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Envisioning the Future:

A Focus on the Front End of Space System Development

AEROSPACE

Assuring Space Mission Success

Crosslink

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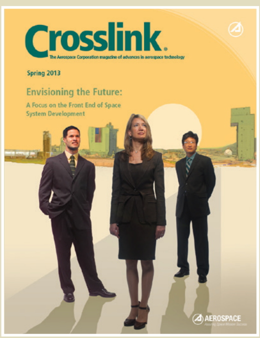

On the cover: Torrey Radcliffe, Debra Emmons, and Inki Min with eyes toward the future of national security space.

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IN THIS ISSUE

From the Editors

The Aerospace Corporation has begun a concerted effort to highlight its capabilities in the "front end" of the space system development lifecycle. This involves assisting the U.S. military, intelligence, and civil space community in defining the next generation of space systems. It follows a decade of a focus on the back end of the process—supporting the production, integration, testing, launch, and early operations of a new generation of Department of Defense (DOD) space systems.

Today, the space industry is facing extensive cost cutting and budget uncertainty to existing and new space system programs. This is occurring in an environment of advancing technologies, evolving threats, and growing customer demands for new capabilities. Finding a balance between the realities of funding and meeting the needs and expectations of customers has become essential.

This issue of Crosslink reveals some of the current efforts at Aerospace related to work on the front end of space system development. The company has an established track record of performing work on the front end, ranging from program initiation, to technology and software assessment, to supporting source selection.

One such area of highlight includes work on developing and analyzing space system concepts, designs, and architectures to help customers make decisions that are intended to save money down the road. The goal is to enable efficient program execution downstream by implementing an organized and structured system engineering process put into place today as a part of the development planning and decision support processes.

The company has renewed its focus on early architectures and acquisition planning, some of which is highlighted in this issue of Crosslink. Aerospace conducts architecture trade studies to assess options and solutions to meet its customers' mission needs while taking into account various uncertainties such as cost, schedule, technology, and integration risk.

One article explores the definition of user needs as the DOD initiates a drive toward closer cooperation between the user requirements and acquisition communities ("Defining Military Space Capability Requirements for Successful Development"). Critical technology selection; parts, materials, and processes engineering; and efforts toward ensuring manufacturing and industry base readiness are also reviewed.

World events and space policy developments have an effect on front-end space system considerations. Decisions made during the early stages of program development have a significant impact on determining system cost and reliability, and these topics are explored too.

Aerospace will continue its mission to assist its customers, evolving as their needs do, and responding accordingly to ensure space mission success. Here, we present some of the many facets of front-end work Aerospace is performing as the company turns its focus toward the future within a cost-constrained environment.

The Art of Designing and Building Complex Space Systems

Donna Born

A 30-year career, motivation, and a willingness to learn and try new opportunities have exposed Andy Amram to many areas of The Aerospace Corporation.

The Aerospace Corporation is highly regarded for its systems architecture and engineering work to ensure the successful design, production, and operation of space systems. A key player in this arena is Andrea (Andy) Amram, who has worked at Aerospace for nearly 30 years, dedicating the last 15 to the development of complex space systems architectures. As general manager of the Environmental Satellite Systems Division, Amram leads an organization that supports the Space and Missile Systems Center (SMC) at Los Angeles Air Force Base. These groups work to create solutions for the modernization of national security space missions, which the leadership uses to make acquisition decisions based on performance, transition efficiencies, resiliency, robustness, and affordability. Architecture analyses and development planning serves as a decision-support framework, linking space system needs to system capabilities, acquisition alternatives, and enabling technologies.

Amram's career has gone in many interesting directions, during which she has been eager to seize opportunities and acquire new knowledge. As a young adult, she earned a bachelor of science degree in zoology and a master's degree in education from the University of Michigan. She then relocated to California to work for a nonprofit organization, and later worked in the oil industry as a chemist, primarily because of former experience in operating scanning and transmission electron microscopes. When that company moved to Colorado, Amram stayed in California, accepting a job with Northrop Electronics and then Aerospace, where she performed failure analysis on hybrid microcircuits. Along the way she earned a certificate in electrical engineering and was promoted to manager, Technology Verification Section, in 1989.

Amram has steadily risen through the ranks to her current position. She attributes this successful journey to several good mentors and a lot of hard work. "I've had numerous people selflessly devote their energies to show me the way," she said. The late Murry Glick, who had been a director in the Engineering and Technology Group, was the first to take Amram under his wing. He encouraged her to further her education in engineering. Glick introduced Amram to Nickie Nelson, now retired, who was working in a program office at the time. Nelson provided Amram with broad exposure to systems engineering concepts.

"She took me to a ground station and let me experience exactly what we were building, and showed me how it was used and operated. This gave me the motivation I needed to return to school to complete my master's degree in systems engineering and architecture." Coincidentally, John Parsons, then senior vice president of the Engineering and Technology Group, was recruiting candidates to participate in Aerospace's first Systems Architecture and Engineering Certificate Program with the University of Southern California (USC) School of Engineering. Amram was selected as one of the first five Aerospace employees to complete a master's degree in the program, working half-time while attending classes full-time.

"I was very fortunate to have Eberhardt Rechtin, former president and CEO of The Aerospace Corporation and founder of the systems architecture program at USC, as my advisor and mentor. He taught me that systems architecting is as much an art as a science, and he pushed me to be creative and innovative while not forgetting my electrical engineering roots. Since then, the systems architecting field has matured, applying many software architecture methods to establish analytical rigor to its analysis methods," Amram said.

When she graduated from USC, Amram relocated to the East Coast as one of three individuals selected by Aerospace to assist Maj. Gen. Robert S. Dickman in establishing the National Security Space Architect's (NSSA) office, a new office chartered to develop next-generation military space systems. "My first assignment was to work on developing concepts for what became the military satellite communications architecture that is in operation today." Amram credits Dickman with teaching her how decisions were made in Washington, and how to present complex technical material to nontechnical people.

Amram returned to California after a year and a half to the position of director, Electrical and Electronic Systems Department. In 2001, she was promoted to principal director of the Architecture and Design Subdivision. During her tenure in this position, Amram helped transition the Aerospace Concept Design Center into a corporate core resource for architecting space systems concepts. She and her team have now completed more than 200 system architecture studies at the center.

Amram's willingness to take on challenges and new responsibilities and to seize opportunity has served her well. One new learning challenge came when Aerospace President and CEO Wanda Austin (who was at that time senior vice president of the Engineering and Technology Group) recommended to the Aerospace board of trustees that Amram be elected chair of the Aerospace Savings Account Plan, which is one of the company's retirement plans. The board agreed, and Amram served as its chair for nine years. "This opportunity introduced me to the business side of Aerospace and heightened my awareness to the complexity of maintaining affordable and attractive corporate benefits," she said.

In 2008 she was promoted to her current position and began collaborating with Inki Min, principal engineering specialist, on a corporate decision support framework and architecting a corporate strategic initiative to strengthen Aerospace's capabilities at performing portfolio-level decision-support analyses. During the last four years this has involved the development of analysis tools and processes that are described in two articles in this issue of *Crosslink*: "The Architecture Design and Evaluation Process" and "Development Planning and Decision Support."

Today, through the establishment of the Space Systems Group Architecture Council, Amram is working to assist Aerospace's customers in creating, managing, coordinating, and publishing mission-area architecting work products such as the core function master plan and integrated planning process documents, and an analysis of alternatives for the recent navigation, weather, and overhead persistent infrared systems studies.

The task of fielding complex space systems consists of two main phases: defining the next generation of space systems required for national security space, followed by the design, building, deployment, and operation of those systems. While historically Aerospace has been strong in "front-end" work (GPS is a prime example), more recently Aerospace has emphasized the "back end" to support the production, integration, testing, launch, and early operations of a new generation of DOD space systems.

"Many of these DOD missions are now operational, and Aerospace is engaged in a strategic shift to recast its workforce to support its customers in the daunting challenge of rearchitecting space through the modernization of existing systems while cutting costs. Thus, the company is embarking on another cycle of space architecture development. The corporation will transition people from testing and integration to system definition and design," Amram explained. "The work of Developmental Planning and Architectures comes in front of the design phase. So we are asking, 'What should we be building next?' "

Amram credits the influence of her parents, who stressed the importance of education, as a vehicle to achieving financial security and independence. "My parents scrimped and saved to send my brother and me to college. My father, who could speak six languages by the age of nineteen, earned his opportunity to emigrate from Casablanca to the United States by working as an interpreter for the U.S. Army in North Africa during World War II," she said.

The skills she learned in her biology and engineering classes led to a lifelong passion to study complex systems, which today range from creatures in the ocean to satellite systems launched into space. One of her hobbies is scuba diving. She and her husband, Richard Boucher, senior engineering specialist, Visible and Infrared Sensor Systems Department, take vacations diving around the world.

Over the years, Amram has been impressed by the versatility of available work experiences at Aerospace. "Aerospace has given me so many wonderful opportunities to participate in the myriad facets of designing and building complex space systems. Aerospace is unique in the industry with its role in understanding what complex systems our customers need to manufacture, and matching that with what the industry is capable of building." Her advice to young members of the technical staff reflects her own choices: "Take advantage of the variety of work available at Aerospace. Challenge yourself to work hard at new things to be successful. Find your strengths and do not get 'hung up' on climbing the corporate ladder. Seek out opportunities that will motivate you to work hard. Being successful at a job and doing it well is the best recipe for moving forward." Addendum

Right from the Start: Mission Assurance at Program Initiation

Sumner S. Matsunaga, Andy T. Guillen, Ray G. Bonesteele, and David L. Wang

Early introduction of mission assurance injects discipline into the development approach. Aerospace is working to ensure that measurable mission assurance products and deliverables are designed and implemented early in the acquisition lifecycle and clearly spelled out in the contract.

A driving principle of acquisition reform in the 1990s was that space systems could be obtained more efficiently through drastic cutting of perceived nonessential activities in system development. On the government side, contract specifications, technical oversight, and independent reviews were curtailed. On the industry side, system engineering and testing were deferred. As a result, inevitable defects in system designs were not detected until late in the development cycle. The resulting rework needed to deliver the intended capability led to long delays and higher costs.

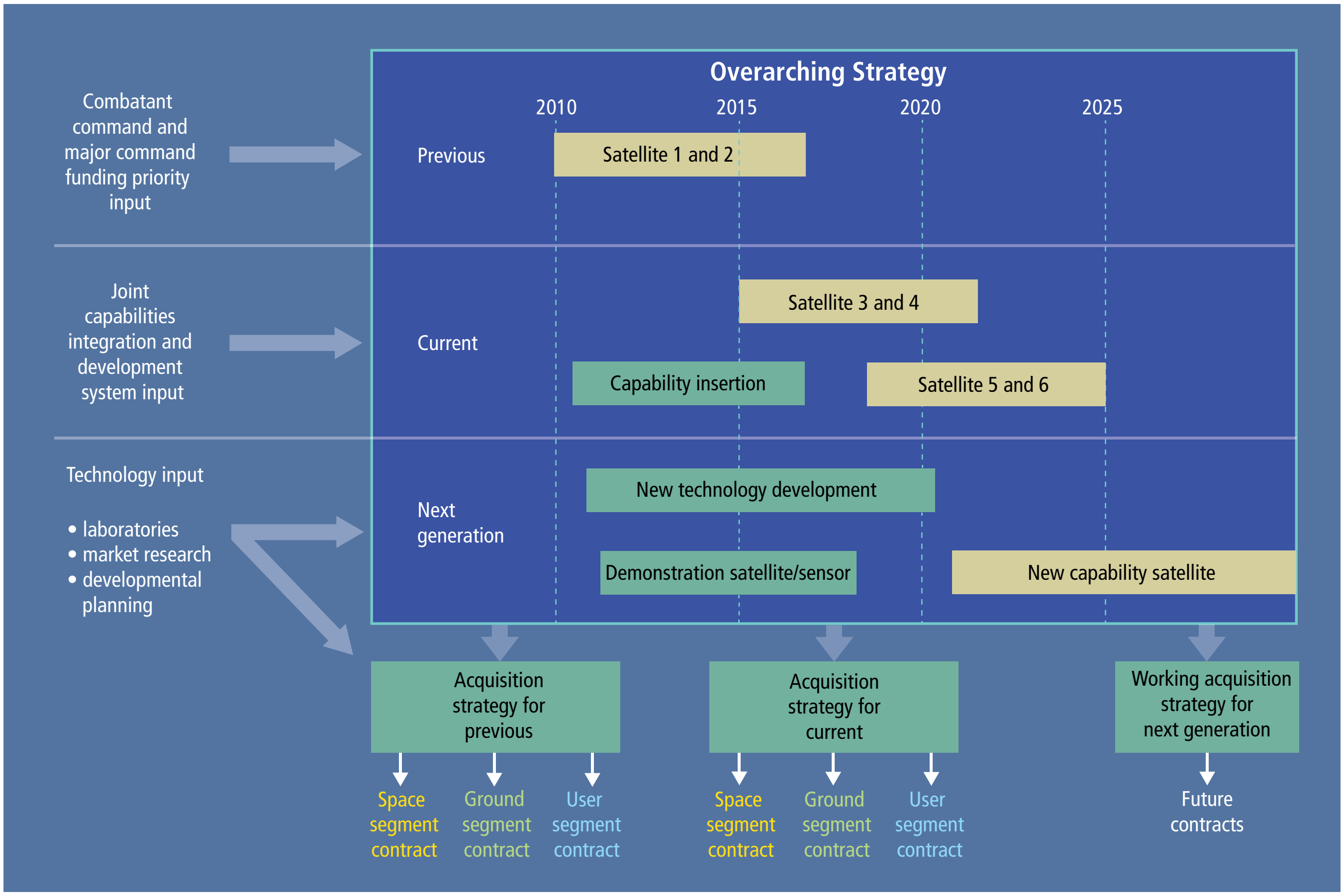
The industry has gradually been recovering from the problems that occurred with this approach. Recovery efforts focused on the effectiveness of mission assurance, as measured by launch and satellite operational success; but adding it after the fact (due to a lack of detailed planning and management) led to unexpected rework that negatively affected cost and schedule. In 2006, Aerospace embarked on an examination of acquisition processes; it became apparent that improvements in both effectiveness and efficiency were possible and necessary. The performance-based view of mission assurance was expanded to include practices and processes focused on meeting cost and schedule objectives. These included the disciplined application of technical and program management principles that collectively contribute to the goal of comprehensive lifecycle success.

Achieving overall lifecycle success begins at program inception. Aerospace is taking innovative actions to increase emphasis on front-end engagement on nearly all Space and Missile Systems Center (SMC) programs. These actions range from early concept development and future architecting to acquisition planning and integrated baseline development, and they rely on Aerospace's core strengths and resources to provide domain-specific expertise in the identification, prevention, and resolution of complex program executability issues. Key to this work is engagement in the early acquisition phases to balance desired capabilities with a variety of constraints, including cost, schedule, risk, technology readiness, and industrial capacity.

Influence on Early Requirements, Concept, and Design Exploration

The development of a new or upgraded system begins when a warfighter identifies new operational needs. These needs are translated into a set of desired capabilities. Aerospace serves as an active participant in needs assessment and requirements definition. Examples include understanding warfighter needs and translating those needs into functional capabilities, helping define feasible system solutions based on engineering principles and programmatic constraints, and providing alternative architectures that help to shape the next generation of military space.

Before any system acquisition can begin, the government must have an approved acquisition strategy that defines the approach to deliver the required capabilities within the approved budget and schedule. The strategy should define the relationship between the acquisition phases, resources, work efforts, and key program events such as milestone reviews, contract awards, development activities, test and



The acquisition community must actively seek out more affordable solutions by trading off new system development, integrating existing systems, and maintaining and modifying old systems. Aerospace helps program offices determine efficient and economical means of progressing from former to future capabilities.

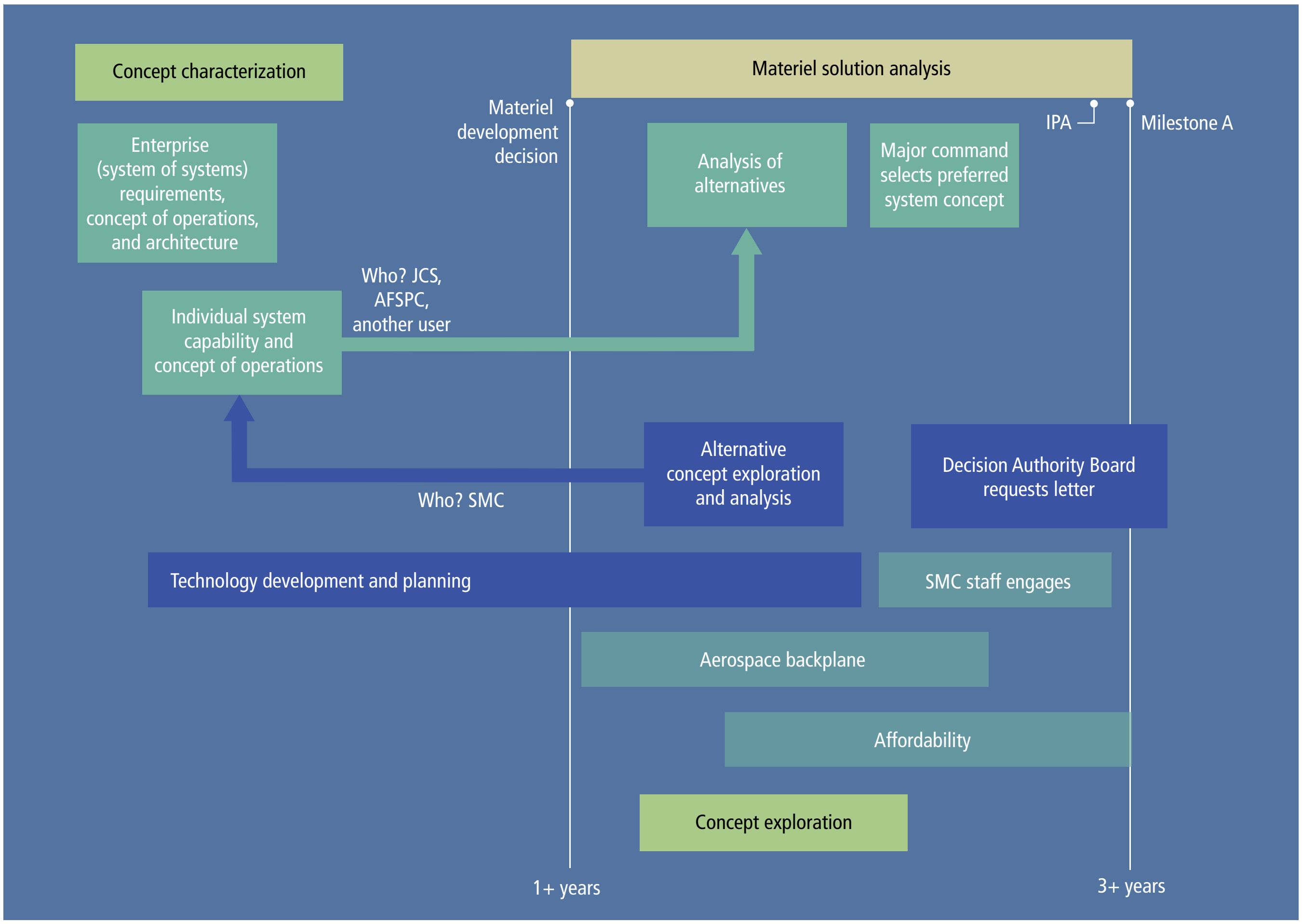
evaluation, production quantities, and operational deployment objectives.

The acquisition strategy assimilates the plans from critical program documents. It starts with the requirements captured in the initial capabilities document, capabilities development document, and capabilities production document, which describe operational performance and contain key performance parameters and system attributes. The capabilities development document is drafted during the technology development phase; it defines measurable and testable capabilities to guide the subsequent engineering and manufacturing development phases.

Other critical documents include the technical requirements document, which translates warfighter requirements into performance-based acquisition requirements. Aerospace is involved in the development of this document—often as the primary author. As such, Aerospace carries the primary responsibility on behalf of the program office for ensuring that all system and technical requirements clearly trace back to user requirements. This requirements tracing task is not a mechanical administrative activity, but rather requires complex understanding of the user's intent, key performance parameters, key system attributes, concept of operations, state of technology readiness, industrial base capacity, verification approach, sustainment concept, and lifecycle budget. Recent policy requires the major command, as user representative, to certify that the technical requirements document demonstrates clear traceability and acceptable decomposition of user requirements and intent. Therefore, this administrative coordination is actually the culmination of a rigorous systems engineering process for requirements elicitation and functional decomposition.

The technical requirements document is the technical description of a new system the government intends to develop. As such, it is the prime component of a request for proposal (RFP), which invites contractors to submit competitive bids to produce the envisioned system. The RFP describes the government's acquisition proposal solicitation elements, defines the content of the required documents with specific implementation details, and ensures coordination of workforce and organizational resources involved in expected contractual tasks. Aerospace is recognized as an expert in RFP development and provides orientation and training to government program managers and staff. In fact, Aerospace developed a template to help programs develop RFPs.

The selection of a contractor must be done in strict accordance with federal regulations. The SMC Acquisition



Aerospace facilitates analyses of mission gaps, affordability, and resiliency on a portfolio basis. Aerospace has been integral in defining the government's baseline plan and anticipating issues in the execution of that plan. Here, concept characterization, materiel solution analysis, and concept exploration are reviewed.

