough to support the program cost, schedule, and technical needs.

A cultural shift was necessary within the company, across multiple organizations, to get a singular geometric master model accepted as accurate, complete, sufficient, and trusted. The changes required to implement new ideas and new tools are significant and encompass company employees and external customers. The elimination of redundant inspection, machining, analysis, tooling, and process planning models (that had a heritage of different modeling software) had to be addressed and differences accommodated. It is often more difficult to achieve the culture change itself than developing the technology needed for the new tools and processes, and some cultural hurdles are more difficult than others. The difficulty of implementation associated with 3-D models, uncertainty quantification, the peer review process, increased challenge and rigor in internal reviews, and rapid learning cycles, was significant and remains on-going. Northrop Grumman has conducted hundreds of training classes inside and outside of the organization to promote the use of digitalization and common methodology and practices.

3-D Models in a "2-D World"



3-D modeling has revolutionized the aerospace industry in recent decades. The last ten years have seen significant progress in 3-D modeling and the opportunities it creates for engineering resources. However, the limitation of designing and inspecting complex 3-D assembly models on a 2-D computer screen at a variable scale can be challenging for understanding of layouts, manufacturability, and build operations.

VR allows full immersion of an integrated product team to see these complex assemblies in 1:1 scale and review the design prior to building. Northrop Grumman created a VR lab that marries advanced 3-D modeling and 1:1 scale viewing in an immersive viewing showroom. Any 3-D based model can be viewed in this immersive atmosphere. This creates significant opportunities to see the product in full scale and rapidly understand design issues including overlap, stay-out zones, cable routing, human ergonomics for installation, support tooling, access for assembly, etc. Even with the sophistication of modern 3-D model software, some subtle design elements might not be found by the design community when assessing the system in "2-D" space. In one example on an OMEGA motor design, approximately a dozen findings were identified at the VR stage of the design cycle, which enabled corrective design changes to be implemented prior to engineering release, and avoided significant re-work later in the product definition and manufacturing flow.

In support of the CBS and GEM programs several assemblies and piece part components were brought into the VR lab. OMEGA teams from vehicle design (Chandler, AZ), operations (KSC, FL), and motor stages (Promontory and Magna, UT), came together in several collaborative meetings to review the design real time, resulting in significant discoveries of design issues and flaws in the build product as well as tooling and support equipment. The program realized substantial cost savings with these issues identified early in the design process rather than flaws surfacing during hardware manufacturing or integration.

User Friendly VR Implementation

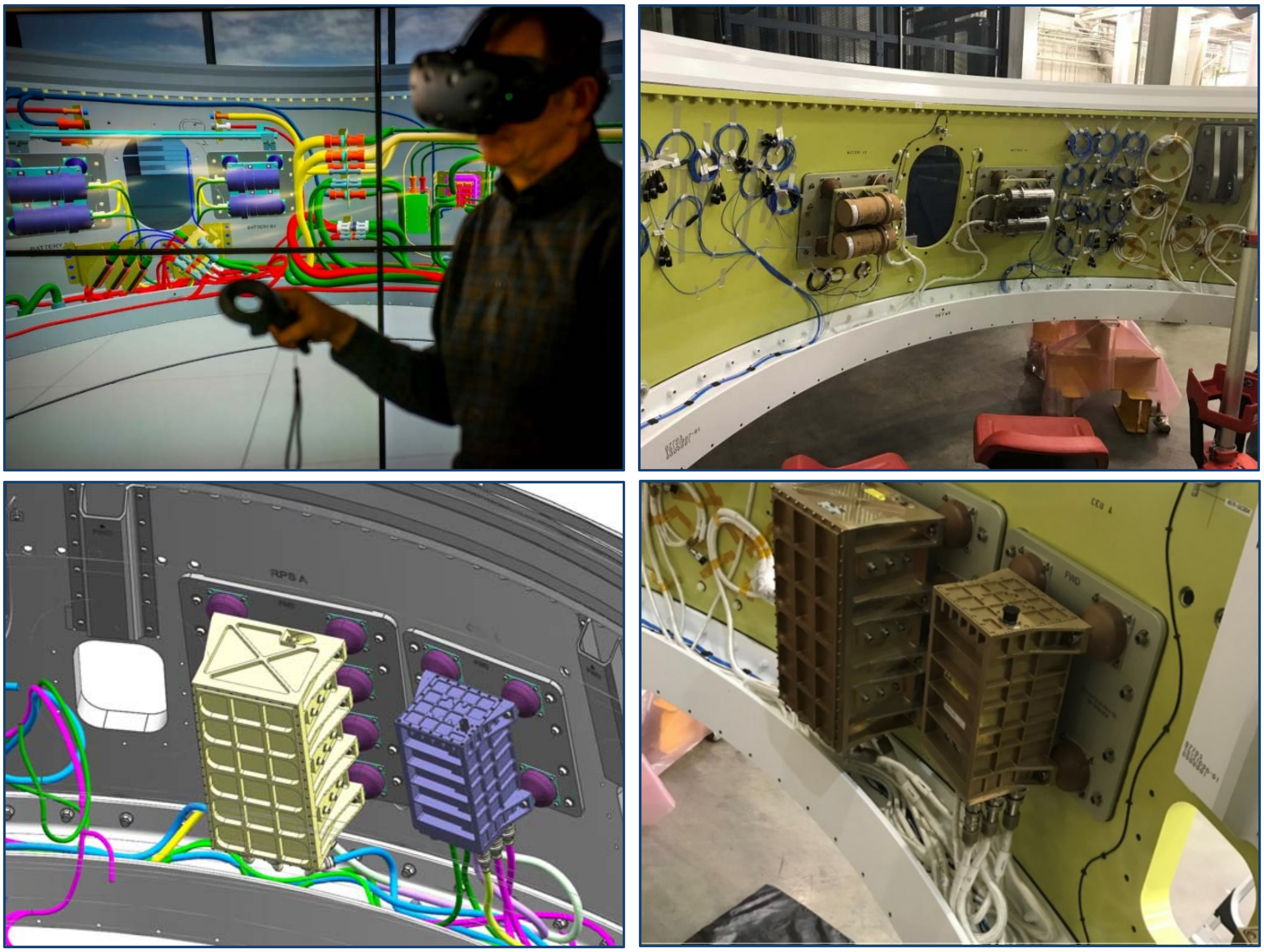
The challenges of implementing VR with MBE were addressed with an affordable innovation approach that was organic, practical, and built to support real-world use with control at the user level. A slew of VR impediments for industrial use had to be overcome, such as wireless capability of VR tracking, and scaling the technology to enable 1:1 scale walk-throughs of a rocket motor case the size of a CBS (>12 feet diameter). Many of these VR challenges, leading edge at the time of CBS development, have now found their way into out-of-the-box vendor offerings.

VR also depends on a trusted model. The process of designing and validating a trusted model is quite complicated. Model integrity checks were developed to ensure models conformed to standards, and design validation and manufacturability checks were developed to ensure downstream products comply with use requirements. Raw/native CAD model files are too big (typically >2GB per assembly) for VR sessions, so lightweight derivative/triangulated models are leveraged as inputs to VR sessions. Care must be taken to ensure no geometric requirements or significant features are lost in translation to derivative formats, so additional integrity checks are performed to ensure derivative formats match the native/source content.

MBE + VR = Priceless

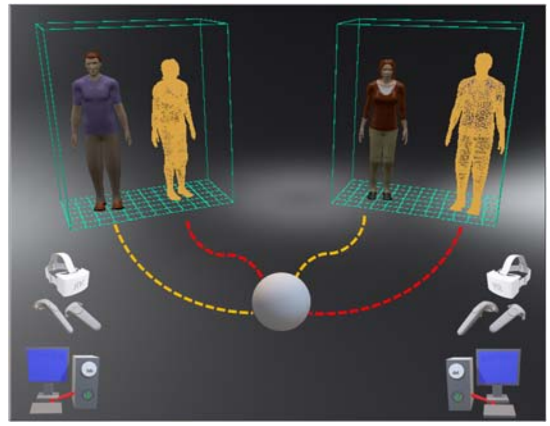
One of the most useful applications of virtual reality at Northrop Grumman was in the design development of the integrated Aft Skirt Assembly (ASA) for the OMEGA first stage. Not only does the ASA form the interface between the 2.7 million pound rocket and the launch pad, it also is the primary interface to all the GEM strap-on motors, and houses the Thrust Vector Control (TVC) system for the first stage motor. The requirements for the ASA design made it one of the more complicated assemblies on the vehicle. The VR lab was instrumental in the success of this assembly development.