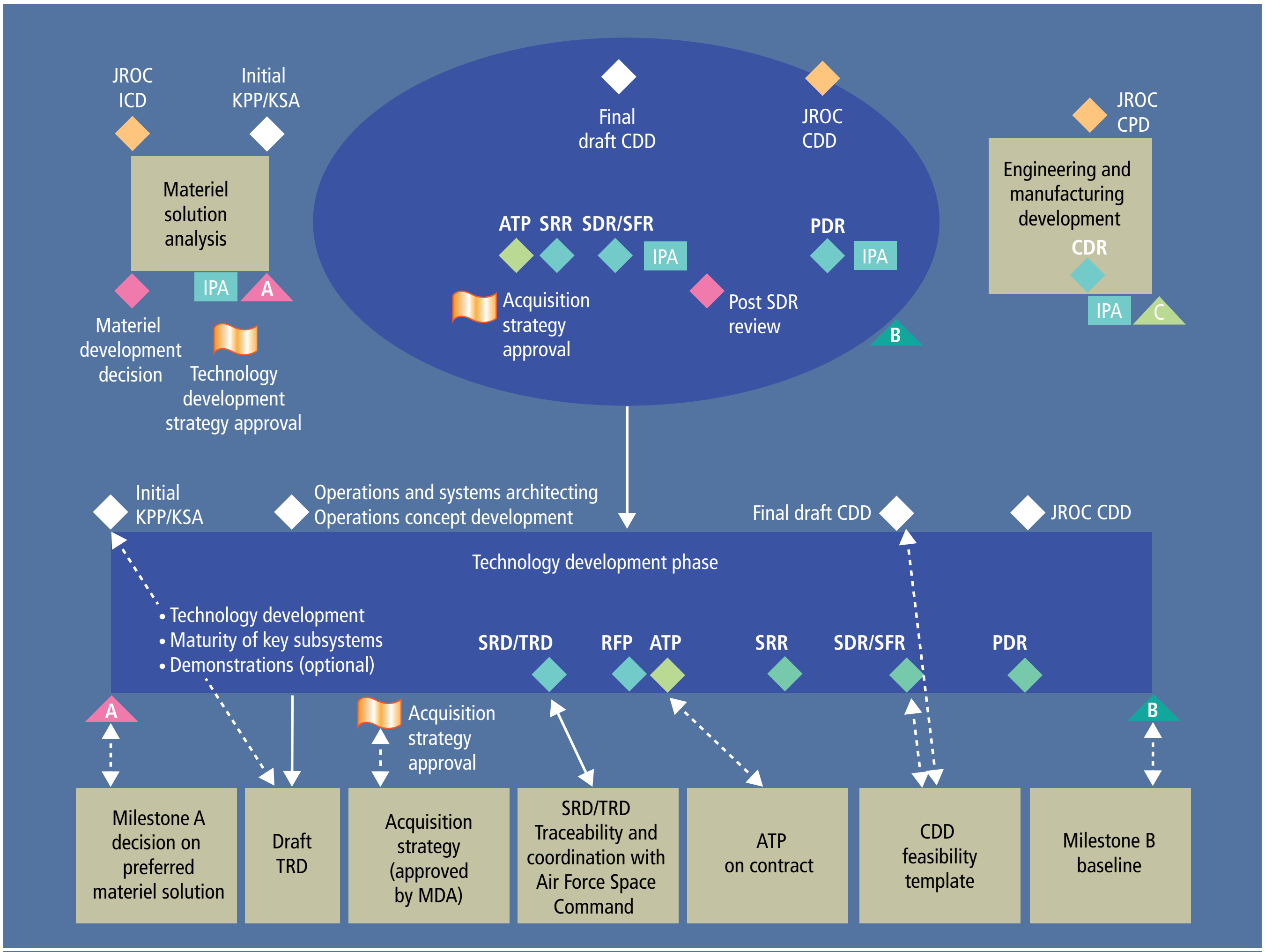
Center of Excellence is responsible for providing guidance and assistance to programs in planning and conducting their source selections. Personnel from the center and Aerospace have visibility across all SMC acquisitions and are well versed in current acquisition policy. This expertise, provided in training sessions and documentation reviews, benefits the programs by decreasing the overall evaluation timeline and reducing the likelihood of a sustainable protest. For example, the Acquisition Center of Excellence and Aerospace provide training in how to evaluate technical capability and past performance both prior to and during source selection. They advise source selection personnel in their role and responsibilities and ensure that source selections are conducted in accordance with acquisition policy, the RFP, and the source selection plan. They develop templates for briefings and decision documents, provide technical support and training for source-selection tools, provide a secure facility for conducting source selections, and collect lessons learned to improve future processes and resources.

Aerospace provides unbiased technical support in the preparation and execution of SMC source selections through service on the source selection evaluation team, the source selection advisory committee, and the multifunctional independent review team. One critical area of support is in the technical evaluation of proposals. Aerospace personnel serve as advisors to evaluate specific areas to determine whether and to what degree the bidder meets the stated requirements. These technical advisors assess the risk associated with an approach and determine whether the cost is realistic. Based on experience supporting a variety of SMC source selections, Aerospace provides training and feedback to help source selection teams make high-quality, defendable evaluations and operate in accordance with applicable policy.

For example, for the AEHF 5/6 production contract, Aerospace provided technical and integrated program management expertise to perform affordability analyses and identify cost-avoidance opportunities. This resulted in a prioritized list of cost-avoidance opportunities with detailed rationale supporting the government positions and use as part of the AEHF 5/6 business clearance. The lessons learned from the AEHF 5/6 proposal evaluation will be applied to other upcoming production contracts.

Mission Assurance on Contracts

Aerospace provides technical expertise for competitive source selection or technical evaluation for sole-source con-



ACE	Acquisition Center of Excellence
ATP	Authority to proceed
CDD	Capability development document
CPD	Capability production document
IPA	Independent program assessment
JROC	Joint Requirements Oversight Council
PDR	Preliminary design review
SDR	System design review
SFR	System functional review
SRR	System requirements review

The standard lifecycle model, as implemented for space systems, involves awarding the prime development contract in phase A and marches through the system engineering gates to define the program baseline at milestone B. Availability of contractor data and key personnel is critical to ensuring that mission assurance is incorporated in the baseline. Maturity of key subsystems, technology development, and demonstrations of functionality are also important milestones in this process.

tracts. The contract defines the government and contractor partnership, affects each partner's structure, and defines the program and contract baselines.

Front-end acquisition activities influence a majority of system costs, but represent only a small portion of the effort; in fact, by the end of the preliminary design phase, about two-thirds of the lifecycle cost is committed. The increasing difficulty in changing a design over time directly translates to higher cost and schedule delays, especially when replanning or rebaselining occurs late in the lifecycle. No amount of government oversight at the eleventh hour can overcome fatal flaws or inadequate test programs that were not addressed early on. Therefore, mission assurance must begin early in the program acquisition lifecycle and continue throughout design, build, launch, and operations. The objective is to arrive at efficient, measurable core mission assurance standards and deliverables that can be placed on contract to provide the government with a positive understanding and appropriate span of control for accessing and mitigating risks in performance, schedule, and cost. Incorporating mission assurance increases knowledge prior to contract negotiation and should lead to higher confidence in achieving overall program lifecycle success.

Aerospace helps to ensure that mission assurance is applied throughout all phases of a program. The level of mission assurance for any point or element is based upon system risk management—the identification, assessment, and prioritization of risks. It is a common thread linking program management, acquisition planning, system engineering, and cost estimation. Aerospace developed and offers a series of

Successful Front-End Engagement

Some noteworthy examples of up-front mission-assurance activities at the Air Force's Space and Missile Systems Center (SMC) include the work of the program engineering acquisition and execution support teams, the Acquisition Center of Excellence, the Program Management Assistance Group, and the SMC Cadre. Each of these functional teams has primary expertise in some part of the acquisition lifecycle, such as the pre-award process, post-award process, requirements definition, acquisition strategy, RFP development, source selection, integrated program baseline planning and reviews, technical reviews, and specifications and standards. Each team uses technical and programmatic experts from the government, program offices, and The Aerospace Corporation.

Engineering Acquisition and Execution Support Teams

The Engineering Acquisition Support Team (EAST) and the Wing Execution Support Team (WEST) have been working to improve SMC acquisitions by assisting the programs in formulating and defining the technical content of space-system acquisition products. Typical projects include concept formulation, requirements development, and preparation of acquisition documents.

For example, during the preparation of a contract solicitation, EAST helps define the program technical baseline, including the associated risks, while balancing the need to apply appropriate specs and standards with the need to manage cost and schedule risk. The team helps tailor SMC standards to the particular program and evaluates the possibility of using the contractor's documented processes instead of such standards. For example, the government allows EELV to use United Launch Alliance processes on its acquisitions because they have proven successful in the past.

In the execution phase, the program office is required to certify the flightworthiness of the system. Front-end engagement by EAST and continued engagement by WEST facilitate the timely verification of flightworthiness criteria through certification planning in the development cycle. EAST identifies the appropriate program-specific accomplishments that will support the flightworthiness criteria and links them to the requisite technical reviews or deliverables, while WEST performs their verification.

Acquisition Center of Excellence

The Acquisition Center of Excellence (ACE) focuses on developing a lifecycle program strategy based on documented core processes. ACE (also referred to as the center) ensures there are no "congenital defects" in any SMC acquisition in terms of the strategy, RFP, and source selection. The strength of the center lies in its construct of experienced program managers, engineers, and contracting specialists, integrated as a cohesive team that takes full advantage of the broad expertise within Aerospace.

ACE also works with other authorities to perform independent assessments on Air Force programs at the end of each development phase. Periodically, the center analyzes recent assessments and distils the information for release to the acquisition wings and senior leadership. ACE also engages with program offices at least one year prior to major decision points to provide clear direction and recent lessons learned and to offer technical and programmatic expertise.

Program Management and Assistance Group

The Program Management Assistance Group (PMAG) focuses on providing program execution assistance throughout the entire acquisition lifecycle. The emphasis is on analyzing affordability, identifying cost-avoidance opportunities, and establishing and assessing risks to the program mission-assurance baseline. The group consists of a relatively small and integrated team of interdisciplinary professionals that leverages the full capabilities of Aerospace.

In the current budgetary environment, program affordability is a key concern. PMAG affordability analyses are used by the program office to prepare for contract negotiations. Lessons learned from each program are applied to subsequent affordability analyses. Through its support of PMAG, Aerospace is becoming more involved in cost-effectiveness analysis and cost-avoidance identification.

PMAG has also participated in the development of program mission-assurance baselines at the front end of the acquisition lifecycle. Aerospace leads the development of training workshops and program-specific assistance in the development of an integrated master plan and integrated master schedule. Aerospace provides collaborative assistance to the program offices to ensure consistency between these plans and all other acquisition planning and solicitation documents.

SMC Cadre

The SMC Cadre coordinates and supplements the efforts of the acquisition planning, program management, contracting, financial management, and engineering organizations. The goal is to provide knowledge and expertise in a collaborative and efficient manner early and throughout the acquisition-strategy development.

The SMC Cadre focuses exclusively on assistance prior to contract award; however, Aerospace has a cadre for complete acquisition lifecycle support, supplying the expertise needed for different acquisition phases. This lifecycle cadre starts working early in the acquisition process—such as with the early strategy session—and proceeds through acquisition-strategy development, RFP release, and source-selection planning and execution. Support continues throughout program execution—hence, this involvement may extend from the technology-development phase through the engineering and manufacturing-development phase and on into the production, deployment, operations, and support phases. The lifecycle cadre is based on a small core team led by a senior advisor from Aerospace with significant program-management experience. The advisor provides continuity and guidance to multiple cadre leads and program managers. All Aerospace products are validated with the core team and approved by SMC, which also coordinates the participating program offices.

– *Sumner Matsunaga, Andy Guillen, Ray Bonesteele, Dave Wang, David Bart, and Sam Peresztegy*

Successful front-end engagement starts with a core Aerospace team. (L-R) Pictured here are Jeffrey Belanger, David Wang, Rosie Duenas, Ray Bonesteele, and Andy Guillen, all of the Engineering and Integration Division.

hands-on workshops to assist program office personnel in implementing the acquisition development process. As one example of these workshops, experts from the SMC Acquisition Center of Excellence and Aerospace meet with the participants to guide risk-workshop outcomes and develop risk-mitigation plans for identified high-risk items.

Availability of contractor data and key personnel is critical to ensuring that mission assurance is incorporated in the program baseline. Contractual provisions regarding contractor activity, procedures, and reporting systems determine staffing requirements and are generally covered in statements of work, compliance documents, schedules, specifications, contract data requirement lists, and data item descriptions. These provisions must provide for adequate contractor implementation and information transmittal; if the mission assurance provisions are not included in the baseline contract, the government program office must identify and implement contract change mechanisms.

Government efforts have focused on specific ways to foster mission assurance by providing contractors with effective incentives. Good mission assurance processes should become a key discriminator in future source selections, and an approach that effectively and efficiently manages risk of system development should be rewarded. Contracts must delineate the required specifications and standards and show how they are reflected in the contractor's command media. The adaption of generic practices and processes must maximize the added value (especially in the reduction of cost, schedule, and performance risks) while minimizing the costs of compliance. As affordability trades are considered, the DOD must guard against creating an acquisition environment that unintentionally motivates contractors to cut corners in mission assurance.

Acquisition reform in the 1990s presumed mission assurance would be automatic, but experience showed that it must be explicitly defined and accepted by the government and contractor. Fiscal conditions in subsequent years also highlighted that full risk mitigation was not affordable. Accordingly, the government realized that mission assurance must be tailored. Tailoring mission assurance is the effective and efficient customizing of proven practices to suit a specific situation and level of acceptable risk. Tailoring strategies typically include transferring or deferring the risk to another system element or time period, avoiding the risk, reducing the probability or impact of the risk, or accepting some of the potential consequences of a particular risk. This tailoring requires an iterative exchange between the party that understands the requirements and situation and the party that understands the proven practices. More often than not, there is a chasm between these two groups, so the government typically errs either on the side of caution (which can result in program execution issues) or carelessness (which can result in failures); both induce cost and schedule overruns or constrained alternatives and inflexible architectures. This interplay becomes ever more complex when a variety of concepts are pursued to achieve resiliency and cost efficiency. Examples include the exploitation of space capabilities through commercial and foreign resources as well as

Courtesy of U.S. Air Force

Pararescuemen secure the area after being lowered from an HH-60 Pave Hawk during a mission Nov. 7, 2012, in Afghanistan.

space-capability enhancements through lateral exploitation of data from existing sources. Aerospace is often called upon to bridge this chasm of understanding.

One major example of mission assurance tailoring involves testing and evaluation, which is performed largely by prime development contractors using their own facilities. Much of this testing is performed at lower levels of assembly because defects identified at that phase are cheaper to correct. System-level development tests are also typically performed at contractor facilities because of the cost, risk, and time involved in transporting a fully assembled spacecraft to a centralized government facility. While these tests are performed at contractor facilities, they still receive robust government oversight—and in most cases, the government team (including Aerospace) helps to plan them, witness their execution, analyze the results, and troubleshoot any anomalies.

The government defines the testing approach and levies test requirements through the disciplined application of appropriately tailored specifications and standards on development contracts. This has led to a dramatic increase in reliability of space and launch vehicles in the last decade. The Air Force is also working to expand and enhance its test and evaluation workforce and continues to develop and apply "test like you fly" principles to space systems.

New Program Exemplar

The first program to benefit from SMC's mission assurance baseline is GPS III. Although all SMC acquisition programs have benefited from the renewed emphasis on mission assurance and program executability, GPS III is the first program to fully implement the lessons learned from a decade of relearning and to incorporate mission assurance from inception.

GPS III program management began with a prioritized set of approved and well-understood system requirements along with senior leadership advocacy and DOD Joint Requirements Oversight Council stabilization. GPS III took six years to understand, vet, and decompose requirements through numerous executive-level reviews. The next step was the development and approval of the acquisition strategy, which was vetted through multiple independent program assessments and a five-month-long integrated baseline review. A number of SMC assistance organizations were engaged as well, including the Acquisition Center of Excellence, the Program Management Assistance Group, and the Engineering Assistance Support Team.

Significant risk mitigation was achieved by thorough concept exploration, ensuring that critical technology elements would all reach appropriate readiness levels. The program maintained two prime contractors from requirements definition through system design review. In addition, key risk mitigators—such as a pathfinder and GPS satellite simulator—were built into the master schedule. The workforce was trained to provide capable and consistent government oversight and system integration. The GPS III baseline included a robust integrated master schedule and independent baseline-review process. Extensive use of the Program Management Assistance Group filled critical program office gaps, and joint training and execution was held with contractor cost-accounting models. Lastly, business execution was held on par with technical execution. Realistic cost estimates resulted in a low-risk schedule and 80 percent confidence based on government schedule estimates with mature technologies. The single integrated performance baseline provided visibility of cost and schedule impacts, and the critical-path analysis allowed for proper allocation of resources and early intervention.

Disciplined engineering for GPS III was also of paramount importance. The integration of program segments—space, control, and user—required a strong configuration control board. Directorate and contractor processes were standardized or integrated and included integrated change management, mission-level system engineering plans, and test and evaluation master plans in concert with industrial-base and manufacturing readiness assessments. Emphasis was placed on subcontractor management (e.g., supplier audits), and FFRDCs were engaged as much as possible; for example, Aerospace served as the squadron's chief engineer. Early compliance with mandatory efforts (such as environmental analysis and information assurance) was performed. Special attention was given to software development, design verification, and satellite modeling. Additionally, fully tailored specifications and standards and lessons learned were on contract.

Summary

In the current fiscal environment, the space community must focus on affordability; however, caution should be taken not to sacrifice mission success, but to always build upon lessons learned and apply proven, disciplined engineering practices that are instituted at the start of acquisition planning and execution. A single catastrophic launch or on-orbit failure of a billion-dollar system carries a high price in terms of lost warfighting capability, replacement costs, and national prestige. The inability to develop and field less expensive systems because of high mission assurance costs is also unacceptable. The space community must turn its attention to early collaboration with the requirements community to define and prioritize warfighter needs in accordance with affordable system solutions balanced across capabilities, cost, schedule, and mission assurance. The government also must reestablish its ability to plan and manage programs. Finally, the government must continue to build its system engineering and integration capability and capacity as well as test and evaluation. Aerospace can influence the acquisition front end and serve as the glue holding it all together across the entire lifecycle.

Further Reading

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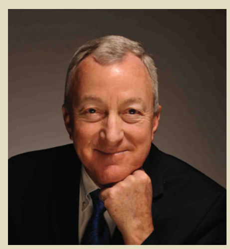

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Defining Military Space Capability Requirements for Successful Development

Jennifer Owens, Jeff Belanger, Ray G. Bonesteele, Andy T. Guillen, and Rosie Duenas

Policies and practices are evolving to ensure that new system developments are executable from the onset. The new approach emphasizes close coordination of requirements definition and acquisition strategy development.

The key to delivering systems that meet operational capability needs on time and on budget involves early trade studies and decisions about the requirements that can be met within the given fiscal constraints. This involves matching up two processes—user requirements definition and acquisition development—that have historically functioned separately. Recent efforts within the Department of Defense are driving closer cooperation between the user requirements community and the acquisition community.

Aerospace supports both communities, helping them reach an appropriate balance between warfighter needs and available resources. In fact, early Aerospace support can be a force multiplier in the long run, creating the leverage necessary to ensure that an operational need can be successfully translated into a space system acquisition program. The earlier Aerospace systems engineering expertise is applied in the acquisition lifecycle, the more efficiently the government can satisfy capability needs across the overall space portfolio.

Tracing Requirements to Combat Needs

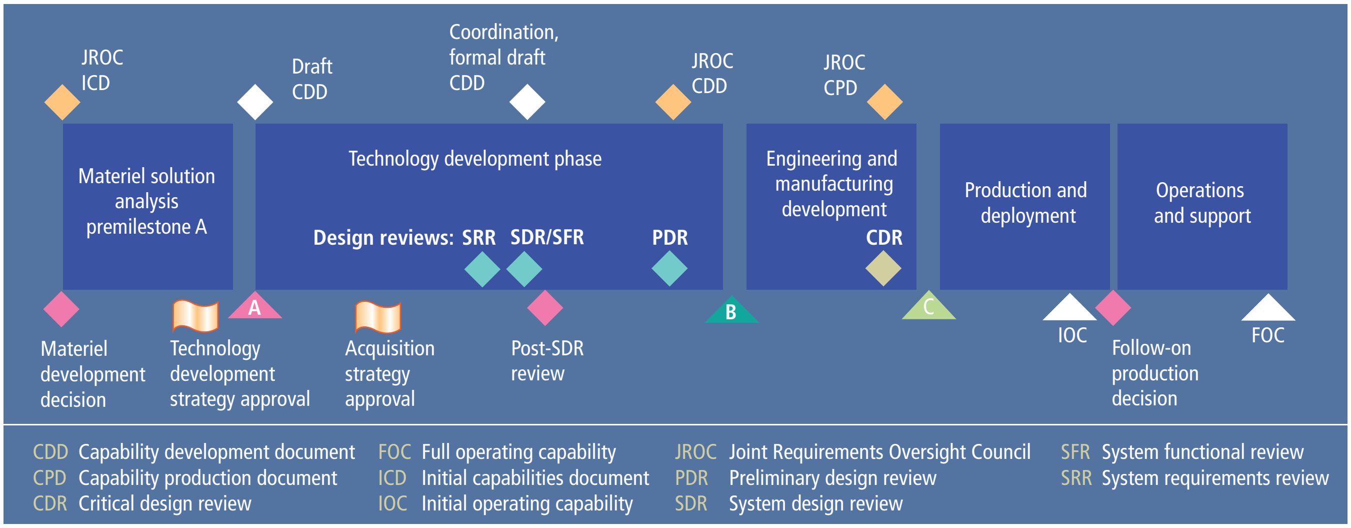
The Department of Defense has divided responsibilities for acquiring systems and establishing operational requirements into two primary chains. The acquisition chain is headed by the secretary of defense and the service secretaries, and the operational chain is headed by the chairman of the Joint Chiefs of Staff. The acquisition process is primarily governed by DoD Directive 5000.01 and DoD Instruction 5000.02, collectively known as the Defense Acquisition System. The operational requirements process is governed by CJCS Instruction 3170.01, which establishes the Joint Capabilities Integration and Development System (JCIDS).

Under JCIDS, warfighter capability needs are established by the combatant commanders—the joint commanders responsible for executing military operations for a functional area (such as U.S. Strategic Command) or a geographic region (such as U.S. Central Command). Within each military service, a major command is designated as the lead command, responsible for organizing, training, and equipping a combatant command. For most space and cyber capabilities, Air Force Space Command serves as the lead command. The bulk of acquisitions within the space mission portfolio are managed by the Space and Missile Systems Center (SMC).