Dozens of VR reviews of the ASA were conducted. Complex cable routing and controller box placement was reviewed in VR, modified in the design, then implemented and built for the aft skirt for the CBS C600 motor. In keeping with OMEGA's high launch availability, batteries in the ASA are line replaceable units. The battery location was scrutinized in VR, the design updated to improve accessibility, then implemented into the build to support OMEGA ground operations at the launch site. Other design aspects were scrutinized, and nearly a dozen potential future Material Review Board escape items were found in VR that otherwise would have resulted in very costly corrective actions downstream (e.g. tooling interface checks, etc.). If a picture is worth a thousand words, then an immersive VR session of a to-scale 3D product is priceless. Maintainability studies for battery loadings, interface checks, etc., all performed virtually reduced risk to the program at a fraction of the cost of traditional physical prototypes. Cable harness routings could be validated virtually to ensure mfg. lengths were correct in 3D space. Among other issues identified in the VR sessions, the team identified bend radii violations, some cables too large for the space allocated, methods of retaining the cables to the aft ring, direct overlap and contact of cabling harnesses, ways to support the actuator during pinning operation, thermal blanket dynamic clearance zone concerns, interference of a tooling bracket to nearby flight hardware, and the need to generate a generic hole pattern for retention bracket geometry.

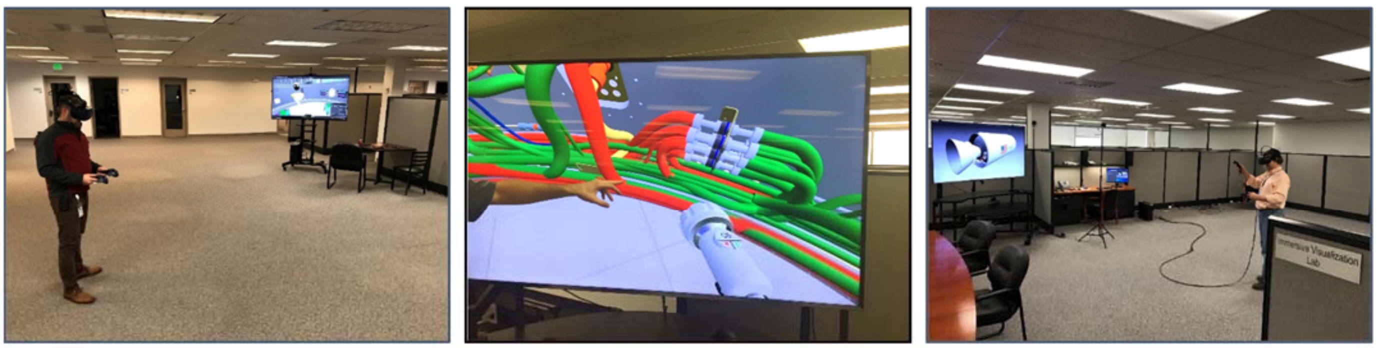


‘Virtual’ VR Sessions

Real-time interaction between the team members performing 3D model review is optimal for understanding design intent and ferreting out design issues. This requires some of the primary team members to incur time and cost to travel to another location to gather together in the VR showroom… or does it? In an effort to maintain synergy between multiple locations within the company, Northrop Grumman created a “virtual” VR technique. With a VR lab at each campus, members of the team in different locations can participate in



the same VR lab session. This group session is accomplished by setting up a VR lab in location B similar to the one in location A, loading the model for review into lab A’s VR environment, and using Virtual Reality Editor (VRED) software and speakerphone teleconferencing to establish a virtual collaborative session. During the real-time virtual session, team members see each other as avatars with head, body, arms, and hands that move in concert with the team member at the other location. Widgets are built into the software to enable flashlights, laser pointers, rulers, and other tools for the collaborative efforts. Utilizing a conference call speakerphone, the two team members can speak to each other and discuss design aspects or issues. This process enables the team members to interact with voice and pointing to discuss particular design issues, just as if they were in the same room.