This duality of having the combatant commanders establish capability needs and the acquisition community fulfill those needs is an effective way to balance needs and affordability. On the other hand, these dual responsibilities have led to problems whereby requirements are validated with insufficient assurances by the acquisition community that they are feasible and executable. Recent changes in both law and policy have sought to synchronize these processes better; these changes affect how system-level requirements are engineered up front, early in the acquisition process prior to any contract award for the system design or development.

Assessing Mission Needs

As a first step in tracing user needs to new materiel requirements, Air Force Space Command conducts a capabilities-based analysis, tied to mission-level architectures, to identify and prioritize gaps in military capability. Aerospace often leads or contributes to these analyses. Specific tasks include



The acquisition and requirements lifecycle, starting at the materiel development decision. This simplified view of the Joint Capabilities Integration and Development System process overlaid on the acquisition process is part of a tutorial on the space acquisition framework, which was developed by the Space and Missile Systems Center at Los Angeles Air Force Base and Aerospace to reflect the integration and alignment of acquisition and requirement milestones in the acquisition lifecycle.

developing integrated architectures to identify mission needs and linkages to system capabilities and performing mission-area analyses and integrated investment analyses to determine the most economical way to satisfy capability gaps within and across mission areas. The products of these activities inform decisions on programming (budgeting) and technology development, and can even indicate which types of materiel solutions should be pursued as future programs. Implicit in this process is technical rigor and freedom from bias—specifically, long-term expertise with mission analysis and architecting, objectivity, and unfettered access to proprietary concepts from industry. This type of work, therefore, lends itself to being done by an independent body such as Aerospace, which is a California nonprofit corporation that operates a federally funded research and development center (FFRDC).

A capability gap may be broad and may be met with new tactics, new capabilities, new materiel, or a combination of all three. When it is determined, based on analysis, that a new materiel solution must be developed, Air Force Space Command creates the initial capabilities document (ICD) to define new requirements and associated gaps. This document is the first to formally trace capability requirements from the mission architectures and underlying analyses to the initial set of system-level requirements. This traceability, both in requirements and in architectures, must be preserved throughout the acquisition lifecycle.

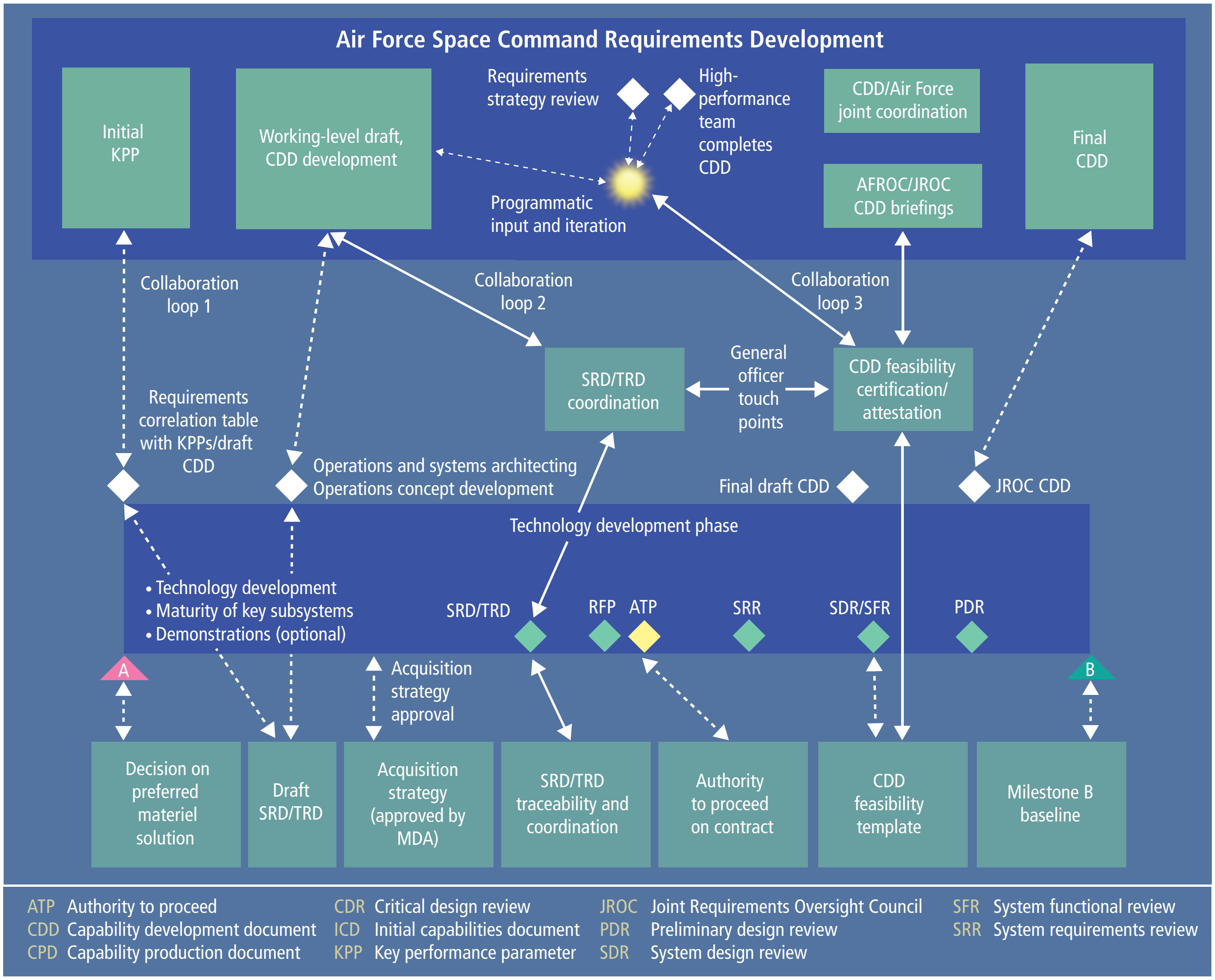
Establishing an Initial Requirements Baseline

The decision to pursue a new system ushers in the materiel-solution analysis phase. Two major activities occur at this time, the analysis of alternatives and the development of an acquisition course of action.

The analysis of alternatives is highly structured and typically led by Air Force Space Command for space programs, but sometimes sponsored or led by other organizations, such as U.S. Strategic Command. Aerospace often serves as the study leader. Team members typically span multiple organizations and communities, including users, headquarters staff, acquisition centers, labs, and intelligence organizations.

As with the capabilities-based assessment, the analysis of alternatives must be executed by organizations and personnel free from real or perceived conflicts of interest—otherwise, industry will not share its system concepts, and decision makers will not accept the results. Aerospace personnel representing multiple organizations often work together on analysis of alternative teams, typically leading technical studies or subgroups developing measures, threat assessments, materiel alternatives, scenarios, and methodologies. The analysis of alternatives is documented in a report which, under the JCIDS process, is coordinated through the Joint Requirements Oversight Council. This report is not openly discussed until published because of the extreme sensitivity associated with comparing the merits of materiel concepts from multiple industry and government sources. The report is required by the Air Force to include a requirements correlation table (RCT), which defines an initial set of prioritized key performance parameters and system attributes for the recommended alternative or set of alternatives. This information will form the basis for a draft capability development document (CDD), which is the formal operational capability requirements document that must be finalized before the acquisition baseline can be approved.

The analysis of alternatives will indicate the most effective means of satisfying the high-level capability needs, but will not contain enough detail to develop an acquisition strategy. Thus, an acquisition course of action must be established. Aerospace supports the process through workshops designed to assist the program office in presenting a common vision and establishing an end state for the program.



The technology development phase involves simultaneous requirements and acquisition processes. Aerospace often facilitates collaboration during the early portion of this phase, where numerous stakeholder requirements are considered. Failure to work collaboratively can lead to rejection at milestone decision points.

These workshops cover program objectives, risk assessments, technology development strategies, and acquisition strategies and help to identify the requirements that most influence cost, schedule, and technical performance. For example, Aerospace recently led a workshop for a program that involved a wide range of operational and acquisition stakeholders. While the only viable materiel solution was a new space-based sensor, the possible acquisition approaches varied widely, from a payload hosted on a foreign spacecraft to development of a new spacecraft. This workshop defined program objectives and key driving requirements and provided the foundation for selecting an acquisition approach. Such early programmatic decisions are often fraught with competing government and industry goals, but the workshop ensured that the acquisition approach was based on solid data and a fair accounting of risks, cost, and schedule considerations as well as technical performance.

The transition from the analysis of alternatives to the acquisition course of action is significant, for it is at this point that the program office begins to set the pace (in terms of budget and schedule) for delivery of a capability. Once an acquisition strategy has been selected and approved, an affordability target must be established and formally documented. To properly integrate affordability into the baseline set of requirements, the systems engineering and architecting performed here must be integrated across system segments and functional disciplines, including program management and control. The systems engineers—which include Aerospace personnel supporting both Air Force Space Command and SMC—must maintain a holistic view of the trade space and not lock in specific solutions that overly constrain other elements. Solution sets that may not satisfy 100 percent of the requirements should be considered with a broader view of balancing cost, schedule, and technical performance. The cost analysis must consider lifecycle and acquisition costs as well as possible impacts to associated systems and operational concepts, such as the need to modify intelligence gathering systems or to commission new military units to implement the new capability. Aerospace supports the decision-making process by managing and executing the independent program assessments required by acquisition policy. There has been a tendency in recent years for programs to skip the materiel-solution analysis phase to avoid preparation and coordination of the requisite documents. This can appear to save two to three years of schedule, but it also eliminates much of the systems engineering that reduces risk and enables effective and efficient program execution.

Requirements Collaboration

Systems engineering activities ramp up in the technology development phase, particularly before a new program can be placed on contract for design and development. High-level policy and instructions typically only identify senior approvals of final requirements and acquisition documents through separate chains of responsibility, and therefore often do not adequately convey the intent that these documents be developed collaboratively and in parallel. Aerospace often facilitates collaboration among the acquisition and user stakeholders during this phase. Failure to work collaboratively will result in rejection at key decision points, leading to delays, rebaselining, and ultimately, failure to deliver a system that meets user expectations on schedule and within budget.

There are three main process loops for requirements collaboration. The first involves the flow down (and up) of requirements from the correlation table or draft capability development document to the draft system requirements document (SRD). The second entails the formal coordination of the final system requirements document included in a request for proposal (RFP). The third generates the acquisition community's formal feasibility assessment of the capability development document prior to approval. Aerospace is involved in each of these process loops, representing various stakeholder perspectives and ensuring that technical issues are resolved early and at the lowest level possible.

Loop 1: Requirements Trades

The tracing of requirements from the correlation table or draft capability development document to the draft system requirements document is performed as part of iterative trade studies. These trades refine key performance parameters, schedule, cost, and technology and manufacturing risk and are performed within the context of larger mission architectures and mission-level capability analyses. Performance must also be traded against operational suitability requirements such as reliability and protection as well as considerations such as operational concepts, staffing, facilities, and training. Aerospace typically leads or supports these analyses, which are similar to the trade studies performed in the materiel solution analysis phase, but at a lower level of detail. Aerospace often also develops the system requirements document on behalf of the program office and helps establish a requirements-management process that includes a mechanism for maintaining traceability both up and down the hierarchy of documentation. Neither the system requirements document nor the capability development document can be completed until affordability targets are fully analyzed and trade studies are completed. Requirements traceability becomes more complicated and more critical as these documents are solidified. A simple table or spreadsheet becomes unwieldy as operational attributes and constraints are translated into materiel development requirements—which is why a formal requirements-management program is essential.

Loop 2: Coordination

It may sound counterintuitive, but the system requirements document (also known as the technical requirements document, or TRD) is finalized and approved before the capability development document. The contractors will use the system requirements document to derive system-level specifications and develop a preliminary design. To ensure that appropriate requirements coordination and traceability is occurring at the working levels, the Air Force now requires all programs to coordinate system or technical requirements with Air Force Space Command prior to issuing an RFP (most SMC programs were already coordinating requirements documents with their working-level counterparts at Air Force Space Command, but were not formally coordinating them above the working level). This requirement highlights the importance of the system requirements document as a critical element of early systems engineering. The key to successful coordination is demonstrating clear traceability and mutually agreeable decomposition of the operational capability requirements and intent into an achievable set of system requirements. Before the system requirements document enters coordination, it must be checked to ensure that it is consistent and traceable to user capability needs and does not represent requirements growth. This task, sometimes performed by Aerospace, requires complex understanding of the user's intent, concept of operations, sustainment plan, and lifecycle budget in addition to the user requirements.

Loop 3: Assessment

The Air Force requires the acquisition community to formally assess the feasibility of the operational requirements in the capability development document before it can be approved. This assessment is certified by the acquiring major command and service acquisition executive (depending on program size). For SMC programs, the acquiring major command is also Air Force Space Command, but in a different role from the one it plays as lead command in developing the capability development document.

Certification is accomplished concurrently with joint staffing of the capability development document, which occurs around the time of the preliminary design review, about

A Focus on the End User

System acquisition is a circular process that begins and ends with the users. For example, a warfighter might define a need based on a capability shortfall in accomplishing a mission. If a materiel solution is needed, the various operating and major commands would then propose a set of possible system capabilities that can be integrated to address the shortfall. Those capabilities might be provided by a new space system or a major upgrade to an existing space system. Air Force Space Command (AFSPC) will work with the user community to generate a capability description document and a concept of operations based on what is technically feasible.

Once a capability need is officially identified, the system acquisition phase begins. This phase has been a traditional focus of Aerospace expertise. The first step is to translate the need statement into verifiable and implementable system requirements that can be used to issue contracts. This requires an understanding of user and operational needs, such as how the system will integrate with other systems, present data to the end user, and interact with the operator; and training; logistics; and maintenance. When trade-offs arise due to budget, schedule, or performance shortfalls, the needs and constraints of the user and operator communities must be considered when developing courses of action.

It is essential for all organizations involved in the development cycle to fully understand the problem space and employ the right people in making technical trades. Aerospace has been active in this environment since the beginning of the Space Age, and has observed the growing complexity of the systems and acquisition process through the years. Space has evolved from a research and demonstration endeavor to a vital component of military operations. The end-user community now includes all the various armed services as well as civil and commercial users. The major command, operations, and acquisition organizations have different roles and consequently do not necessarily share a common perspective or understanding of the entire development lifecycle. Aerospace is unique in supporting all aspects of the system lifecycle, including needs analysis, requirements and concept development, acquisition, and operations and sustainment. The company is therefore well positioned to address issues that arise by integrating its efforts.

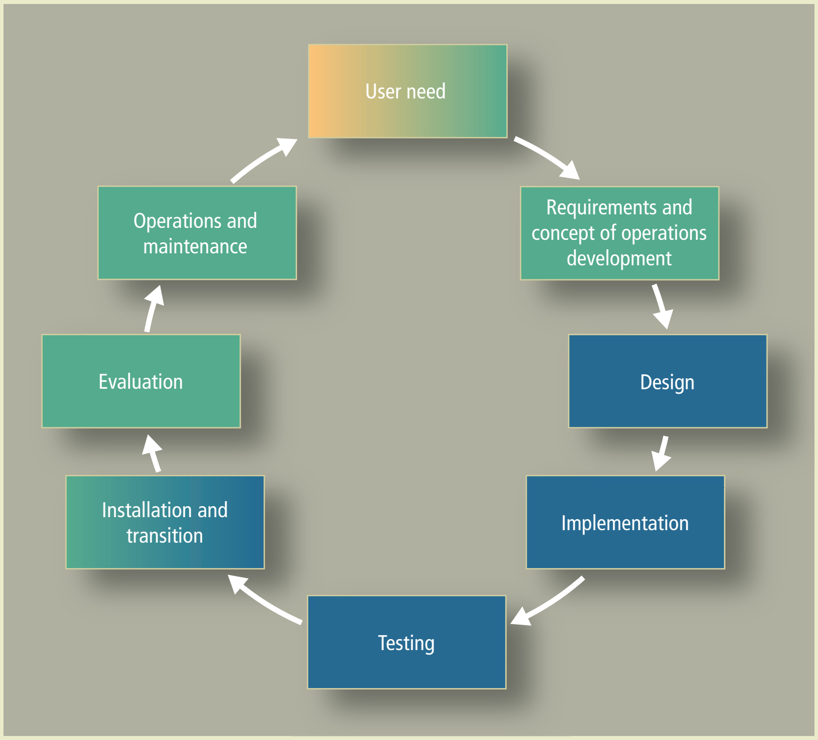
Aerospace has continued to develop resources and expertise to help integrate efforts across its organizations. One such resource is the Concept Design Center (CDC), a collaborative environment that has been expanded to help systems planners develop and refine capability descriptions and concepts of operation. When Space Radar was an active program, Aerospace program office engineers worked closely with Aerospace representatives at Air Force Space Command and, using the CDC to refine concepts, were able to delineate what capabilities could be developed and the inherent trades between radar imaging and ground moving target indications. This, in turn, helped Space Command work with end users to gain consensus regarding requirements and operational concepts. In another case, the transition to operations of the first major upgrade of the GPS control segment was accomplished through close integration between the program office, on-site test and verification personnel, transition experts, and the operations community. This was only possible because Aerospace had personnel in each of those organizations. The lessons learned during that transition are now being applied to the acquisition of the next-generation GPS control segment (OCX). In this case, transition to operations is a key factor for success. Therefore, operations personnel are being involved at critical design points, so that issues impacting transition and operations can be addressed early.

Aerospace is working on several levels to capitalize on these successes and increase the overall focus on the front end for all programs. For example, the corporation is developing resources and a cadre of engineers experienced in system transitions into a Transition Center of Excellence, to ensure user and operator needs are properly considered in new or upgraded space systems and to better plan for transition to operations. A resource known as the integrated Mission Assurance Tool is being upgraded to include more aspects of the development and operations cycle, and the Aerospace President's Reviews have been expanded to include focus areas not previously considered in this process, such as the operational readiness of ground systems.

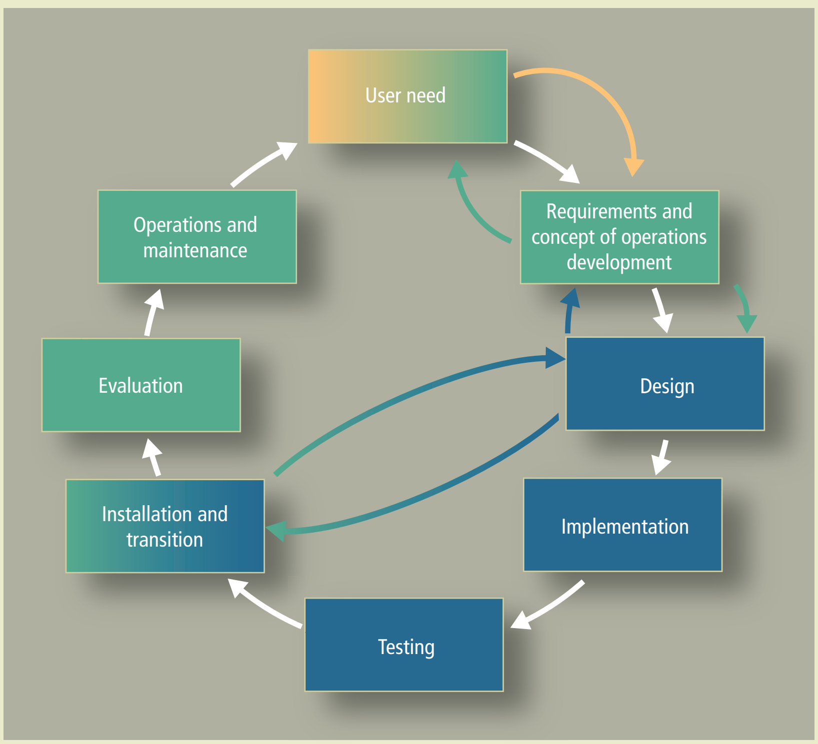
The emerging model of mission assurance recognizes that the front end of the requirements process and the back end of system acquisition and operations exist at the same point in the system lifecycle. This point is occupied by the end user and system operator. Focusing on this area throughout development should naturally lead to greater mission success. Aerospace already provides expertise throughout the cycle, with personnel on-site at key locations. By coordinating the priorities of operators and designers alike, Aerospace can ensure a crisp definition of requirements, a timely and accurate acquisition that meets user expectations, and a successful transition to operations. This is the foundation of mission assurance.

– Jon Davis, senior engineering specialist, Colorado Engineering and Technology Office

a year before the acquisition program baseline is finalized. For the certification to occur, the program office and Air Force Space Command must have worked together to finalize the document requirements. As the user representative for the program, Air Force Space Command is responsible for engaging warfighters and other operational stakeholders as well as programming and acquisition personnel in developing the document. The formal mechanism for doing so is the integrated concept team. Aerospace supports these teams through multiple stakeholder organizations,



The focus on the front end is one step in a circular process that begins and ends with system users. For example, the warfighter defines a need based on a capability shortfall in accomplishing a mission. The various operating and major commands propose a set of possible system capabilities that can be integrated to address the gaps. This will result in a capability development document and concept of operations.



The first step of the acquisition process is to translate the needs statements into verifiable and implementable system requirements that can be used to issue contracts and acquire the system. This requires working closely with users to ensure the system will meet their needs as envisioned. When the inevitable trades arise due to budget, schedule, or performance shortfalls, user needs and constraints must be considered.

including the program office, U.S. Strategic Command, and operational units as well as functional areas within Air Force Space Command staff such as operations, testing, training, logistics, basing, and information assurance.

In support of both SMC and Air Force Space Command, Aerospace also ensures that the capability development document and system requirements documents, as well as operational and system architectures, are synchronized and also leads analyses to ensure that all requirements are feasible from a technical, cost, and schedule perspective.

For the government, Aerospace also leads the resolution of requirements issues across Air Force Space Command, the program office, and user organizations such as U.S. Strategic Command and the intelligence community, as it is uniquely positioned within each of these organizations to provide continuity as well as technical expertise.

Certain elements of the capability development document must be included in the acquisition program baseline—specifically, the key performance parameters table, dates of initial and full operating capability, and cost thresholds. Aerospace personnel supporting a program must be aware of the acquisition program baseline (APB) thresholds and corresponding capability development document thresholds in order to monitor progress against the baseline and avoid a breach in cost, schedule, or technical performance. Consistency across the acquisition and requirements baselines is especially critical, because a program in breach of its acquisition program baseline or capability development document baseline must be staffed through the acquisition chain of command and also have its requirements revalidated.

Closing the Affordability Gap

In the interest of closing the affordability gap between capability needs and program baseline, the requirements process (JCIDS) and the acquisition process (DoD Instruction 5000.02) have been synchronized such that the capability development document is finalized around the time of the preliminary design review. This is intended to ensure that the document presents an affordable set of requirements and that the program baseline is based on a mature system design. This principle encourages knowledge gained during early system-level design to influence the requirements process.

This approach, however, presents a paradigm shift for the space acquisition community. Traditionally, the prime development contract was awarded midway into the technology development phase, and the contractor was allowed to mature the design through the system engineering design reviews. But history shows that changes in contractual system requirements after the prime development contract is awarded jeopardize the negotiated contractual baseline; contract modifications after contract award are challenging for the government to negotiate.

The traditional solution to this challenge, which is deeply embedded in SMC culture, has been to insist that Air Force Space Command lock down operational capability requirements early in the technology development phase. However, this cultural aversion to keeping requirements flexible during the early stages of design has, on more than one occasion, had the unintended consequence of forcing a contractor to attempt to design and develop a system to meet an operational requirement that turned out to be infeasible with regard to cost, schedule, or the current state of technology. In some cases, a formal request for relief was made only after a breach in the cost, schedule, or technical baseline had occurred. This overly formal type of relationship between user requirements and program acquisition is one of the problems that was targeted in the Department of Defense mandate to treat affordability as a key performance parameter.

To achieve the efficiency and economy envisioned in the latest guidance, innovative strategies are needed that allow affordability updates to flow into the program and contract baselines. One strategy might involve competition all the way through to the preliminary design review; however, carrying two (or more) industry partners would be a costly proposition unless the contracted efforts were confined to specific subsystems or limited areas of the overall system design. A full and open competition would be advantageous to the government, but would shift the financial burden to the competing contractors. Another strategy might involve a contract structure that anticipates changes to the requirements baseline that is implemented through some predetermined cost of the anticipated changes.

Aerospace can help program office personnel select and formulate the most effective top-level acquisition strategy and contractual approach to achieve program success under the certain conditions of constrained budgets and a flexible requirements baseline.

Summary

Aerospace has many roles to play in helping program offices define and manage affordable and traceable requirements. Early Aerospace involvement in requirements definition and management is critical to the success of the acquisition in any era, but is even more critical in a time of shrinking budgets. Moreover, Aerospace is positioned to foster teamwork across multiple organizations; such collaboration enables effective responses to time-critical issues and ensures that requirement trades are considered and assessed at a technical level. Such support across the entire system lifecycle can have far-reaching benefits when combined with a relatively small increase in Aerospace participation at the front end of requirements and program definition.

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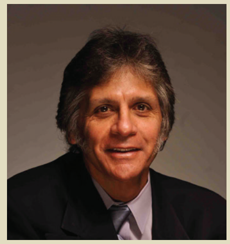

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Development Planning and Decision Support

Ljubomir B. Jocic and James Gee

Implementing a decision support framework in front-end systems engineering and development planning improves acquisitions for space programs.

Since its inception more than fifty years ago, The Aerospace Corporation has been supporting space system concept exploration, planning, and government decision-making in many programs and at different levels. Aerospace's decision support includes architecture and concept development; utility, capability, and performance analyses; risk evaluation and program acquisition planning; and portfolio assessment. The backbone of this decision support is the objective technical analysis by subject matter experts using many tools, models, and methodologies.

Traditionally, multiple models and individual experts were employed. Customer demand for timely analysis and advances in modeling capabilities have led to the integration of numerous models into a decision support framework and the pooling of specialists into concurrent-engineering teams. The teams often use Concept Design Center (CDC) and concurrent program development environment processes and facilities to perform required studies. Through these practices, Aerospace is involved in systems engineering and architecting in support of the Air Force Space Command investment strategy and DOD space program decision-making.

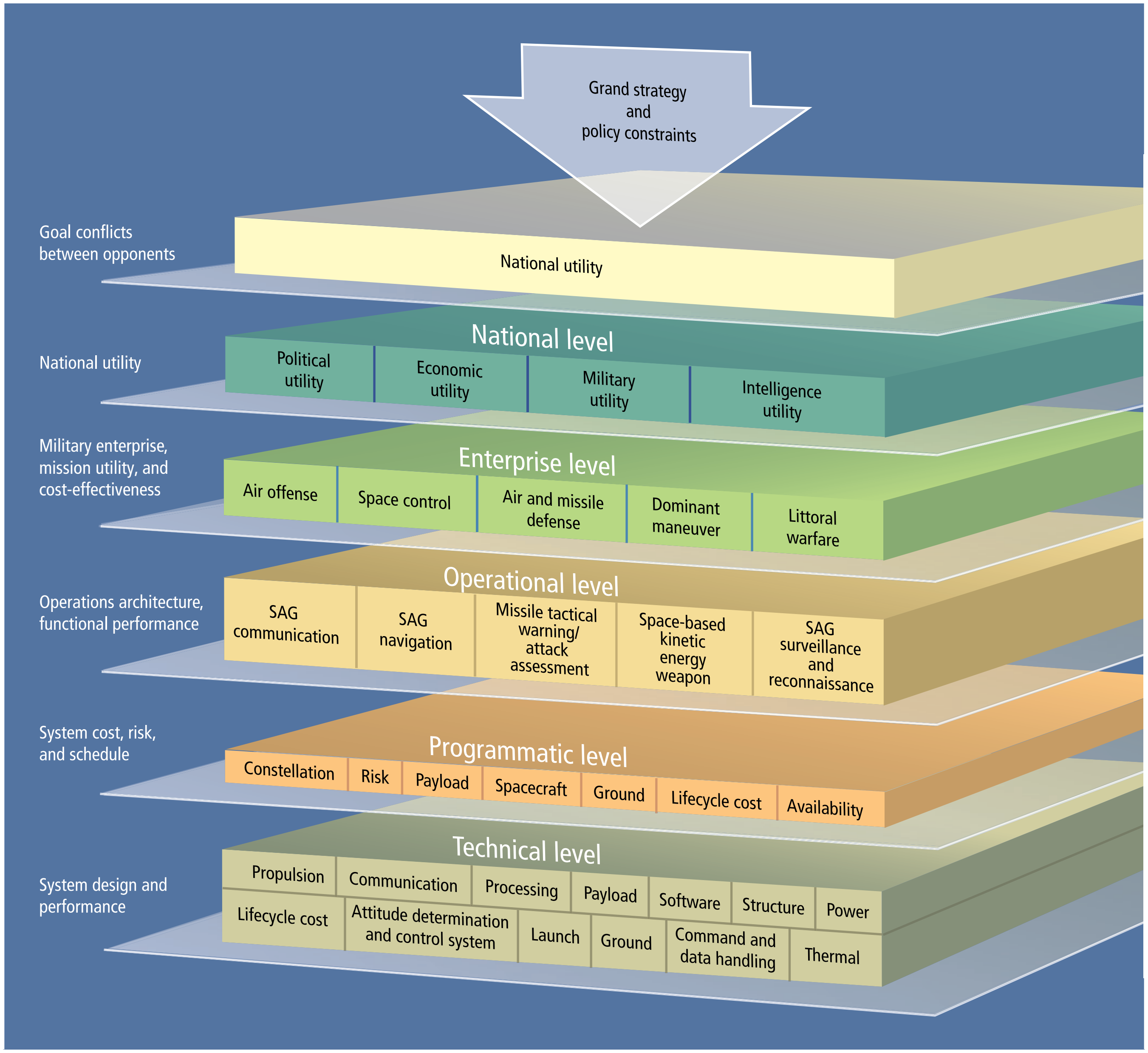
Current fiscal pressures as well as shrinking and uncertain budgets are increasingly challenging the national security space community to deliver affordable, resilient, and responsive space system capabilities. However, the introduction of rapidly evolving technologies and changing user needs into space architectures is constrained by lengthy space system acquisition cycles, growing system complexity, and the diversity of user needs.

These challenges and constraints have led to the Air Force mandate for better and earlier systems engineering on the front end of space program development. The emphasis of systems engineering has shifted toward the preacquisition stage, which precedes the materiel development decision and offers critical early information to milestone decision makers. The scope and requirements decisions made at this stage, which occur before program initiation, tend to drive subsequent development and production costs.

The opportunity to influence program cost, schedule, and risk rapidly diminishes as the acquisition process progresses. Improved early systems engineering enables the acquisition review authorities to evaluate the maturity of proposed technologies against acceptable program risks and decide whether technologies and concepts should be further developed before committing to system development and demonstration.

Such front-end systems engineering corresponds with recommendations by the U.S. Government Accountability Office (GAO) to separate technology development from systems acquisition. The GAO has recommended committing to a program and product development only if a technology is sufficiently mature and has reached a threshold of technology readiness, the requirements have been stabilized early, and the systems engineering techniques have been fully applied.

Aerospace is in a unique position to play an essential role in providing early-decision quality information to acquisition authorities. Aerospace's front-end systems engineering offers critical information on mission capability and requirement trades, concept creation, preliminary concept of operations, architecture development, performance and risk



The layered approach to capability evaluation. The grand strategy and policy constraints must be balanced with the needs of the military and warfighters. Costs, functional performance, and the operations architecture are considered along with schedule, risks, system design, and anticipated performance.

assessments, and cost scoping. Aerospace delivers alternative system concepts and architectures; evaluates them against performance parameters, capability attributes, and engagement scenarios; develops program strategies; estimates order-of-magnitude costs; and provides necessary evaluation models.

Development Planning

The Air Force established a development planning process for all acquisition programs that occurs prior to the materiel development decision. Development planning is important to ensure a new program is initiated with the systems engineering foundation needed for success. Sound planning employs early systems engineering to connect defense strategy and joint warfighting concepts of operation with the materiel solutions that are available to address capability gaps. Development planning describes alternative courses of action by linking measures of operational effectiveness to system concepts and their implementation through the building, integration, testing, verification, and validation stages. The three phases of system concept development are trade space characterization, candidate solution set analysis, and implementation analysis.

According to the Air Force developmental planning guide, published in 2010, the trade space characterization phase occurs when the system concepts are defined and candidate solutions are evaluated. System concept definition begins with analysis of user needs, constraints, and assump-

Development Planning for an Overhead Persistent Infrared Program

Aerospace's decision support framework was recently applied to an overhead persistent infrared (OPIR) enterprise development planning study. The study was prompted by downward funding trends and enhanced operational capability needs. Funding for OPIR missions may be restricted to current program resources in the near future. Meanwhile, national security space strategy realizes that space systems architected during the Cold War need to be adapted to remain relevant and effective in today's ever-changing world. The evolving operational needs of the military also require architectural changes to the OPIR program because of a number of world events that need constant monitoring, and because of the increasing number of users requiring access to data.

Acquisition trends affecting OPIR programs have moved toward evolutionary acquisitions of simpler systems. For example, system solutions using smaller, "good enough," limited-function satellites are attracting more interest from decision makers. A reduced emphasis on achieving individual satellite reliability may be balanced with the potential of a resilient architecture that can exploit functional redundancy and operational fallbacks across the larger enterprise. As an added benefit, architectures based on disaggregated space assets could more readily sustain multiple industrial sources, reinvigorate the industrial base, and provide more options through competition.

Such political, economic, military, social, infrastructure, and information analysis considerations for OPIR have helped to establish new architectural guidelines for future program development. Goals include reduced cost through competition, more sustainable production orders, and prompt evolution of next-generation satellites. There is also the potential for an increase in satellite production rates because of the avoidance of multiple missions with sensors being integrated on a single spacecraft, and by limiting investments in life extension and redundancy. This may also simplify development efforts by using mature sensor designs and netcentric ground assets.

A set of feasible development approaches for OPIR was also identified in this study. These include performing missions with a single sensor per satellite, adding hosted payloads with staring sensors to improve resiliency, and complementing the geosynchronous Earth orbit constellation with low Earth orbit and narrow-field-of-view sensors to perform additional missions.

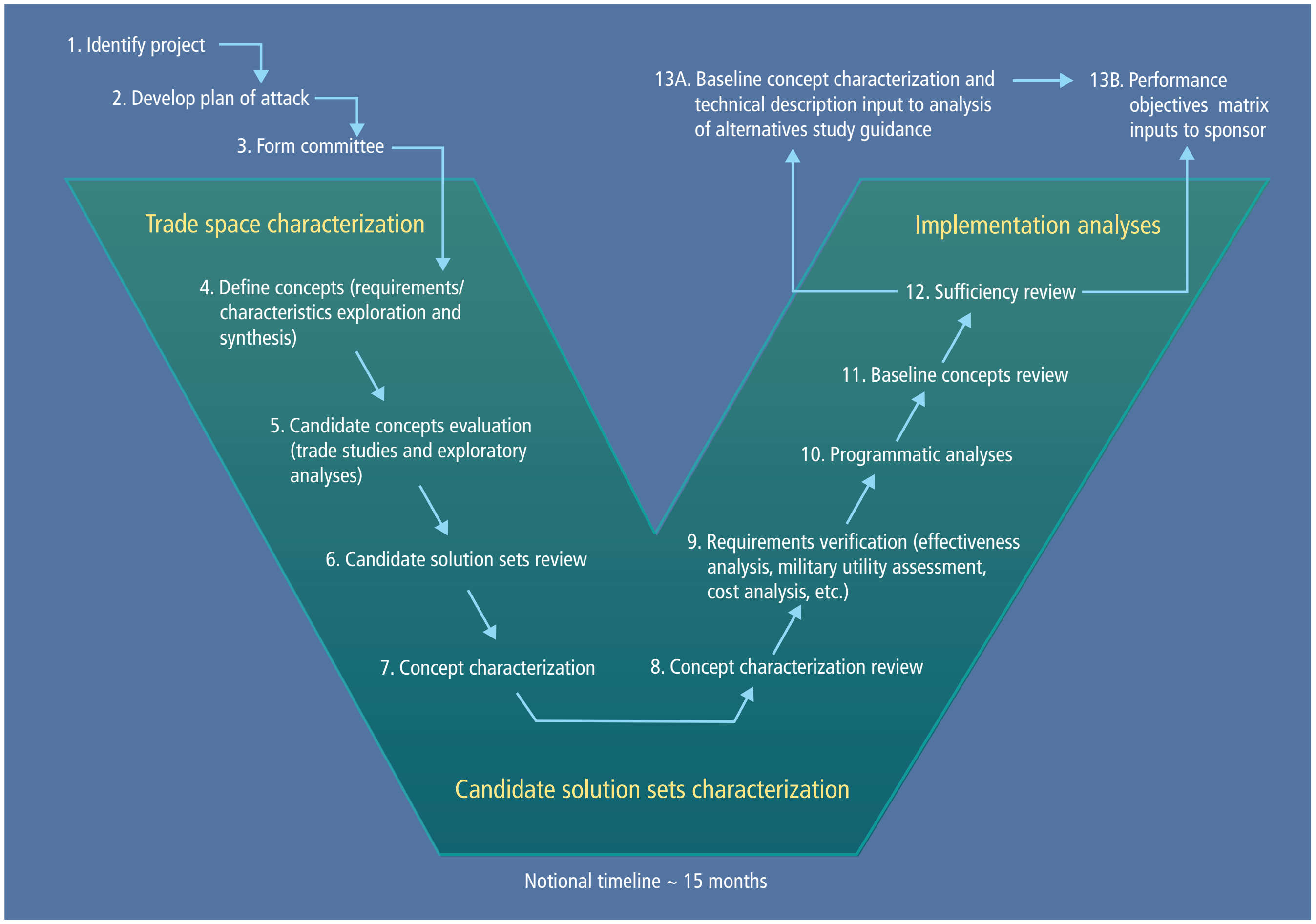
tions. At this stage, the developmental planning team creates an initial work breakdown structure and researches applicable technologies and associated technology/manufacturing readiness, costs, and risks. A methodology is established to evaluate candidate system concepts, score alternatives, and rank candidate concepts. Operational views are developed to graphically depict the relationship of the architecture components, infrastructure enablers, and potential systems-of-systems interfaces.

Following the initial trade space characterization and review of candidate solutions with sponsors, the team further analyzes the more promising concepts. Such analysis includes a reexamination of ground rules and assumptions, development of additional architectural views and work breakdown structure details, systems interface descriptions, and cost updates. This is accomplished through modeling and simulation, and the ensuing analysis helps to determine if system capabilities can meet mission needs. Such early systems engineering serves to identify acquisition resources, helps to establish schedules, and assists with estimating costs for each candidate solution.

To ensure their sufficiency, the more promising system concepts undergo initial military capability/utility assessments at this point. The program leadership also reviews the

Courtesy of United Launch Alliance

June 2012: An Atlas V readies for flight on the launchpad in Cape Canaveral, Florida.



Courtesy of U.S. Air Force

Concept development phases from the U.S. Air Force's development planning guide. Once a project has been identified and a plan of attack defined, trade space characterization, establishing candidate solution sets and their characterization, and implementation analyses become key phases to finalizing the approach.

reasonableness of lifecycle cost estimates, schedule, and risk assessments that are described in the concept characterization and technical description document produced by the development planning team.

A robust development planning and early systems engineering process relies on contributions from systems engineers who are knowledgeable about the domain in which the program is being developed. It is vital to have experienced engineers and managers in key positions during these early stages of program definition.

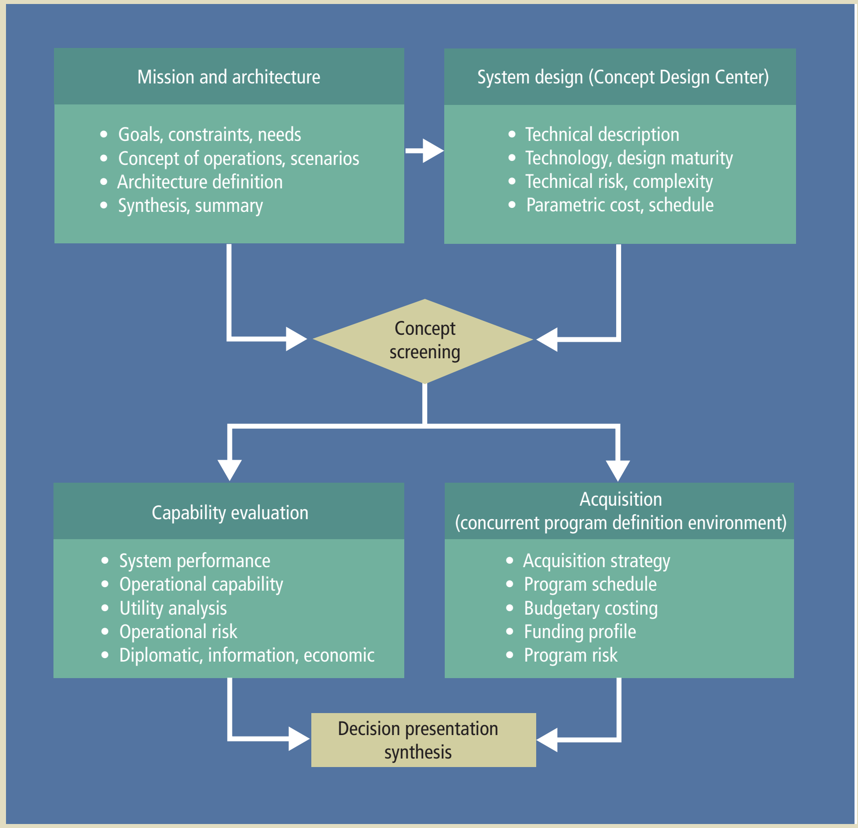
Aerospace is well suited to support these front-end, critical development planning and materiel development decisions. The company has personnel skilled in the depth and breadth of activities required for program development in all mission areas including architecture and concept development, capability and performance analyses, risk evaluation, program acquisition planning, and portfolio assessment. The Aerospace teams supporting development planning and early systems engineering processes encompass mission and architecture, system design, capability evaluation, and acquisition development.

The Decision Support Framework

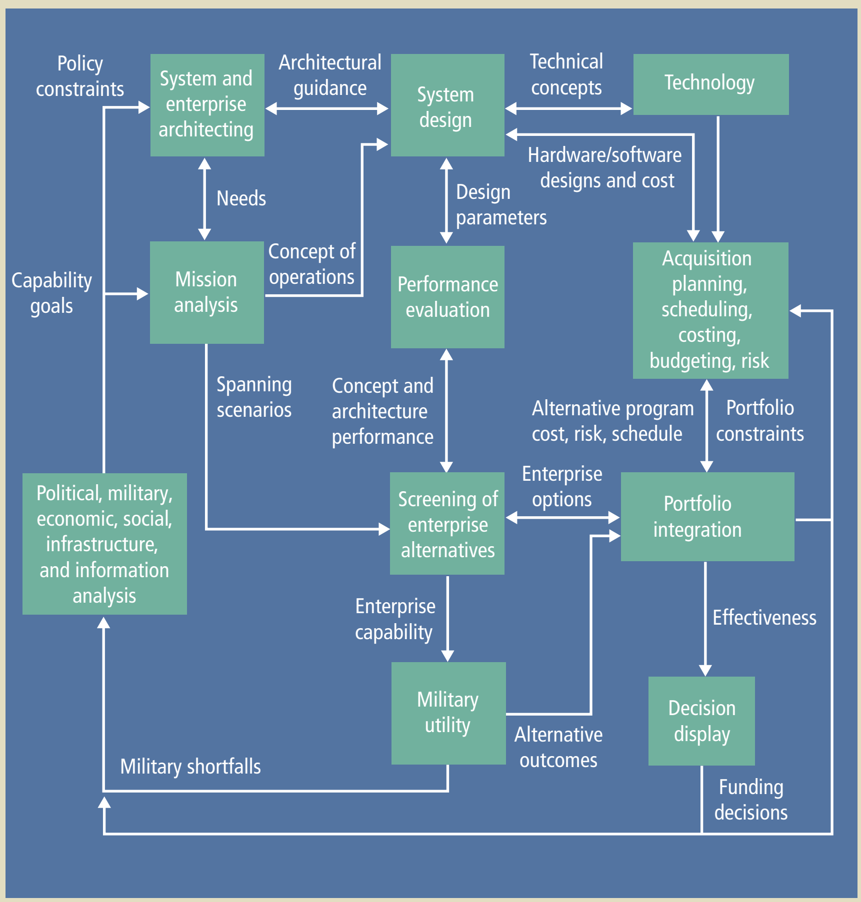
Aerospace developed a framework in support of government decision making, front-end systems engineering, and development planning. The framework relies on analysis and persuasion to generate an interpretive story, which in turn generates action. The decision support framework embraces a larger scope than traditional models that are focused on how to buy systems for approved requirements. It addresses three parallel government processes: requirements, budgeting, and acquisition. Multiple models, tools, methodologies, and processes are employed to characterize cost, schedule, performance, and risk of proposed programs. This layered approach integrates policy and operational analysis models with system and program engineering models. A comprehensive framework for modeling national, enterprise, operational, programmatic, and technical layers is required to capture alternative courses of action. Analysis modules included in the decision support framework are briefly reviewed here.