Concurrent Collaborative Model Review at Promontory and Bacchus, 100 miles Apart

ORGANIZATIONAL BEST PRACTICES AND TEAM LEADERSHIP

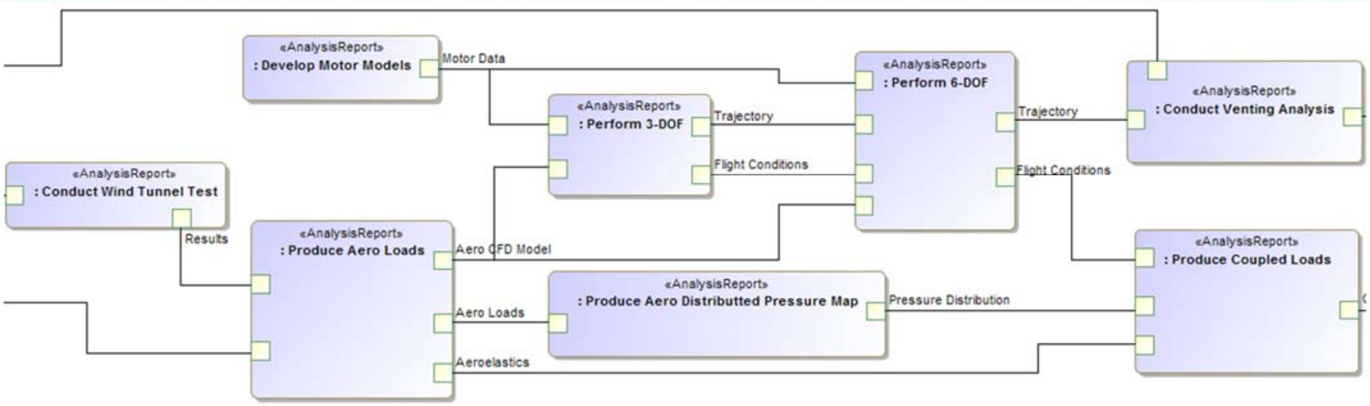
The Practice of Model Based Engineering

OMEGA’s MBSE approach provides a template for how SE is done for new programs within Northrop Grumman. The OMEGA MBSE model utilizes the complete systems engineering tools from requirements verification to functional analysis to physical layer decomposition and combines them in a single verified source or truth. The team worked across functional departments and mission managers representing the customer to establish stakeholder needs, then incorporated these needs while architecting a modular product line approach for the OMEGA SE digital model. This cross-function and customer community partnership work validated the methodology before the labor was expended to build the MBSE products and ensured the end product would meet expectations. OMEGA’s MBSE methodology provides a digital thread that links the truth models to integrate directly with Product Lifecycle Management (PLM) and supply chain operations.

> *MBE Is a Significant Tool for Northrop Grumman*
>
> - MBSE enables significant reduction of labor and schedule for engineering product development
> - OMEGA truth models reduce redundancy, conflicts, and issues in downstream phases of the product lifecycle
> - Issues caught in VR can be addressed, fixed/-redesigned, and reviewed in the same day
> - Today’s younger workforce is experiencing the benefits of model-based engineering

The impact to program performance has been to enable a high degree of mission variability while maintaining a high production rate, holding recurring costs low. The team eliminated the recreation of the SE products for each mission by reusing modular building blocks within the model. These building blocks are used to rapidly create vehicle configurations and SE deliverables that are less error-prone since they rely on a single source of federated truth. The digital model links performance analysis results and manages the