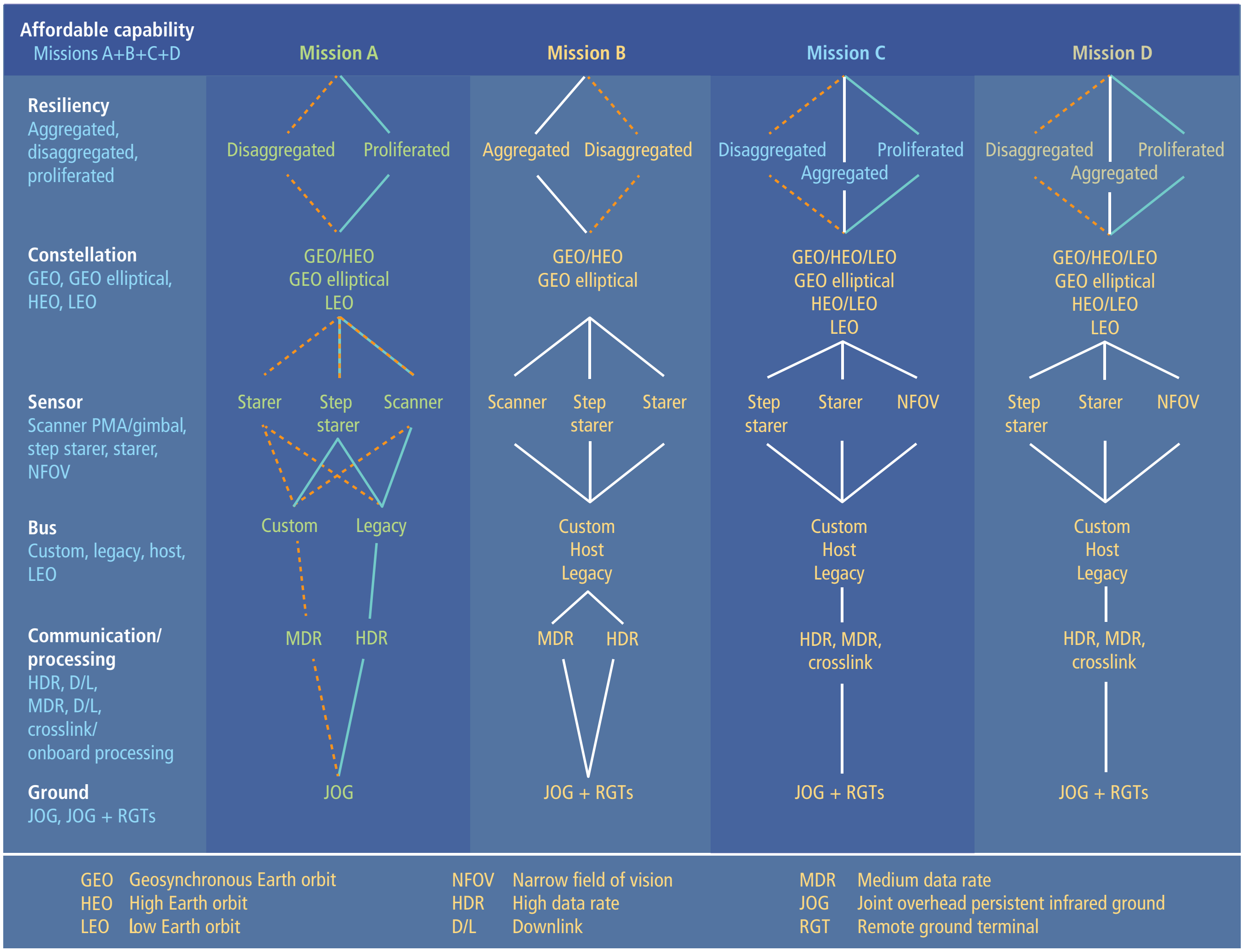
The political, military, economic, social, infrastructure, and information analysis module helps one to understand

The development planning and decision support teams.



While the decision support framework scope appears complex at first look, a closer examination reveals that it includes a standard strategy-to-task mission analysis, system and program engineering, and options for portfolio and enterprise analyses. The framework's flexible (open tool) and evolutionary nature enables tailoring of a study processes flow and composition to meet individual customer needs. Another important attribute is that this framework can capture and assess sensitivity by considering alternate scenarios and outcomes. The decision support framework has implemented concurrent and repeatable decision support processes, tools, and teams that are organized into four engineering groups.





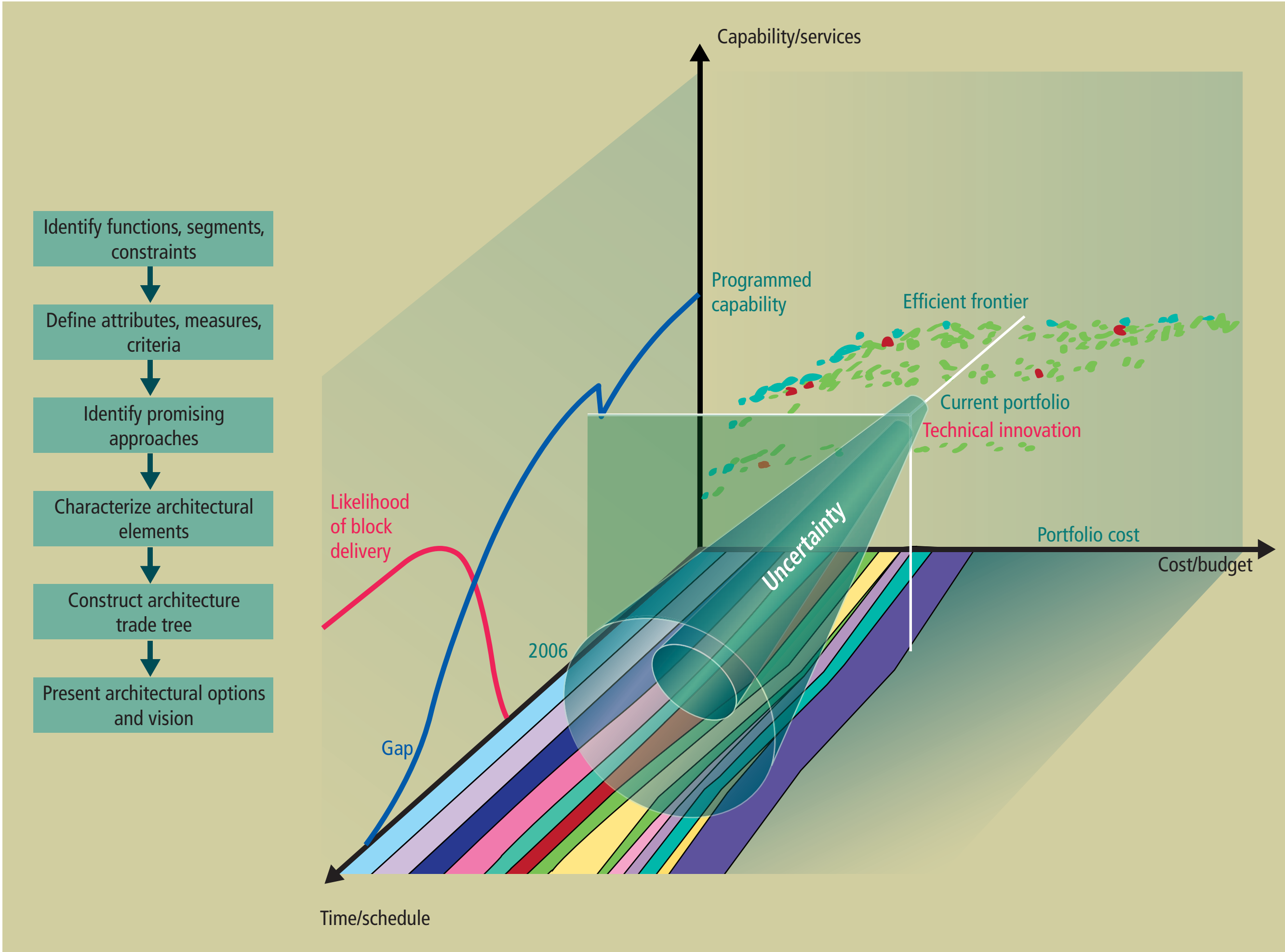
In this overhead persistent infrared architecture trade tree, the hosted partial Earth starer appeared in all combined mission architectures as a theater complement to global sensors. Resiliency and a variety of constellations, sensors, buses, and communication/processing modes are considered at ground stations in the study.

conflict effects, national priorities, policy constraints, and boundaries for the mission and military utility analyses. Different conflicts may elicit various national strategies that employ diplomatic, information, military, and economic instruments of state power to find resolutions. The resulting courses of action may involve military conflict scenarios and operational architectures based on operational plans and military tactics, techniques, and procedures. The strategic (national command authority), operational (theater of operations), and tactical operational architectures are materially enabled by systems implemented through acquisition programs.

The mission analysis module translates capability goals into mission needs and concepts of operations for a set of conflict scenarios. This is facilitated by a qualitative evaluation of system concepts against conflict scenarios that span the entire capability space of systems under consideration. This evaluation provides operational context and enables initial system capability characterization in terms of end-user effects. In addition, it helps reduce the number of alternative architectures, systems, and scenarios to be evaluated in the detailed military utility simulations.

The critical contribution of military utility analysis at this stage is to assess the conflict outcomes in the presence of alternative architectures and systems and to elucidate their engineering performance goals. The performance goals tend to drive the system capability and cost, and with human-in-the-loop command and control policies, help to define levels of sufficient system capability. This insight enables decision makers to select more affordable, resilient, and sustainable system solutions.

The system and enterprise architecting module consists of the structuring and parametric phases that can be applied sequentially or individually, depending on the issues being analyzed. At this point, side-by-side qualitative and quantitative comparisons of alternative architectures alongside key evaluation criteria are used to iterate and converge on a small subset of solutions. The selection process involves expanding the trade tree, followed by pruning away the dominated/inferior alternative architectures. The pruning



A comparison of space services delivered by multiple systems in a portfolio allows a normalized valuation of disparate system features and can be visualized via a three-dimensional graph consisting of capability, cost, and schedule axes. Portfolio optimization is attained by being within the efficient performance frontier in the cost-capability plane, staying within the budgetary constraints in the cost-schedule plane, and decreasing the likelihood of a capability gap in the schedule-capability plane. The desired portfolio capability is derived from the conflict scenario outcomes that are generated through military utility analysis.

is based on the key architectural criteria of affordability, resilience, capability, and schedule needs. This iterative and interactive architecting process is performed via a systematic six-step process.

Structured architecting allows for a rational and transparent identification of candidate architectures. The trade tree pruning process reduces the number of options to be evaluated by orders of magnitude while preserving the decision maker's insights into the key architectural choices. The architecture trade tree enables the architecting team to consider component-level implementation while addressing broad issues such as impacts on the industrial base, programmatic risks, and enterprise integration. The work product from the architecting module is the architectural vision and guidance for the system and program engineering.

There are many current challenges, opportunities, and strategies being considered for national security space within the context of shrinking and reduced budgets. Recent development planning studies have considered key factors in this mix including the disaggregation of integrated, multifunction, multiuser satellites, the exploration of payload hosting opportunities, and the use of commercial buses and launch vehicles. Other catalysts of affordable architectural transition include technology advances that facilitate simpler, smaller, less-expensive payloads and architectures, freedom to accept and allocate mission requirements to better match available system implementations, and the ability to employ streamlined, rapid-acquisition approaches. Aerospace will continue to work closely with its customers to develop these next-generation development and planning approaches.

Developing alternative engineering concepts has long been established as a concurrent engineering activity at Aerospace's CDC. The designs produced here serve as inputs for a number of evaluation tools that generate systemwide performance measures, which are used to evaluate concept performance against the spanning scenario set. This performance evaluation step reduces the requisite number of engineering concepts for detailed utility and program evaluation. The performance measures are also used to characterize system services.

Contributions of disparate systems to an enterprise are evaluated using the concept of space services delivered to end users/consumers. For example, communication services include protected, wideband, and communications-on-the-move. Navigation services include position determination, navigation, and timing. Intelligence, surveillance, and reconnaissance services include detection, tracking, identification, characterizing capability, and determining intent. These services are compared in the three-dimensional space of capability/services, cost/affordability, and schedule/risk. Portfolio optimization is attempted alongside the "efficient performance frontier" in a cost-capability plane, and within the budgetary sand chart constraints in the cost-time plane, with the goal of decreasing the likelihood of a capability gap in the schedule-capability plane.

Program definition takes place in the concurrent program definition environment activities typically implemented as companion sessions in CDC facilities. The subject matter experts use various acquisition planning, cost, schedule, and risk evaluation tools and databases to produce a draft acquisition strategy plan for each alternative system concept. Initial parametric cost and schedule estimates and technical risk assessments developed during CDC design sessions are correlated with relevant historical data and anchored in a specific program-acquisition strategy.

The effectiveness of the system or enterprise alternatives is summarized in a tailored table format using the major categories of capability, cost, schedule, and risk. Effective communication of decision options is enabled through side-by-side comparisons of feasible solutions. The decision display's credibility is supported by full traceability to analysis assumptions and insights into modeling methodologies. Such insights and traceability are documented in technical reports.

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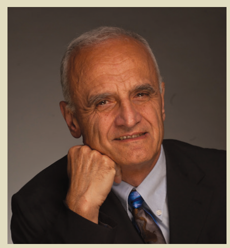
About the Authors



Ljubomir B. Jocic, Principal Engineer, Developmental Planning and Projects, leads innovative concept development and program definition studies, architecture trade space characterizations, and early space system engineering studies for space communications, navigation, radar, and sensing missions. He joined Aerospace in 1983 and has more than 30 years of industrial and academic experience in architecting, designing, and evaluating complex space systems. He was introduced to electrical and complex systems engineering at the University of Belgrade and earned a Ph.D. in electrical engineering from the University of Santa Clara, California.

James Gee, Principal Director, Developmental Planning and Projects, leads support to the Space and Missile Systems Center at Los Angeles Air Force Base's Developmental Planning Directorate, including concept development, technology integration, utility and alternative analysis, and development of future space systems. He joined Aerospace in 1980, and among other responsibilities, provides corporate memory for Cold War–era survivability efforts. He is an expert in weapon effects, hardening, active countermeasures, and attack reporting. He has a Ph.D. in chemistry from the University of California, Santa Barbara.

The Architecture Design and Evaluation Process

Inki A. Min and Ryan A. Noguchi

The Aerospace Corporation conducts architecture trade studies to assess options and solutions to meet its customers' space system program requirements.

In the early stages of developing a new space system program, U.S. government decision makers need to be assured that they are making the best acquisition choices, while also handling uncertainties such as cost, schedule, technology, and integration risks. Architecture trade studies are performed during this front-end, formative stage of a program. By examining the large trade space of alternative solutions and improving the understanding of the myriad of available technical and program options, decision makers can then use these study results to determine how to allocate their limited budgets and identify the options that are most likely to succeed. The Aerospace Corporation regularly conducts these studies for its customers, who use the findings to better understand the options, benefits, costs, and risks of the alternatives.

Aerospace has been conducting concept and architecture studies since its earliest days, and the general principles remain the same. The steps involved in this process facilitate the transfer of knowledge from long-time employees to the newest generation of engineers and scientists, and ensures consistency and access to study team members, tools, and techniques, so that they can be applied in a repeatable and successful manner across the corporation.

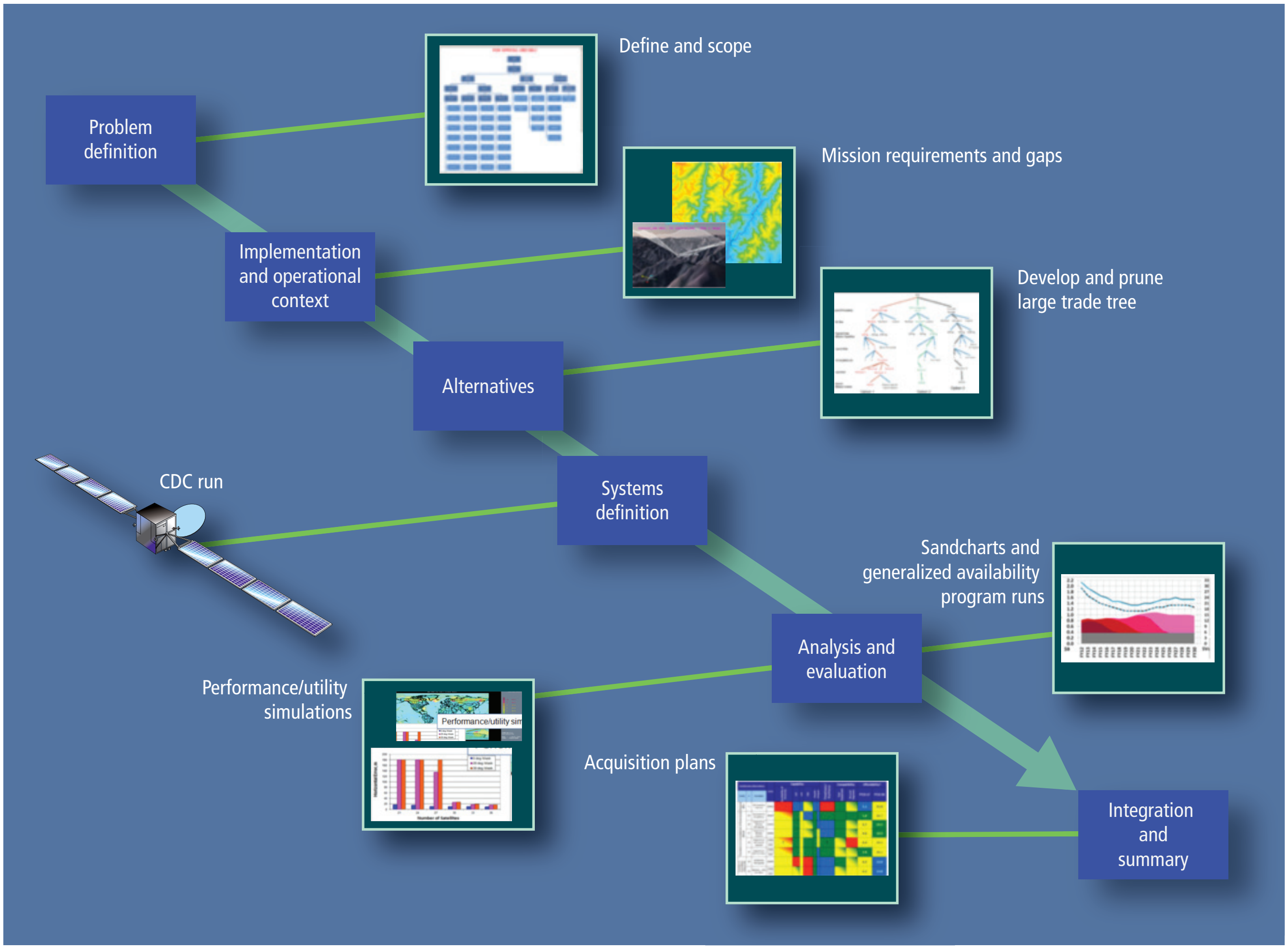
This decision support framework establishes a traceable structured process for making defensible decisions and recommendations. Aerospace's technical expertise spans the gamut of disciplines and perspectives. Trade studies typically include Aerospace experts in system requirements, conceptual design, technology readiness assessment, system performance analysis, utility analysis, and acquisition planning. The principal job of the architecture trade study lead is to elicit and coordinate the findings of these experts.

The Architecture Study Process

Architecture studies can be performed at the earliest stages of or prior to a program's formal inception. In some cases, they can be performed before a program's requirements are specified and validated. After all, requirements should not be dictated in a vacuum, but rather should be based on what is feasible and consistent with the available budget and other constraints. Architecture studies provide a better understanding of the relationships among requirements, cost, and capabilities, thereby facilitating a more informed decision regarding the best trade-offs among these factors.

Once a program is given the authority to proceed into the materiel solution analysis phase, a formal analysis of alternatives is conducted. This is a general systematic approach to developing and comparing alternatives and can be applied to any trade or concept exploration study. The "Analysis of Alternatives Handbook," published in July 2008 by the Air Force's Office of Aerospace Studies, outlines the recommended process. A prestudy is often performed to refine the trade space of alternatives, flesh out the analysis process, prepare the study team members, and establish roles and responsibilities. Aerospace's architecture trade study process is compatible with the guidelines in this handbook, and adds some of the details of how these studies are implemented at Aerospace.

Experienced study leads understand that each architecture trade study differs due to the various constraints of



The six steps in the architecture design and evaluation process. These include problem definition, implementation and operational context, consideration of alternatives, systems definition, analysis and evaluation, and integration and summary. The Concept Design Center (CDC) is Aerospace's in-house alternatives analysis site.

individual customers, time, resources, and other stakeholder interests. Therefore, the methodology outlined here serves as a guide for best practices that can be tailored to specific situations. Other uses of the architecture study process include assisting with the concept characterization and technical design, developmental planning, or preanalysis of alternatives, which are also performed at the front end of an Air Force, National Reconnaissance Office, or civil program formulation.

Aerospace has a six-step architecture design and evaluation process, which is the foundation for conducting an architecture study. These steps include problem definition, implementation and operational context, alternatives, system definition, analysis and evaluation, and integration and summarization. The steps do not need to be performed consecutively, nor does each need to be completed before the next one begins, but none should be skipped. The study team's understanding of the problems and trade space will mature as the study progresses, so iteration among the steps is imperative to take advantage of the lessons learned along the way, revisit assumptions, and refine analyses as additional information is attained. System architecting is as much art as it is science, requiring creativity and intellectual agility.

Problem Definition

The problem definition phase involves defining the architecture trade study's main parameters and developing a step-by-step plan for executing the study. At this early stage, frequent and effective communication with the customer is critical to ensure that the objectives of both the overall architecture and the study are established, and that the study scope, ground rules, assumptions, and constraints are identified. These factors must be documented in the study's terms of reference or statement of work, and the major stakeholders who are commissioning the study must concur with them.

Another key factor to establish early in the architecture trade study is the set of key decision metrics, criteria, or measures of effectiveness that will be used to compare the alternatives. These include measures of system performance, cost, schedule, and risk, as well as operational resilience or

Past to Present: Forging a Way Forward for National Security Space

The national security space enterprise has successfully exited one of its most challenging decades since the dawn of the Space Age. This was a decade of intense technical challenges, and seemingly relentless programmatic challenges, leading to many painful cost and schedule overruns. Yet the decade culminated in the successful delivery of unprecedented military and intelligence capabilities on orbit that will serve the nation well for many years. These first-of-a-kind missions that have been successfully fielded offer order-of-magnitude improvements in capability or capacity in almost all mission areas. When the history is written, this past decade might well be regarded as the most significant period of military space modernization on record.

The United States and its allies now face a new decade with different, but equally challenging, hurdles. Tight budgets, escalating threats, and industrial base uncertainties are some of the challenges on the horizon. However, for the space systems engineering enterprise, these challenges represent opportunities to excel.

Many factors contributed to the troubles that were faced, and eventually overcome, in national security space acquisition in the decade of the 2000s. Simultaneous recapitalization across all major military space mission areas led to the stretching and breaking of available space development budgets. Poor program formulation during the birth of these programs in the acquisition reform era led to later issues with program execution. The elimination of appropriate specifications, standards, and the principles of systems engineering led to late discovery of latent defects and extremely costly repairs late in program development lifecycles. An overreliance on what seemed to be a burgeoning commercial space enterprise contributed to overly optimistic budgets and technology development timelines. Rapid consolidation of prime and sub-tier vendors caused hard-won manufacturing and test recipes to be lost.

At the same time, the nation's dependence on the space enterprise became paramount. In the global war on terrorism, there was no room for gaps in the fundamental enabling of space capabilities. These new space systems needed to be delivered, and they needed to work.

Fortunately, the space enterprise rallied to the cause, and the necessary capabilities became a reality. In some cases, significant redesign of space system programs was necessary. Parts procurement and testing processes were made more robust wherever possible. System test philosophies were improved. In many cases, robust system-level testing was implemented as a last resort to weed out latent defects that might have been missed in poorly formulated component and unit-level testing earlier in space systems. While it is never a good philosophy to try and test for quality late in a program, many of these programs faced no other choice. This was not the optimum way to run complex development programs, but everyone in the space business had to play the cards that had been dealt by the choices and philosophies of the prior decade.

The U.S. government space system acquirers contributed to the ultimate successes by adapting contractual requirements, improving government oversight, accommodating some painful expenses, and taking on clear accountabilities for the outcomes. Industry primes, subs, and sub-tier vendors worked to recapture the lost recipes and build back disciplined, repeatable processes.

The Aerospace Corporation adapted its workforce, tools, and focus to help tackle these challenges. The company instilled a culture of personal and corporate accountability for the success of critical missions. It also helped reinvigorate the systems engineering process discipline, and revived or improved relevant specifications and standards. Aerospace helped formulate an independent program assessment process that has now become an industry standard for providing senior government leadership with an unvarnished, truthful assessment of a program's health as it prepares for key milestones. While this is sometimes referred to as going "back to basics," it is not really as simple as that. Many of the specifications, standards, and processes used in the development of space systems were not just rediscovered—they were improved or streamlined. For example, Aerospace recognizes that some situations warrant specialized or tailored treatments, such as where risk acceptance is higher, or where design and manufacturing maturity allow for reduced oversight.

compatibility with legacy systems. The deliberation leading to the selection of the decision metrics should include identifying stakeholder interests as well as the analysis, models, and methodology that will be used to assess the quantitative and qualitative factors determining the architecture alternatives. This process ensures a discussion about the level of depth for the study. The ideal level of depth of the study includes sufficiently detailed analysis to provide the architecting team with the insight to discriminate between the options under investigation.

The architecture trade study's definition and planning also involve negotiating the study delivery schedule, funding level, roles and responsibilities, points of contact, rules of engagement, and delivery product. Concurrent with these negotiations, key team members should be recruited and consulted for engagement in the study planning activities, and their commitment for performing the actual study downstream should be secured.

Implementation and Operational Context

An important early step in the architecture design and evaluation process is to understand the context in which the system is intended to operate. This process should identify the end users, policy drivers, other stakeholders, technology availability, use cases, scenarios, and concept of operations. Understanding the functional capabilities and mission needs that the objective architecture is intended to meet is critical. For the Air Force, such formal system requirements are often

A key change that is being made within Aerospace today—and across the space industry—is a shift in focus to the front end of the systems engineering and program formulation processes. This is sometimes referred to as "recasting." This enhanced focus on the front end of programs manifests itself in different ways. For example, the nation's fiscal challenges have forced an urgent need to find more affordable solutions to today's space system challenges. The evolving global space environment, often characterized as congested, contested, and competitive, has driven the space industry to look for more resilient architectures that will assure users of these critical space capabilities that they will not be denied their use, despite escalating threats in space and cyberspace. Toward this vein, Aerospace is contributing to the rearchitecting of more resilient and affordable space architectures, and helping to identify key investments that will be needed to enable the transition to these architectures.

However, recasting is not just about architecting. The aerospace industry has a responsibility to capture the lessons from the past decade across all of the engineering disciplines, so as not to repeat the same mistakes in future blocks of satellites or in new programs. For example, during the past decade, a lack of appropriate parts screening and unit-level testing led to the need for costly and risky rework late in the integration phase, and this occurred across many critical programs—these shortfalls in parts screening and unit-level testing turned out to be a false economy, and we cannot allow early perceptive testing to be swept up in the name of efficiencies. Systems engineering shortfalls caused gaps in system testability, leading to functionality escapes that required corrective actions, sometimes as late as on orbit. Here too, we need to help define the appropriate, uncompressible level of systems engineering effort that will lead to successful programs. The space programs of the recent past also suffered from overly optimistic applications of new technologies—we need to critically assess technologies and manufacturing readiness, and clearly communicate these objective assessments.

I am often asked whether the shift toward the front end of the systems engineering process will require a significant shift in the engineering and scientific skills mix. Although some shifts are required, particularly in areas of evolving threats such as cyber, many of the engineering and scientific disciplines that have contributed to the modernization of the fleets during the last decade are readily applicable to the front-end work that will be needed to make future programs affordable and executable. For example, parts, materials, and process experts who have been heavily engaged in assessing noncompliant parts or materials in first-of-a-kind systems are well positioned to help assure that appropriate screening is in place to rid future programs of these issues. Similarly, scientists who have been engaged in root cause analysis on various component or system anomalies can readily contribute to assessments of technology readiness and the art of the possible for future architectures.

In aligning Aerospace's efforts for the future decade it is important to keep one thought in mind: the past decade was not the baseline. The past decade was a mad scramble of urgent, overly parallel development of programs that were formulated based on false economies. The future decade offers many new challenges, including tight budgets and evolving threats, but these are challenges that are in the sweet spot of good systems engineering and the mission assurance discipline. The space industry has an opportunity to get it right.

Much good work is already being done to address these challenges. Some of this is described in this issue of *Crosslink*. This magazine issue spans a range of topics from policy to parts, and from requirements definition to system testing. Several articles detail current work in the area of developmental planning and architecting. Others touch on program formulation and acquisition support across the lifecycle. These are just a sampling of the fine work under way as part of a recasting effort at Aerospace to address the front end of the space systems engineering process.

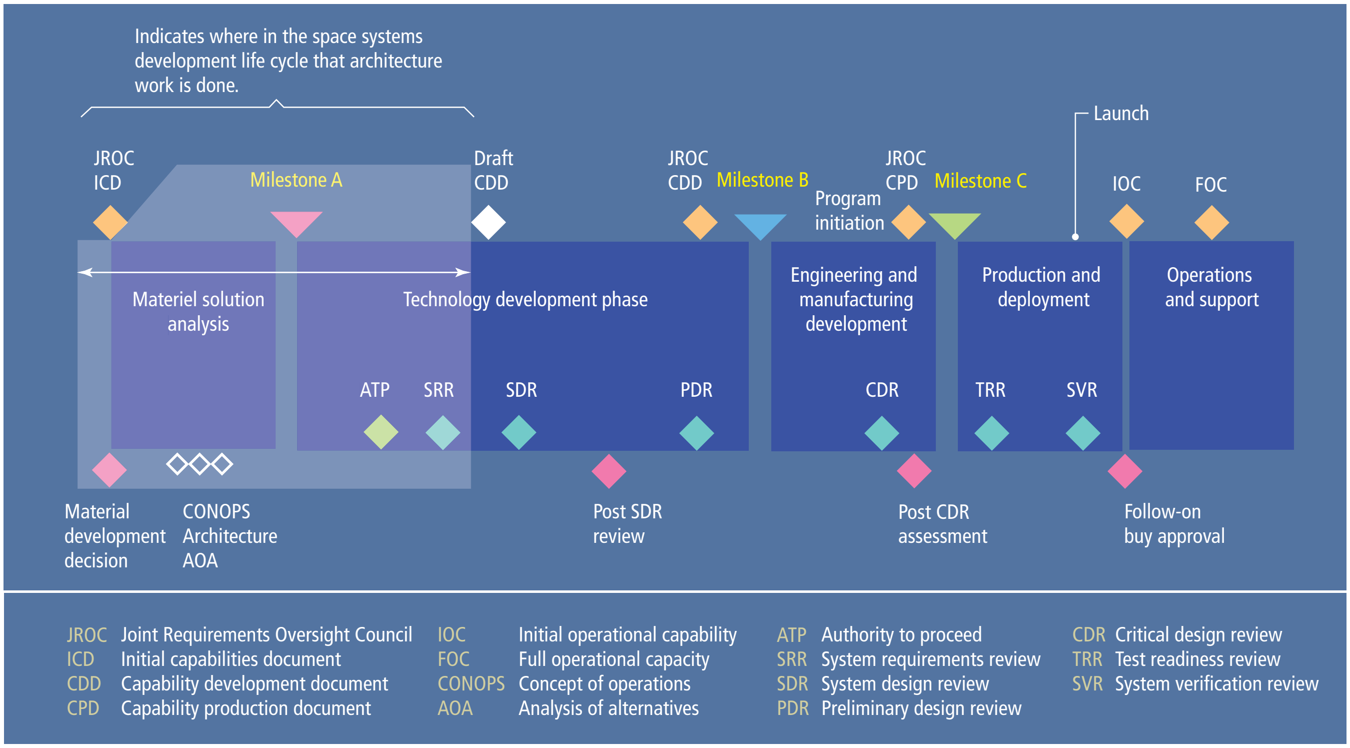
– Dave Gorney, senior vice president, Space Systems Group

documented in the DOD Joint Requirements Oversight Council (JROC) approved initial capability document (ICD), if the program has matured to that point in the defense acquisition lifecycle. However, some architecture trade studies are performed prior to this, with the intent of iteratively developing requirements based on what materiel solutions can affordably provide versus nonmateriel solutions.

Since precisely meeting all stated requirements often results in an unaffordable system, understanding the extent to which these factors are flexible or negotiable is important. A good architecture trade study should provide the decision makers with an understanding of the trade-offs between cost and performance across a broad range of potential solutions. Since requirements documents typically do not state cost constraints, a key objective of the architecture study is to provide information about the potential costs—in terms of funding, schedule, and the risks of not meeting these budget and schedule targets—to implement the materiel solutions and bring the capabilities to realization. The architectures considered should be robust to the uncertain future in terms of budget availability, threats, operating environment, and technology.

Exploring Alternatives

To mitigate the risk that the architecture trade study will prematurely focus on a limited set of possible solutions representing only minor deviations from the status quo, exploring the widest possible trade space early in the study



The DOD acquisition life cycle. The dotted line indicates where in the space system development mission lifecycle the architecture work is done. Milestones include materiel solution analysis, technology development, engineering and manufacturing development, production and deployment, and operations and support.

is important. Early brainstorming efforts are often useful for flushing out innovative solutions. A systematic approach of mapping out the entire solution space is also an effective approach to ensure consideration of all options.

The solution space can be envisioned as a multidimensional volume of possibilities, with each dimension of that space being a tradeable parameter. Each architecture option is a single point within that multidimensional trade volume. The tradeable parameters of interest often include at the system level payload type and technology (e.g., traveling wave tube amplifiers vs. solid-state power amplifiers; gimbal vs. pointing mirror assembly), bus technology (e.g., lithium ion vs. nickel hydride batteries; reaction wheels vs. control moment gyroscopes), and platform (e.g., free flyer vs. hosted vs. small satellite vs. commercial). At the architecture level, the tradeable parameters of interest include constellation, acquisition, and ground systems options. A table is created that captures the range of likely options for each trade space parameter.

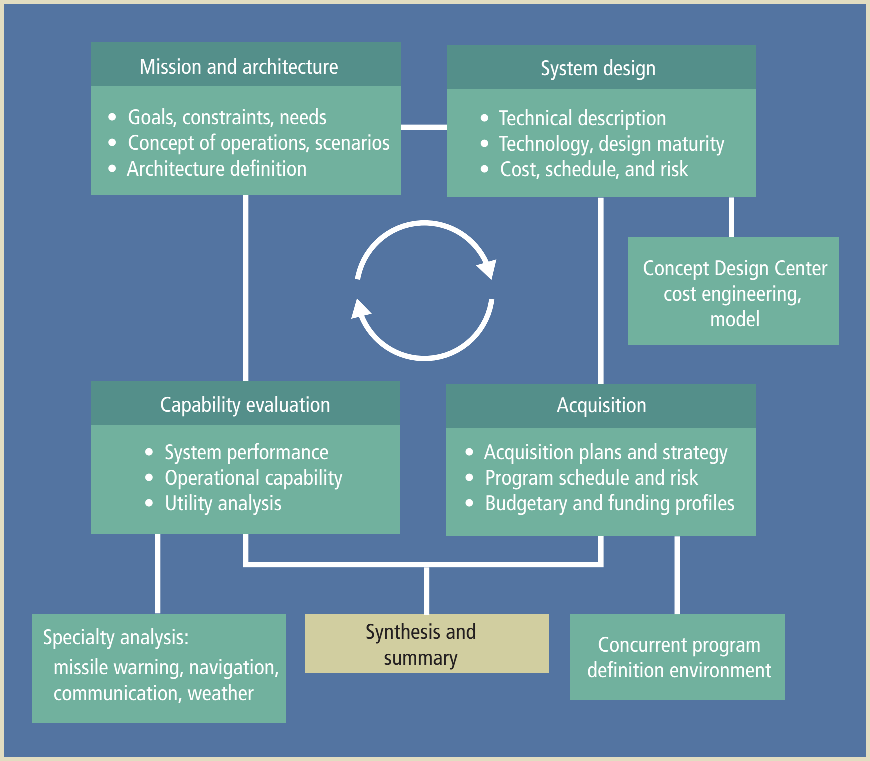
Architecture candidates are formulated from combinations of the parameters and are often depicted in a trade tree, with the tree branches representing families of solutions or individual solutions. While the architecture candidates do not have to exhaustively cover every possible solution, they should address the full range of decision criteria or measures of effectiveness that are of interest to the customer, and should ascertain from the multidimensional parameter space the best and worst case solutions. For example, the study team members would want to see what a fully capable solution looks like (although it may be unaffordable) and what an affordable but high-risk or low-performance solution looks like.

Systematically exploring the key trade parameters and candidate architectures early on allows the study leads and customers to better understand the solution space and express their preferences for which areas to filter for more detailed study later. Engaging customers to capture their direction and preferences for the study and iterating the steps of the study in small cycles is better than waiting for the final results to get their feedback and then repeating the study.

A reasonable number of candidate architectures should be selected, covering as much as possible within the range of potential solutions. A good rule of thumb is to assess approximately half a dozen potential solutions, but the list usually grows as iteration of the architecture study continues, more information becomes known, and more stakeholders join the discussion.

System Definition

Once the full range of architecture options has been pared down, each candidate architecture is defined as much as possible with roughly the same amount of detail, which allows direct comparisons between them. The candidate architectures' characteristics are documented, identifying their constituent systems and interdependencies. Any known significant risks or issues like the inability to satisfy any



The Aerospace decision support framework. Moving from concepts to architectures to decisions. The figure depicts this integration, which is built on core corporate analytical capabilities.

Type and size of payload	Orbit and constellation	Bus/ platform	Mission data distribution	Other trades	Acquisition
Operating band (EO/IR and RF)	LEO, MEO, GEO, or other	Clean sheet design	Direct to users	Advanced vs. available technologies	Continue buying clones of legacy program
Resolution (EO/IR)	Disaggregated or distributed	Commercial bus	Crosslinked satellites	Dual launch or alternate launchers	Evolve legacy program
Power level (RF)	GEO/LEO mix	Hosted	GEO relay	Legacy vs. new ground systems	Start new program
Size and coverage	Core plus augmentation	Shared bus	Store and forward		Start new augmentation program and reduce core buys
Sensitivity (EO/IR)					

EO/IR Electro-optic/infrared
LEO Low Earth orbit
MEO Medium Earth orbit
GEO Geosynchronous Earth orbit

An example of a trade table used in the alternatives analysis phase of space system design and architecting. The solution space can be envisioned as a multidimensional volume of possibilities, with each dimension of that space being a tradeable parameter.

The architecture study planner serves as a guide to ensure that all of the different activities necessary to conduct a good study are covered. Although individually each of these items might appear obvious, the planner aids the study lead in keeping track of these tasks and captures best practices to facilitate repeatability of the study process across The Aerospace Corporation. Each item on the list requires critical thinking and rigorous debate to execute properly. The planner can also be used as a guide for independent reviewers tasked to assess the quality of an architecture study performed by others.

Architecture Study Planner

Problem definition	
Study plan	Define a step-by-step plan for executing the study. Ideally, start with the DSF study planner template, and assign each task a POC, due date, and rough plan of attack. Provide justification for each task that will be omitted. Ensure participation from key analysts and experts.
Scope	Define the boundary of the system of interest (SOI) and all important constraints. Identify what classes of system elements will be considered and what will not be considered within the scope of the study.
Objectives	Identify the objectives of the study and the objectives that the SOI is intended to achieve. Document them in the study terms of reference. Obtain concurrence by key stakeholders as early as possible.
Capabilities	Identify the capabilities that the SOI is intended to accomplish. Capture the definition of the baseline "as-is" or program of record (POR) architecture, the capabilities it satisfies, and the known capability gaps.
Decision criteria	Define and organize the factors that are most important for deciding between architecture alternatives, typically captured as measures of effectivness (MOEs). Identify analysis approaches required to quantify all of the metrics in this list.
Implementation and Operational Context	
CONOPS	Define the general concepts of operations for the capabilities being provided by the SOI. Define the functional architecture, identify external systems with which the SOI will need

requirements or the need for high-risk technology development should also be identified. A work breakdown structure, an operational view diagram (such as an operational concept graphic from the DOD Architecture Framework), and possibly other architectural description diagrams should be generated to communicate the candidate architecture's content and distinguish these from the other alternatives.

At this stage, conceptual design activities, such as those performed by Aerospace's Concept Design Center, are conducted to give more substance to the definitions of the architectures and the system solutions for those architectures. System solutions should be defined to a level of detail that facilitates estimating lifecycle costs, which usually means quantifying mass, power, and size for determining the costs of space and launch segments, and ground operations.

The system definition should extend beyond technical concepts at this stage by including the programmatic trade space and the identification of approaches to realizing the envisioned architecture through the acquisition process. For each candidate architecture, acquisition strategies and procurement options, identification of budget and schedule constraints, transition approaches from the current baseline to the new architecture, and program risks should be developed.

Analysis and Evaluation

Next, the candidate architectures should be evaluated in terms of the high-level decision criteria and the detailed performance capability measures that were defined earlier during the problem-definition phase of the study. These include measures of performance, cost, schedule, and risk.

Teams of experts representing each of these areas conduct the evaluations. The system performance team is the most varied since each mission area has a different subject matter expert. For example, depending on whether the current architecture study is related to missile warning, navigation, communication, or intelligence, surveillance, and reconnaissance, different analysis tools and experts are needed. A key function of the architecture study lead is to know who the experts are and what knowledge, experience, and credibility they can bring to the evaluation effort. Analyzing a candidate architecture's military utility helps to determine the system's value to warfighters. Other analyses help to determine technical measures of a system's performance or capability.

Estimating the costs and cost risk of each of the candidate architectures is the next step. This should include nonrecurring development and recurring production costs. The roll-up of costs should be performed across the time period of interest and the near-term future years' defense program horizon. If possible, operations costs should be included. Similarly, the schedule for implementing the architecture and transition from the legacy system needs to be evaluated.

Integration and Summary

The architecture study's final phase is conducted to gather the assessments of the various candidates and provide a balanced view of the advantages and disadvantages of each. For example, a comparison might include reviewing candidate architectures for high performance at high cost vs. reduced performance at reduced cost. The main activity during this phase is capturing and summarizing the observations about

From back to front Paul Massatt, Whitney Plumb-Starnes, Ryan Noguchi, David Christopher, Ranwa Haddad, Inki Min, and Heidi Graziano develop and discuss alternative GPS architectures in the Concept Design Center at Aerospace.

the principal trade-offs between the study decision criteria and any other meaningful observed trends and insights. These observations should include the results of sensitivity analyses performed throughout the study process to reflect deep uncertainty present in any investigation of the future.