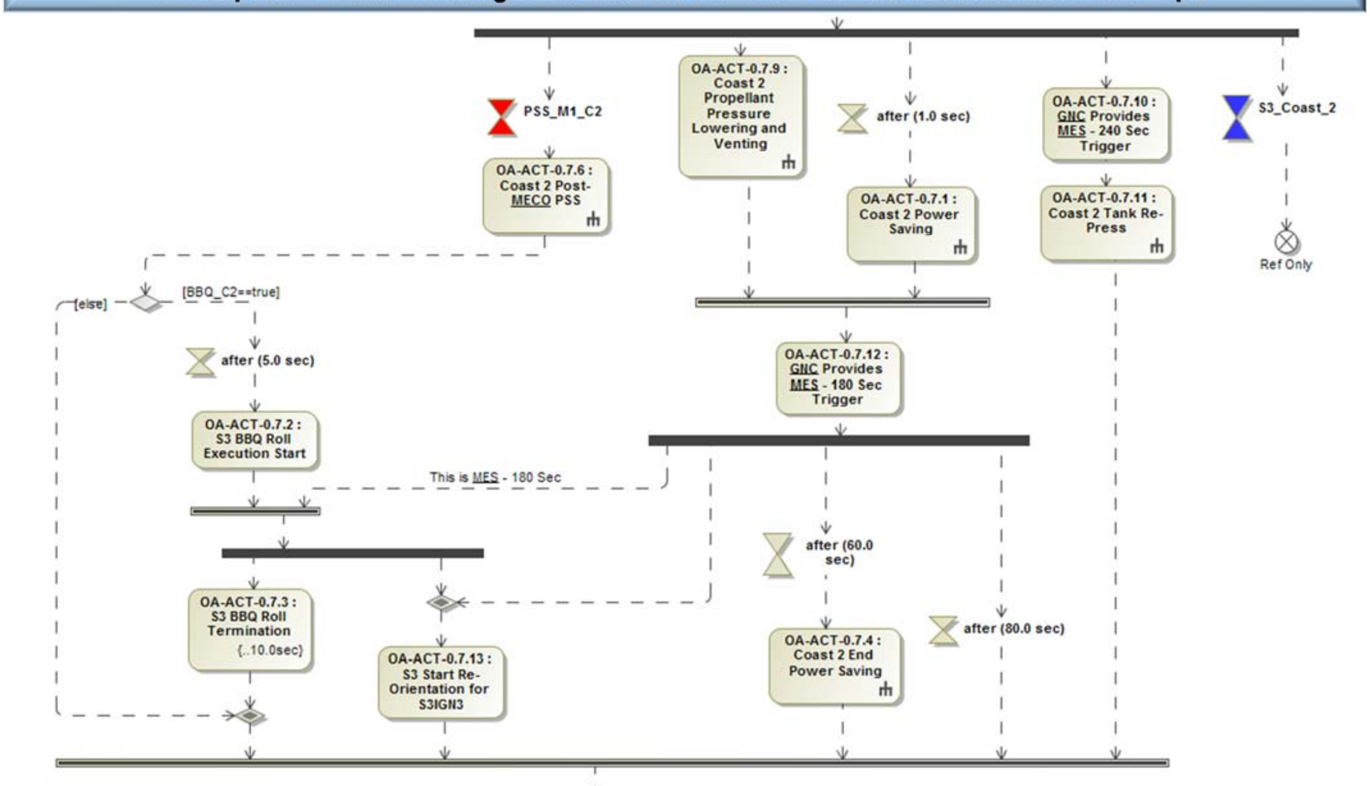
OMEGA MBSE Models Discipline Analysis Relationships and Coordinates Analysis Results



interfaces between them. OMEGA uses the model to track the impact of changes to the design during the development phase to make sure the affected disciplines respond faster. This saves valuable development time that would otherwise be lost to iterative labor churn if the disciplines were not coordinated in this way. The combination of these SE methods with PLE tools reduces labor and cost while allowing product artifacts to be created faster to meet more demanding customer schedules.

As an example, the MBSE models the flight timeline and the logical relationships between the various vehicle functions. The model is designed to be universal to capture all possible vehicle configurations and includes the functions of the vehicle as they align with PLM tools on the hardware side as well as verification tests. The timeline portion of the tool models the entire vehicle, including all hardware/software interfaces. With the MBSE Timeline, the OMEGA SE team can prepare and conduct a Critical Timeline Review (CTR) within 2 weeks of receipt of a baseline trajectory, and complete the Critical Timeline Verification Review (CTVR) within 3 weeks. For heritage programs and methods, these efforts would require several months each. This is only one example of the cost savings that MBSE yields by creating a single source of

Example OMEGA MBSE Flight Timeline Model with Vehicle Functional Relationships



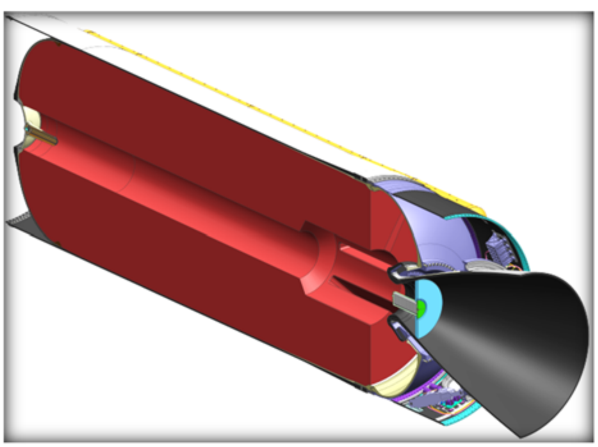
truth, and applying the methods universally with PLM creates cost savings for each mission in the tens of thousands of hours across the entire interface management SE landscape.

For OMEGA motor development, an MBSE approach and methodology was used to capture functions, requirements, system structure, key system parameters, specification type views, verification methods, interfaces, potential failure modes and hazards, and mitigating design characteristics. MBSE system models are integrated with basic one-dimensional simulations, analytical models, uncertainty quantification models, or other empirical models, for use in cost/capability trades, proposals, and early product reviews. A key focus has been on integrating MBSE models with PLM information flows to manufacturing to ensure closed-loop verification/in-house validation with operations. Digital elements that are useful in multiple forums and do not require data to be re-entered (e.g., databases or exportable file information, not PowerPoint slides or PDF files) are used across multiple disciplines including systems engineering, reliability, safety, design engineering, analysis, manufacturing, supply chain, quality, inspection, tooling, facilities and test. A singular, toleranced, annotated geometric master model of the motor assembly and various components is used across multiple organizations for all product activities and subsequent decision making. This eliminates the need for released 2D drawings and the associated configuration management challenges that arise by keeping multiple depictions of the same system.

The OMEGA project team is playing an important role as an educator to our customers about the benefits that Northrop Grumman brings to them through the use of these MBSE tools within SE. The OMEGA program showcased this capability during the vehicle Critical Design Review (CDR) as a method of highlighting to the customer that Northrop Grumman is ahead of much of the industry in the use of innovative digital tools to help reduce cost and increase throughput by reducing the time to create the recurring engineering products needed to support launch vehicle production rate requirements. The team recently received DoD customer endorsement for these efforts, with a recommendation that this methodology be a showcase for how Northrop Grumman is meeting the directive of the DoD 2018 Digital Engineering Strategy.

The Master Model and the Tools to Manage It

Northrop Grumman's revolutionary model-based transformation was enabled by thoroughness in planning detail/activity and of processes, tools, and standards. Rigor in key areas, such as data hand-offs and items that interact, enables effective agile processes rather than inhibiting them.



The master geometric model is the 3D part of the authoritative source of truth. All elements of the design are represented by the 3D model, as the model is the result of the discipline analyses, which output key geometry linked with traceability through systems engineering practices. All master models are configuration controlled in a single PLM database using common change management processes. The PLM database supports coordination across the geographically dispersed OMEGA program locations in Arizona, Utah, Florida, etc., enabling better team collaboration. Using master models reduces development time by reducing redundancy in models and potential conflicts between models, but more significantly reduces recurring build timelines by simplifying configuration management of those redundant and conflicting models. Configuration controlled technical data package baselines are key, and there are model-specific issues for management of models and PLM system elements that can challenge full efficiency of an MBSE construct. Siemens NX and Teamcenter™ Unified Architecture (TcUA) software offer the opportunity to utilize a certain part number and make incremental "freezes" shown as soft revisions against a revision of a model.