In the final phase, it is critical to communicate the architecture study results clearly and effectively to all stakeholders. While conveying the bottom-line results of the study to the decision makers is important, it is also crucial to provide a clear description of the methodology, rationales, and assumptions that were used, so they will have confidence in the chosen solution. Decision makers need to be assured that the study has been conducted as thoroughly as possible and with a level of analytical rigor and process discipline that is commensurate with the weight of the decision. Providing a means of interactively exploring the solution space via visual tools, thereby giving decision makers the ability to ask and answer what-if questions in real time, is ideal.

For many years, the architecture design and evaluation process has been implemented in several front-end studies at Aerospace. The architecture trade study process can be described in different ways, and its actual practice may vary from study to study, but the fundamental steps of an architecture study described here can be applied to many different types of space system evaluations. Aerospace's training arm, The Aerospace Institute, offers courses covering much of the material in this article as part of the "Aerospace Systems Architecting and Engineering Certificate Program."

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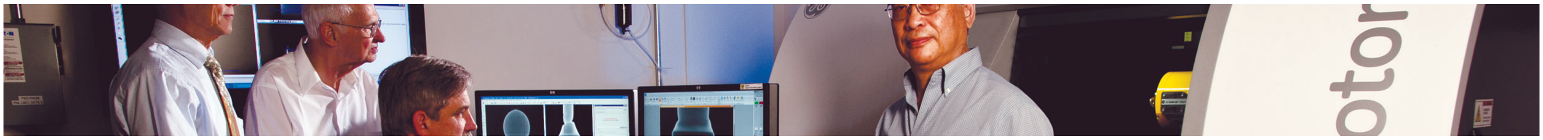


The Aerospace Corporation's Role in Ensuring the Availability of Critical Technologies

Aaron Tout and John Adams

Aerospace and a consortium of industry partners work to identify and mitigate risks in the technology supply chain.

The Aerospace Corporation's understanding of the space enterprise is broad and profound, gained from 50 years of experience of operating a federally funded research and development center (FFRDC). Its matrix organizational structure, with many subject matter experts residing in the corporation's Engineering and Technology Group, allows technology experts and space program offices to share knowledge of the industrial base that affect the government's ability to acquire critical technologies for satellite programs. In addition, Aerospace's operation as an FFRDC enhances not only its ability to handle proprietary information that relies on nondisclosure agreements between the suppliers and Aerospace, but also the willingness of industry to share emerging issues based on decades of trust built by Aerospace working alongside government and industry experts.

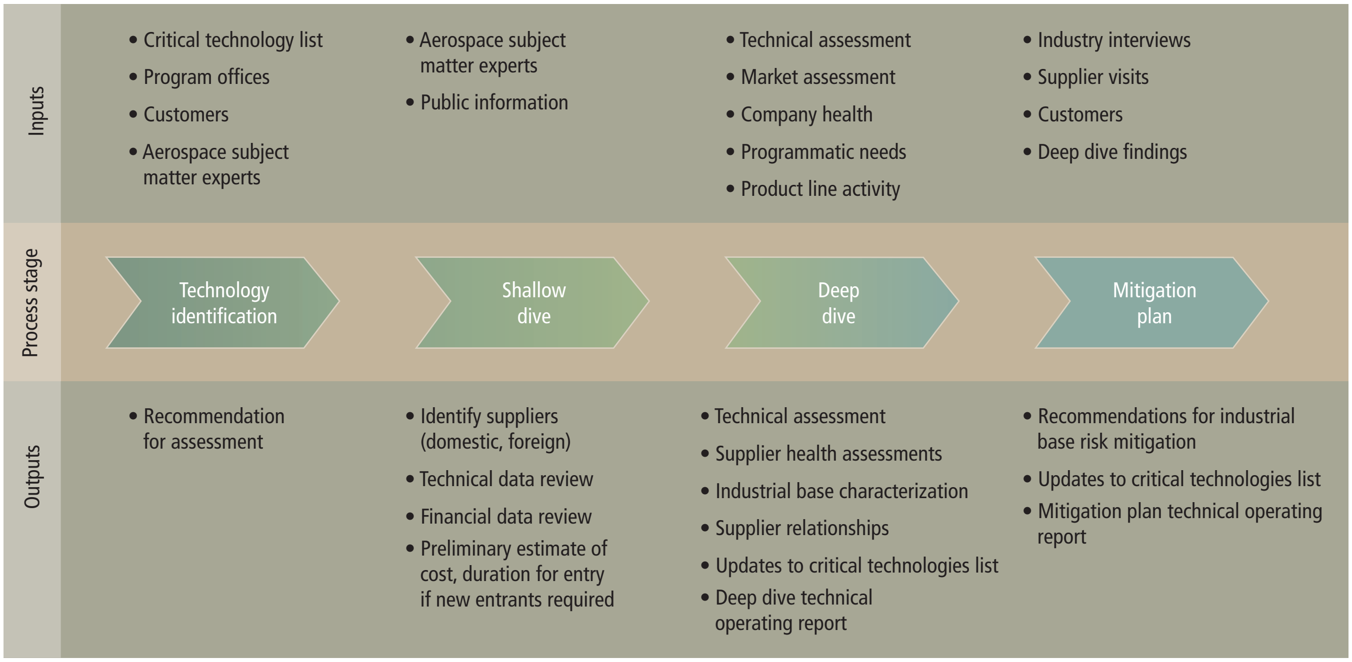
Aerospace has long been involved informally in ensuring the viability of the space supplier industrial base. In 2002, the corporation began facilitating a more formal consortium consisting of the Air Force Space and Missile Systems Center (SMC), the National Reconnaissance Office (NRO), and the Missile Defense Agency (MDA) to identify common industrial base problems and to pool resources to address them. The consortium formed the heart of the Critical Technologies Working Group (CTWG), which was chartered by the National Security Space Office in 2005 to support the Space Industrial Base Council in creating, supporting, and stabilizing a domestic industrial base for national security space (NSS) and civil space programs.

The CTWG, whose members include representatives from all procuring agencies for government space systems, identifies and funds the most urgent industrial base issues. It meets regularly, four or five times annually, to identify viability issues in the space industrial base and to ensure the health of the companies in the base. To accomplish this, the council provides funding to develop new products or improve existing products at vulnerable companies, or recommends policy changes that can strengthen their technical or financial health.

The Critical Technology Assessment Process

The basis of the CTWG efforts is the Critical Technologies List (CTL), started in 2003 as a joint effort of Aerospace, the SMC Engineering Directorate, the NRO, and the MDA. The list was initially ad hoc, generated by nominations from various experts at Aerospace, and combined with surveys of system program offices at SMC and NRO. A priority list is created based on factors associated with criticality and vulnerability of each item. An Aerospace subject matter expert is assigned to each item to provide ongoing technical assessment of the technology.

Led by the Engineering and Integration Division working with the Aerospace Economic and Market Analysis Center—the corporation's focal point for space-related market research and economic analyses—a team performs "deep dives," which are in-depth looks at market and technical analysis, including a review at the manufacturing site on



The Aerospace Corporation's industrial base assessment process for critical technologies. Working through these stages helps to identify technologies to be considered and whether they require a shallow or deep dive assessment, as well as the mitigation of current and emerging industrial base risks.

the most critical items. The CTWG then addresses the most urgent items on the list by acting on recommendations of the deep dives, which have typically been different for each item. At the successful conclusion of each program resulting from these recommendations, the deep-dive process is started again on new items that have reached critical status. The health of the suppliers that have been assisted by these efforts is monitored after each program is complete.

In 2009 the Air Force, NRO, and MDA entered a memorandum of agreement to provide a shared pool of funds to support specific industrial base issues as appropriate. Each agency maintains control over its share of the funds and may support or abstain from supporting individual projects as they see fit. The most common funding strategy has been to channel funds into the Defense Production Act Title III program, which was enacted in 1950 and provides broad authorities, including nonexpiring funding, to the U.S. president to ensure the ability of the domestic industrial base to supply materials and services for national defense. Another strategy entails funding a manufacturing technology via a program enacted in 1956 as a congressional mandate to advance the maturity of manufacturing processes to bridge the gap from research and development advances to full-scale production.

It is important to recognize that industrial base issues are those related to the overall health of the space industrial base and not necessarily to specific delivery problems at individual suppliers. Often programs have challenges in acquiring specific components due to isolated technical or schedule anomalies originating at the supplier, which are not necessarily indicative of the health of the industrial base. These isolated issues are generally dealt with on a program-by-program basis and are not the target of an industrial base mitigation effort unless the issue represents a broader or systemic issue.

Defining the CTL is one of the first steps in the process of technology identification. In this stage, the space acquisition community and Aerospace subject-matter experts are consulted to identify critical technologies. Over the years, the specific metrics and methodology used for determining priorities have evolved as Aerospace and its government counterparts have developed a deeper understanding of the issues affecting the industrial base. In 2008, Aerospace conducted an in-depth review and update of the methodology and assessments contained within the CTL. As a result, a rigorous process has been developed to prioritize individual technologies based on a risk matrix examining the severity of consequence and the likelihood of occurrence.

The 2011 updated CTL contained more than 75 technologies based on inputs from the supply base, SMC program offices, and other government agencies, along with an analysis by technical and financial subject-matter experts on the criticality and vulnerability of each technology. Each technical expert was interviewed by Aerospace's Economic and Market Analysis Center, which compiled all the inputs into a common framework in a single database. The center has taken the lead for Aerospace in maintaining the CTL, a dynamic database regularly updated as technologies are added

Parts, Materials, and Processes Engineering in the Early Stages of Program Execution

Electronic hardware—electrical, electronic, electromechanical, electro-optical—parts, materials, and processes (PMP) are fundamental to mission reliability and program success. Just as dependable space operations rely on robust designs, electronic hardware designs depend on robust PMP to ensure that elements have been fully screened and qualified for long life as well as for tolerance of the harsh environment of space. Similarly, the characteristics, performance, and requirements of a program's PMP must be well understood by the space system design team to preserve any inherent robust capabilities. The Aerospace Corporation's PMP engineering department is a critical resource and process with distinct activities throughout all phases of space system acquisition, ensuring program and mission success.

Much activity is performed in the early stages of space system acquisition. During concept studies (phase 0), Aerospace helps to develop the PMP language used in requests for proposals or statements of objectives. Aerospace also reviews contractor proposals, participates in source selection, and reviews or helps develop any tailoring to baseline PMP requirements that are unique to a program. Aerospace's expertise and experience in PMP engineering and its insight across programs, contractors, and the supply base have been used to develop a common set of appropriate program requirements for space PMP. These requirements form the basis of PMP rigor for a program and have a significant benefit on the cost, schedule, and reliability of a given space system. For example, higher-quality space parts mean higher and longer reliability; and sound mission assurance practices reduce part failures during production, system and spacecraft testing, and operations, thus reducing total lifecycle costs.

In the concept development (phase A) PMP engineering helps provide inputs to the development of system requirements documents, verifies that the contractor's PMP control program plan defines necessary tasks and is consistent with mission and contract requirements, and verifies the contractor has organized a PMP control board per required policies. The control board is a formal contractor organization established to manage and control the selection, application, procurement, qualification, and inspection of PMP in accordance with the program requirements.

Phase A is the stage when evaluations are conducted relative to top-level PMP requirements as part of the systems design review. This is also the stage for verification of the flow-down of requirements to subcontractors, reviews of new technology, and qualification planning for insertion into new and existing programs. Aerospace has developed a set of guidelines for technology insertion that assist in this activity. This is appropriate for PMP that have not been qualified for application with-in the specific space environment, or for those that have undergone changes that may alter the performance, functionality, or reliability of spaceflight hardware. The document is intended to provide guidance to the government, program managers, and technology insertion boards for an understanding of the total magnitude and effort required to evaluate necessary areas of concern. Aerospace has assisted in the incorporation of this concept and requirements into MIL-PRF-38535, the military standard for integrated circuits, to ensure the quality and reliability of new technology.

During preliminary design (phase B), which is followed by the preliminary design review, PMP engineering evaluates the contractor's preliminary design PMP process, contractor and subcontractor control plans, and radiation assurance plans for adequacy and adherence to the tailored PMP requirements and processes in accordance with program requirements. Aerospace engineers also participate in PMP control board and control functions. This activity is the key management process for PMP risk management, and is where Aerospace plays a critical role, especially when contracts have acquisition and government approval authority. For example, Aerospace reviews the contractor data products in accordance with the control plan, such as characterization data, preliminary approved parts and materials selection lists, and PMP approval of nonstandard approval requests. In addition, Aerospace reviews new technology insertion plans and tests, ensures consistency of PMP across subcontractors, reviews stress and end-of-life derating, evaluates contractor test and qualification plans, and reviews test data as it becomes available. These reviews are valuable in the early detection and prevention of reliability-suspect PMP and inadequate test and qualification programs that could result in higher costs and risks to the schedule and mission from part failures during system tests and operations.

to the list and as Aerospace conducts more in-depth assessments that update the risk rating of the specific technology. The 2011 update also provided a review and categorization of technologies originally identified for inclusion.

Given the large number and the future growth of CTL items, it is important to establish a preliminary risk assessment, which measures the relative risk of each item based on a standard framework. The result will enable resources to conduct shallow- and deep-dive assessments to further validate industrial base issues for the items to be investigated. An added advantage of using a standard framework is that it enables the risk profile of items to be updated in the future.

Each CTL item is ranked based on the likelihood of occurrence and severity of consequence. The likelihood of occurrence is a metric to predict the possibility the technology will not be available in the future by examining factors such as single source, foreign source, expertise, and infrastructure and equipment. The severity of consequence provides an estimate of impact to NSS programs if the technology is no longer available by evaluating factors such as time to reconstitute supplier, cost to reconstitute supplier, availability of substitute products, performance degradation caused by loss of item, and number of programs impacted.

By using a common risk assessment process, the CTL

PMP engineering must work closely with design engineering to prevent selection of parts and materials that are not readily available at the quality and reliability levels required for the mission as specified in the control plan. The designer's choice of technology during this phase determines subsequent cost, schedule, and reliability of the end system. For example, use of commercial-off-the-shelf parts designed and manufactured for the commercial market may have unique failure risks depending on the technology and application. These parts typically reduce the reliability of the system and require special qualification, screening, and radiation test programs, which can drive costs and affect the schedule. Thus the program-approved selection and as-designed PMP lists should be independently reviewed to identify and manage risks early in the program.

Independent from specific activities performed during the acquisition execution of a program, PMP engineering performs a variety of functions related to the maintenance and improvement in the industrial base and to specifications and requirements used for each PMP technology. Aerospace partners with other government agencies to participate in auditing the industrial supply base to ensure products are being manufactured according to their space requirements and leads information-sharing forums and working groups such as the annual Space Parts Working Group conference. Aerospace and its partners also operate alert systems, such as the PUMPS (parts, units, materials, processes, and subsystems) problem-alert database for cross-program sharing of issues and common problems. This prevents issue proliferation, helps to determine impact risk across programs, and facilitates issue solutions. Aerospace laboratories also perform independent research and reliability studies to better understand and reduce risks with new technology insertion planning for space systems. For example, Aerospace has led a study to determine the reliability and risk of a particular field-programmable gate array technology, performing extensive physical analysis and long-term reliability life testing.

Aerospace also helps to develop and review new test methods and standards to ensure product reliability and incorporate lessons learned into the methodology. For example, Aerospace helped to facilitate a cross-program and contractor solution to a radio frequency attenuator issue by implementing a new test and screening at the parts level to identify and prevent a suspected product from entering flight hardware. This solution was later incorporated as a new revision to the military requirements standard used to procure the technology. Three of the latest requirements specifications being published—following extensive industry reviews—are revision B to the two Aerospace PMP program requirements documents covering the PMP control program and detailed technical requirements, and a photonic device standard to be published by Aerospace and the Defense Standardization Program Office, Office of the Secretary of Defense.

A wide range of skills and knowledge bases is required to support these PMP activities. These include an in-depth understanding of applicable military standards for various types of PMP and their associated standard testing methods, and a thorough understanding of the underlying technologies and their applications, including hardness assurance requirements. A comprehensive understanding of the related industrial base is needed to ensure the lowest-risk part or material is selected that meets system performance needs. Similarly, manufacturing engineers are required to select low-risk, qualified reliable processes for which a team of technical specialists is needed. Aerospace plays an important role in providing the necessary resources and expertise for helping assess and supplement the depth and breadth of the government and contractor PMP engineering team.

Further Reading

Aerospace Report No. TOR-2006(8583)-5235, "Revision A, PMP Control Program for Space and Launch Vehicles" (The Aerospace Corporation, El Segundo, CA, 2006).

Aerospace Report No. TOR 2006(8583)-5236, "Revision A, Technical Requirements for Electronic PMP Used in Space and Launch Vehicles" (The Aerospace Corporation, El Segundo, CA, 2006).

Aerospace Report No. TOR 2007(8546)-6018, "Revision B, Mission Assurance Guide, Chapter 15, Parts, Materials and Processes," pp. 335–355 (The Aerospace Corporation, El Segundo, CA, 2007).

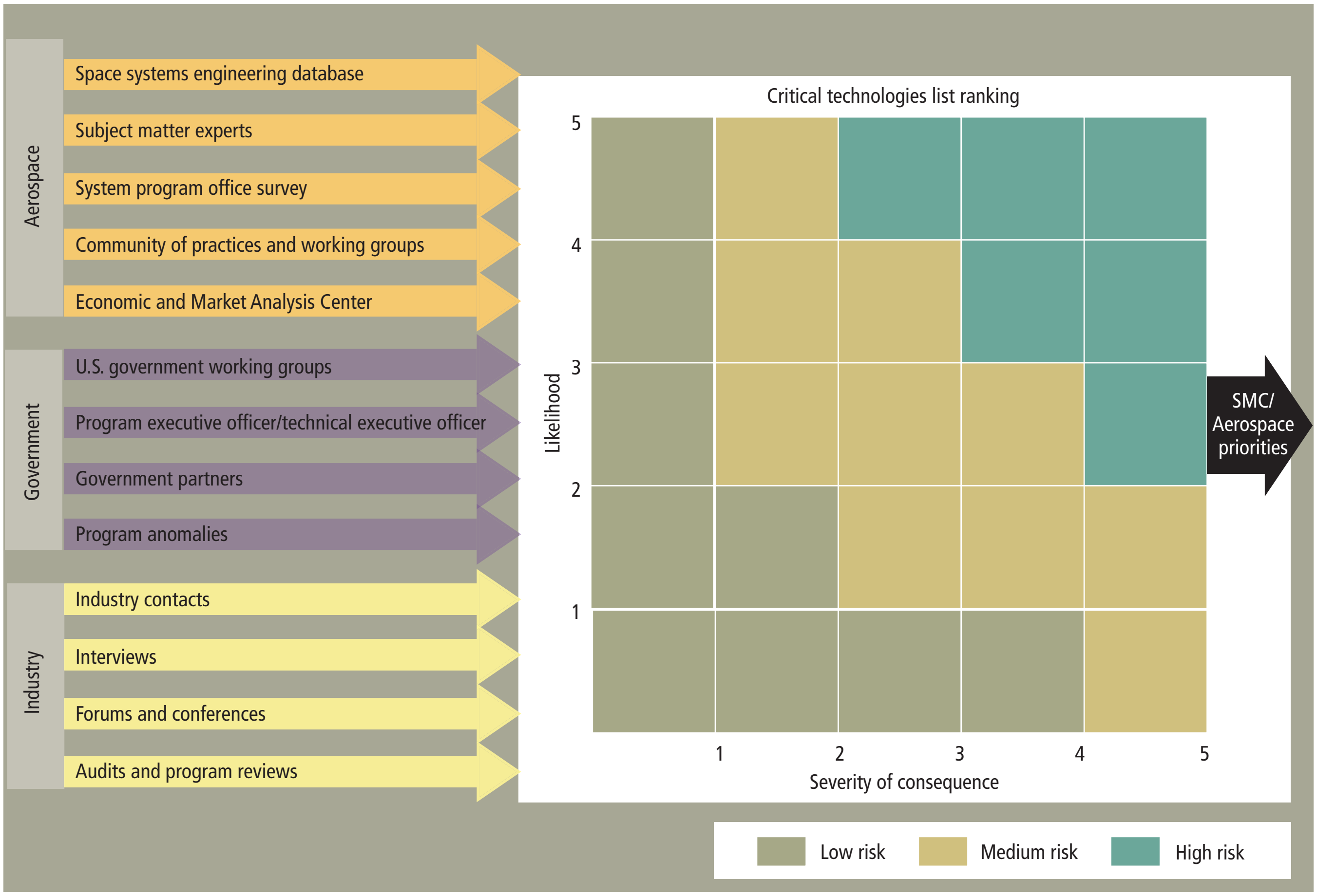
Aerospace Report No. TOR-2012(3909)-16, "Optoelectronic Device Qualification for Extreme Environments" (The Aerospace Corporation, El Segundo, CA, 2012).

– Steven Robertson, director, Parts, Materials, and Processes Dept.

provides a relative risk rating of each item to inform stakeholders of potential industrial base challenges. The risk ratings are not intended to provide the complete evaluation of technology risk, but to provide priorities for further technology assessments. The CTL does not take into account marketing assessments, such as specifics on profitability of product lines compared with other items sold by the same supplier, or the parent company's profitability. Further in-depth analysis is conducted for all technologies identified as high or medium risk within the CTL.

The proprietary nature of CTL data limits distribution to the U.S. government and Aerospace personnel only. Key takeaways from the CTL risk-assessment process are that it provides a priority list of technologies for further investigation and provides awareness of potential critical technology challenges to the government.

The second stage in the technology-assessment process is referred to as a "shallow dive." In this stage, the Aerospace subject-matter experts and the Economic and Market Analysis Center examine the technology application, market, and supply base. The experts provide in-depth knowledge of the technology, and the Economic and Market Analysis Center adds additional perspectives by examining the business aspects of the technology and supply base to provide a fuller



An illustration of the input and output of the critical technologies list. The likelihood of availability and the severity of consequences are generated for each item. Aerospace and the Space and Missile Systems Center determine priorities on this list, gathering input from the government and industry partners.

assessment. Aerospace typically conducts five or more shallow dives each year depending on demand from customers. The shallow dives are primarily used to confirm if there are potential risks for satellite programs in continued acquisition of the technology.