Product baseline updates are provided throughout the development process, allowing all disciplines the ability to conduct technical reviews from the latest digital artifacts. This allows teams to make informed, system optimized decisions quickly. This agile process approach enables design teams and program management to move quickly from early design phases in multi-disciplined systems to more mature designs with fewer errors and reworks in later phases of the product lifecycle.

The geometric master model is utilized in the manufacturing and inspection of piece parts, subassemblies, and top-level assemblies. New digital Coordinate Measuring Machine (CMM) inspection software makes direct use of the master model. Digitally defined tolerances, inspection criteria, and product manufacturing instructions in the master model further ensure that CMM systems inspect parts with the proper criteria. Northrop Grumman has found value in providing customers and suppliers the digital models to support informed decisions and solutions as well as enable a collaborative environment.

Native master models for geometric components and assemblies are automatically converted into a lightweight file for downstream consumption and use. These lightweight models provide customers, suppliers, and partners with easy access to product visual and geometric information. Automated validation is in work to ensure derivative models match authoritative master models. This has been key for design reviews and for suppliers that are not as experienced with 3D annotated, tolerance models. The master/derivative model combination is also essential to making VR work effectively with rapid learning cycles. Historically, VR model building was a time consuming and largely artistically based process, requiring so much effort that only one or two finalized VR models could be reviewed. The master model facilitates nearly automated VR model generation that is accurate and configuration managed to match the latest design iterations

The master model is also used with additional lightweight digital models of surrounding facilities from other suppliers, for mass properties, human factors analysis, and ergonomic studies. This integration of system-level models provides an early view of concept-of-operations and product field operations long before first articles are built. The master model is also used as the starting point for alternate designs, and iterative master model baselines are utilized throughout the agile design process. Additionally, the master model, coupled with a standard for design and production cost and schedule data, are used in the proposing process with the ability to identify risk areas as compared to relevant actual historical programs. The cost and schedule data are used to perform initial program planning to facilitate efficient program startup that is responsive to emergent customer needs.

The Role of Virtual Reality

The ability to leverage VR (and eventually Augmented Reality) has created a new and unique technique for designing and building launch vehicles. This enhanced technology is now being actively used for the design and development of many major rocket motors produced by Northrop Grumman, including Space Launch System (SLS), OMEGA, and GEM boosters. Utilizing full immersion VR, the design team is able to review full scale versions of components and assemblies during the design process. This allows the team to find issues that are missed using traditional computer aided design techniques. It also allows the operations team to review the design very early to find impingement points or other human factor or ergonomic issues and fix them before they are constructed. This decreases the need for costly prototype, mock-up, and stages for rocket motor design. If an issue is found, it can be addressed, fixed, redesigned, and reviewed in virtual reality *in the same day*. This is an enormous cost savings opportunity compared to traditional turnaround time in the aerospace field for dispositioning design and operations issues.

Highlighting the cross functional collaboration enabled by these VR sessions is important. Stove pipes were reduced or eliminated as tooling, manufacturing, design, test, etc., worked together in a virtual 3D space to mitigate potential disconnects. Many program risks arise at interface points and these virtual reality sessions put a spotlight on those interfaces to ensure virtual mitigations before costly physical mitigations.

The Evolving Workforce

Recent demographic shifts have compounded the challenges while bringing needed energy and innovation to the aerospace industry. A decade ago, the engineering workforce was largely highly experienced. Northrop Grumman Propulsion Systems business unit was typical of the industry in that less than 10% of the workforce had fewer than three years' experience. That workforce was more than twice as large as it is today and worked on one or two new development activities (along with the production programs) that commonly took from five to ten years to get to flight. Today, even with less than half the overall workforce, more than a third of whom have fewer than three years' experience, Northrop Grumman is demonstrating getting from concept to static test in 16 months and to flight in less than three years. This agile development is achieved with the insurgence of new approaches to engineering from the next generation of rocket designers, and especially enabled by the combination of model-based and VR technology.