The most in-depth studies conducted by Aerospace are referred to as deep dives and mitigation plans. Because of the resources required to conduct this level of study, only one or two are performed annually based on the technologies of highest concern. At this stage, Aerospace conducts interviews with industry suppliers and buyers to identify industrial base issues with the technology and estimate the market supply and demand. A financial analysis of each supplier identifies potential business-related issues that could have an impact on the availability of a technology in the future. Financial reports of the company and credit ratings can indicate an emerging issue that could affect the company's willingness and ability to continue offering a product. Interviews with the suppliers provide insight into how the technology fits into the company's overall strategic plans.

At the conclusion of a deep dive study, Aerospace provides recommendations to the government on whether or not the technology is believed to be at risk. If the risk for continued access to the technology is at a level unacceptable to government customers, Aerospace will build upon the deep dive to provide potential mitigation strategies for the government to consider. The mitigation strategies span the spectrum from maintaining awareness to identification of specific risk mitigation plans.

Examples of various risk mitigation strategies recommended include maintaining awareness, stockpiling, improving efforts to develop technologies development and improve production, gaining advocacy, and policy changes.

The CTWG is currently funding and/or monitoring approximately 15 industrial base items. These include traveling wave tubes, solar cells, solar-cell substrates, readout integrated circuits, Li-ion batteries, star trackers, visible sensors, cryocoolers, infrared detectors, infrared detector substrates, reaction wheels, bearings, printed circuit-card assemblies, and cover glass. These items are in various stages of activity. Currently, Defense Production Act Title III programs are in progress related to readout integrated circuits, traveling-wave-tube amplifiers, Li-ion batteries, and complementary metal-oxide semiconductor imagers for star trackers.

Providing Quick-Look Impact Assessments

The establishment of a common database identifying critical technologies, suppliers, and technology used on programs at Aerospace has proved to be valuable in providing quick assessments to the government on the impact of natural disasters to the supply chain.

On March 11, 2011, Japan experienced a 9.0 earthquake in the Tohoku region, resulting in significant loss of life and damage to several companies from the earthquake, aftershocks, and a tsunami. The initial impact of the earthquake and tsunami on the NSS supply chain was unknown because programs and industry partners typically hold supply chain data. Aerospace initiated a quick-look study for SMC to identify Japanese suppliers in the supply chain and understand any potential supply chain risks for the programs. An initial supplier list was developed using the Aerospace CTL, prior system program office (SPO) surveys, and supplier lists from the national security space primary contractors for satellite systems. To assess the potential impact, Aerospace reviewed news reports, company press releases, and disaster reports from Japan, and leveraged the technology subject-matter expert knowledge of the specific suppliers affected. The experts' long-standing relationships with the supply base enabled them to provide insights that would not have been available from any other sources.

This assessment identified suppliers with the highest potential to have an impact on the NSS supply chain based on reporting of damage to their facilities and product types. Aerospace found that a majority of the suppliers primarily sustained equipment damage, power outages, and transportation infrastructure damage; however, none of the suppliers identified are known to have been affected by the tsunami or radiation exposure. The assessment provided to Aerospace's customers within two weeks of the disaster enabled NSS programs to quickly assess the status of their critical supply chains and any cost and schedule impact that would likely have occurred. This report highlighted some potential uncertainties to ongoing programs, which instigated immediate discussion for implications.

The earthquake in Japan helped Aerospace to establish a framework to assess the impact of disasters on the NSS supply chain. Using that framework, Aerospace was able to quickly generate an assessment of flooding in Thailand, which occurred later in the year.

Interaction with Government SPOs and Industry

In 2008, Aerospace conducted a survey in collaboration with SMC to establish a prioritized list of critical technologies from the SMC SPO perspective. This survey was conducted to potentially provide a different perspective on the critical technology industrial base issues from the surveys conducted with the Aerospace subject-matter experts.

In addition to interviewing government SPOs, Aerospace is involved in industrial base interviews to discuss current and emerging supply-chain issues with supply-chain managers at NSS primary contractors for satellite systems.

As part of the technology assessment process, Aerospace conducts in-depth interviews with technology suppliers. Aerospace's Engineering and Integration Division and the Economic and Market Analysis Center typically lead these interviews. Previously, engagement with industry had been focused on the technology; however, these interviews are increasingly focusing on business aspects such as globalization, international traffic and arms regulation, and commercial markets, as well as issues concerning science, technology, engineering, and mathematics.

Supporting the Government in Programs to Ensure the Availability of Technologies

The assessment process is an important first step in ensuring a stable industrial base, but without action to mitigate the industrial base risks, ensuring continued access to the technologies for NSS programs cannot be achieved.

The formation of the Space Industrial Base Council and its primary working group, the CTWG, has been a successful multiagency collaborative effort in developing and implementing industrial base risk-reduction plans and projects. The Space Industrial Base Council was established in 2005 to provide senior-level oversight of space industrial base issues across the space enterprise. Initially chaired by the DOD executive agent for space and the director of the NRO, the membership included all space acquisition organizations and others interested in the success of the space industrial base. The executive committee consisted of the executive agent for space, the director of the NRO, the administrator of NASA, and the director of the MDA. The president and CEO of Aerospace was an invited member and provided updates on the Aerospace-facilitated industry forums, the Space Quality Improvement Council, and the Space Supplier Council.

In 2005, the Space Industrial Base Council chartered the CTWG to "ensure that critical and vulnerable technology management and procurement practices within the government and industry will provide a long-term stable source of technologies and capabilities required to meet the missions of the NSS community." In December 2009, a memorandum of agreement between the Air Force, NRO, MDA, and DOD Defense Research and Engineering was approved, establishing the CTWG risk mitigation portfolio. The agreement identified a formal process for approving the multiagency industrial base risk reduction projects, and determined funding contributions from the Air Force, NRO, and MDA. It also identified the process for approving the implementation process. The Defense Production Act Title III office was identified as the procurement agency for the CTWG risk-management portfolio.

Aerospace provided technical and program management support for the formation of the CTWG charter, the development agreement, and the development of the presidential determination documentation. Aerospace also provided industrial base assessment, risk-based priority methodology, and mitigation recommendations to customers at SMC

Standard Establishes Test Requirements for the Acquisition of Space Hardware

Today's spacecraft specifications and standards incorporate lessons learned since the 1970s. These best practices for the design, analysis, and testing of spacecraft hardware encompass a broad range of technical disciplines and have evolved under sponsorship of the U.S. government's procurement agencies. It is common practice to modify, or tailor, these approaches to reflect the situations that are unique to specific programs.

The extent of permissible tailoring is a significant part of contractual discussions during the preacquisition phase of a program, as the program office and potential contractors attempt to find a reasonable balance between cost and risk. Ideally, a process that results in well-defined, mutually acceptable modifications to the basic specifications and standards will permit proper costing and avoid contention on the scope of work from program initiation through initial operational capability. The challenge is to complete such a process before the contract is awarded, after which any changes can create significant additional costs for the customer.

Military Standard 1540 is a prime example of a test standard that, when tailored, has far-reaching effects on a program's cost and schedule, and thus is closely scrutinized by customers and contractors. Starting with Mil-Std-1540A, the standard has been in use since 1975. The current proposed revision, Mil-Std-1540E, is based on The Aerospace Corporation's technical report, "Test Requirements for Launch, Upper Stage, and Space Vehicles" (TR-2004 (8583)-1, Rev. A). The standard establishes baseline environmental testing requirements for launch vehicles, upper stages, space vehicles, and their subsystems and units. Thermal, acoustics, random vibration, shock, and low-frequency dynamic environments are considered. This standard is applicable to the procurement of space system hardware as a compliance document and can be tailored to meet individual program needs and buyer risk positions. The overall test program outlined focuses on design verification and the elimination of latent workmanship defects to help ensure a high level of confidence in achieving successful space missions.

A complete test program encompasses development, qualification/protoqualification, acceptance, and pre- and post-launch validation tests. The test methods, environments, and measured parameters are selected to permit the collection of empirical design and performance data for correlation and trending throughout the test program. The test strategy selected, such as qualification or protoqualification for the first build of the space hardware, impacts cost, schedule, and mission risk. These elements are balanced to achieve an optimum mix for a customer's risk position.

Qualification tests demonstrate satisfaction of design requirements, including margin and product robustness. A full qualification validates the planned acceptance program, the in-process environmental stress screening, and any potential retests that might result from rework after a test failure. As a general rule, qualification hardware is not flown, and the test articles are amortized over the number of vehicles flown. This approach presents the highest degree of confidence that flight vehicles subjected to acceptance testing have adequate margins to survive the rigors of launch and maintain usefulness throughout the on-orbit life.

Protoqualification tests demonstrate satisfaction of design requirements by using reduced amplitude and duration margins on first unit flight hardware. These tests are appropriate for designs that have limited production and in which test units will be used for flight. The test program is supplemented by analyses, development, and other tests to demonstrate margin and viability. Protoqualification test hardware is flown at increased risk. The risk for subsequent acceptance hardware is reduced but is also elevated relative to the full qualification approach.

The baseline test requirements of Mil-Std-1540E are derived to encompass ground operations, launch, and mission profile. They are tailored to a specific program after considering design complexity, margins, vulnerabilities, technology state-of-the-art, in-process controls, mission criticality, lifecycle costs, number of vehicles involved, prior usage, and acceptable risk. The technical rationale for each tailored requirement is established and considered during the tailoring process. If the baseline qualification requirements in the standard are not tailored by the contract, they stand as written. In all acquisitions, the customer program office is the final approving authority in the tailoring process.

For competitive bid acquisitions, a team consisting of the customer and Aerospace personnel conducts the process of tailoring the standard to a program, even before a request for proposal is developed. The results of the tailoring process are included in the request for proposal so that contractors can reflect them in their bids.

For sole-source acquisitions, tailoring of the standard occurs later, usually near contract award. In this case, the team consisting of the customer, Aerospace, and the contractor performs the tailoring. Tailoring the standard for sole-source acquisitions is more detailed than tailoring for competitive bid acquisitions, since it can account for the contractor's mission history, processes, and heritage hardware. Tailoring takes into account contractor-requested changes to the requirements.

Implementation of Mil-Std-1540 requires teamwork between the customer, contractor, and Aerospace program offices and engineering. The Aerospace team responsible for maintaining this environmental test standard continually works with its industry counterparts to monitor ground test and flight data to assess the effectiveness of environmental testing for improvements in future applications.

– Erwin Perl, director, Environment Test and Assessment Department

and NRO in support of the CTWG. This data provided the technical background for the projects that would later be targeted for mitigation efforts.

The current CTWG risk management portfolio contains programs that strengthen the domestic industrial base for solar cells, infrared sensors, star trackers, traveling-wave tubes, and critical supply chain elements in support of these technologies. CTWG risk management portfolio members continually assess technologies and industries to identify potential candidates for inclusion in the portfolio.

Mitigation efforts are not limited to the funding available within the CTWG risk management portfolio. In many cases the CTWG collaborates with other government industrial base efforts to develop a comprehensive mitigation approach to maximize synergies and reduce the overall cost to the government. These include NSS agency-specific mitigation efforts, the Defense Production Act Title III office, DOD manufacturing technology offices, the Defense Logistics Agency Strategic Materials, and the Radiation Hardened Electronics Oversight Council.

The U.S. government uses the Defense Production Act Title III Program to establish and maintain the production capability of critical technologies at domestic suppliers the government uses. Aerospace provides technical guidance to its government customers in identifying programs and reviews throughout the program cycle.

The Strategic and Critical Materials Stock Piling Act is one of the potential avenues for mitigating potential risks in the acquisition of critical technologies. The Defense Logistics Agency Strategic Materials manages the national defense stockpile for the government, and this effort supports the risk reduction by stockpiling materials used in critical technologies that could be at risk because of dependence on foreign sources.

In the late 1990s, radiation-hardened electronics supplier issues started to become critical, and the Radiation Hardened Electronics Oversight Council was established by DOD's Defense Research and Engineering. Industrial base concerns related to these items are continually monitored by subject-matter experts at Aerospace and within the CTWG member agencies as part of the Radiation Hardened Electronics Oversight Council activities.

To ensure continued access to critical technologies for NSS programs, a collaborative effort is often required. An example of a collaborative effort is the establishment of a domestic source for a specific material. The CTWG has worked with the Strategic Materials Agency to establish a stockpile of several different types of critical substrate materials to reduce industrial base risks in the short term while also working to establish a long-term domestic source of supply. Collaboration with the Strategic Materials Agency is critical for those high-risk industrial base materials that require long domestic source development cycles. In several other cases, the group has decided to make last time buy of materials because future technologies will make the material obsolete.

Aerospace subject-matter experts and program-management experts support all CTWG efforts along with many other government agency efforts that promote domestic supply of critical space materials. The collective knowledge of Aerospace subject-matter experts is critical in determining the short- and long-term mitigation plans and in understanding the long-term use of a particular material or technology.

Conclusion

Maintaining a healthy industrial base for space-system critical technologies is a difficult effort in the current financial environment. The bulk of the focus by procurement agencies today is centered on reducing the cost of existing systems and not on considering the long-term effects of losing a critical technology. The CTWG focuses on the longer-term viability of critical sources so that future programs have an available source of supply. The risk-evaluation process that Aerospace has developed, coupled with the multiagency CTWG risk-mitigation portfolio and multiagency risk-reduction approaches, provides an efficient way to identify and mitigate the risk of losing critical technologies and materials needed for future NSS programs.

About the Authors

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John Adams, Senior Project Leader, Engineering and Integration Division, has more than 30 years of experience in space and airborne radar and optical sensors. He was director of space manufacturing at Raytheon before joining Aerospace in 2008. As a member of the Critical Technologies Working Group, Adams works closely with the Space and Missile Systems Center at Los Angeles Air Force Base, the National Reconnaissance Office, and the Missile Defense Agency to develop statements of work and funding profiles. He has a B.S. in electrical engineering from California State University, Fresno.

Designing a Better Future through Policy and Strategy

Jack Clarke and James Vedda

Aerospace works closely with its customers to keep them informed of what is happening in the policy and strategy arena and how those outcomes may affect space system acquisition planning.

Policy and strategy are very much at the front end of space system acquisition planning. Understanding these ever-changing factors helps to define the direction of U.S. national space programs and guide the organizations that oversee those programs. Simply stated, policy is what to do and why it is important to do it, while strategy is how to do it. The process of formulating, implementing, monitoring, and revising policy is quite complex. This is especially true when factors such as advanced technology, geopolitics, and international economics intersect.

Policy drives requirements, directs research, and guides space system acquisition and operations. Without sufficiently understanding the policy environment, it can be difficult to see how a particular technical solution supports, or might detract from, broader national objectives. Policy needs to be integrated into technical studies as a reality check on proposed solutions to meet the nation's or a particular customer's needs.

The Aerospace Corporation has a substantial presence in the Washington, D.C., area where issues of policy, strategy, law, and regulation dominate the environment and drive choices for technology programs and their manner of implementation. As the federally funded research and development center (FFRDC) for space, Aerospace must ensure that its analysis and technical solutions—for requirements definition, anomaly resolution, assessment of options, and other needs—are grounded in a sound understanding of the policy environment in which they will be delivered.

Policies and strategies at the national and government agency levels impact the choices that are available for architectural and other technical efforts for space system planners and demand that Aerospace keep an eye on the future. Space planners must remain vigilant of political, economic, and other societal trends in addition to technical advances. Aerospace tracks the trends and shares the lessons learned with its customers to help avoid pitfalls and delays that can undermine programmatic and mission success.

Aerospace personnel apply their expertise to the analyses of budgets, policy proposals, legislation, and regulatory changes in these national, agency, and programmatic contexts. The challenge is to make sure that new and updated policies align with technical realities, observed trends, and the language and intent of related guidance, including those related to international commitments.

Organizational Resources

Aerospace has a history of performing policy-related functions for a variety of customers since the company's formation in 1960. The Strategic Awareness and Policy division (also known as Project West Wing) is located at the company's El Segundo, California, headquarters and has traditionally focused on threat analysis. This group's work on the Counter Space Sensitive Technologies list has assisted U.S. government policymakers in the understanding of foreign counterspace technologies and has aided in export control licensing decisions.

In 2000, Aerospace established the Center for Space Policy and Strategy (CSPS) in Arlington, Virginia. This group's mandate is to provide policy and strategy support across the civil, commercial, and national security space customer sectors of the company. CSPS keeps abreast of current national policies and laws related to space and monitors developments and trends beyond the traditional space engineering disciplines that may affect Aerospace's activities, such as economic and technological globalization, geopolitical developments such as those happening in many Asian nations, domestic and international financial crises, environmental degradation, energy, and climate change.

In addition to strong familiarity with a wide range of issues, solid analysis requires knowledge of the entire policy environment, including insight into the history, rules, behaviors, and even the personalities involved in the formulation and implementation of various policies. This involves keeping track of a constant flow of government policy documents, think-tank studies, scholarly papers, trade press reporting, and Internet updates.

In Washington, Aerospace has provided policy support to the U.S. Office of the Secretary of Defense (OSD), providing current policy, acquisition, systems engineering, and intelligence information. Aerospace also reports on policy information to the DOD Executive Agent for Space. Aerospace supports NASA, the Department of Commerce, and the Department of Transportation in these areas too. In the intelligence community, Aerospace has provided policy in-formation to the National Reconnaissance Office (NRO), the National Geospatial Intelligence Agency (NGA), and the Director of National Intelligence (DNI).

Increasingly, space activities and their related issues cross over among the civil, commercial, and national security sectors, so a broad, integrated perspective is essential. The geopolitical and operational field is constantly shifting, driving the evolution of customer needs. Aerospace has a multidisciplinary team keeping up with this complex, dynamic environment and is ready to support space program decisions. In addition, the corporation's outreach to the policy community provides a window into the environment and processes that shape government policies and programs.

Examples of Policy Support

Aerospace does not write policy; that is the government's responsibility. However, many times the company has been asked to study options or give advice to government agencies, providing a valuable supplement that allows its customers clearer insight into developing long-term strategic planning on sound technical footing.

For example, in recent years the NGA has worked to integrate commercial satellite imagery into its operations. Aerospace has conducted several studies for the NGA to assist in its decision making. By studying current and future prospects and surveying current policies, laws, and international agreements governing satellite remote sensing, the studies have chronicled the evolution of civil and commercial policy and looked ahead toward future policy and market scenarios.

Top Future Policy Issues

- **Hosted payloads.** Further clarification and adjustment can be expected on national policies regarding space transportation and export control as applied to U.S. government payloads flying on commercial satellites and foreign launchers.
- **International partnering agreements.** The design, deployment, and operation of space assets shared with coalition partners must be considered in the context of treaty implications, congressional concerns, and technology transfer.
- **Space situational awareness.** The effort to build on these capabilities and share data must be weighed against tradeoffs between greater investment in U.S. systems and teaming arrangements with foreign entities.
- **Commercial satellite imagery.** As commercial and foreign capabilities increase, relevant national policy, statutes, and department policies must keep up with the implications of technical advancement.
- **Commercial human spaceflight.** Should this industry's regulatory regime be modeled after commercial aviation, or something else? How will the direction of its policies affect current and future government programs in human spaceflight?
- **Space exploration and development.** NASA is developing a new transportation system for human spaceflight. At the same time, the agency is encouraging private-sector advances in human and automated space systems. Should the next wave of activity be driven by destinations, as in the Apollo era, or should it focus on capabilities, like on-orbit servicing and utilization of extraterrestrial resources? How should NASA's role evolve?
- **Industrial base and workforce.** The space industrial base has not reversed the trend of a shrinking technical workforce and loss of expertise. Is there anything that government policymakers can do to improve the situation? Might the answers be found in government programs, or in the emerging commercial space sector?

One of Aerospace's customers for policy-related work has been the Federal Aviation Administration (FAA), Office of Commercial Space Transportation. The FAA is responsible for the licensing and regulation of commercial launch and reentry operations. Aerospace has developed two reports for Congress at the request of the FAA. The first was an 18-month effort to support a congressional decision on an extension of the U.S. government's third-party liability risk sharing for commercial launch providers. The second was a one-year analysis of human spaceflight safety, a diverse study that included policy components. Aerospace also delivered a 90-page study to the FAA that examined the regulatory

Recasting Aerospace Support/Strategy Team

Delivering unrivaled space and missile system capabilities to the U.S. military and its allies is a primary goal of the Space and Missile Systems Center (SMC) at Los Angeles Air Force Base. SMC, along with The Aerospace Corporation and its contractor partners, has been very successful in achieving its goals over the last several years. An unprecedented number of new satellite systems were launched in a relatively short timeframe, including: Advanced Extremely High Frequency (AEHF), Global Positioning System-IIF (GPS IIF), Space Based Infrared System (SBIRS), Space Based Space Surveillance (SBSS), Space Tracking and Surveillance System (STSS), and Wideband Global SATCOM (WGS).

Aerospace has always positioned itself to support SMC and its other government customers in all phases of the space system acquisition process with world-class talent across the company. Personnel within the Aerospace program offices and the Engineering and Technology Group (ETG) have demonstrated an exceptional capability to supply expertise in the various disciplines of science and engineering to meet a wide range of technical issues throughout the lifecycle of a space program. As is often the case with extremely complex, sophisticated systems, many challenges arose during qualification and acceptance testing as programs were developed during the last decade. In addition, optimistic timelines to conduct spacecraft assembly, integration, and testing were exceeded as Aerospace experts collaborated with contractors and government teams to ensure that the systems being developed would meet warfighter needs. The teams aggressively resolved design, production, and testing issues, resulting in the delivery of exquisite capabilities to the warfighter.

It is now time to reflect back on the lessons learned from these recently delivered capabilities and determine how to position Aerospace for the future, given fiscal realities, technical capabilities, mission threats, and the current state of existing space capabilities. After completing several first-of-kind systems, SMC is looking to the future to deliver an evolving set of space and ground capabilities. Likewise, Aerospace needs to realign its focus as it works with its customers to achieve the next series of successes. Just as Aerospace gradually shifted its technical support to the tail end of the systems engineering processes for recently fielded systems, it now needs to shift talent back to the front end of the systems engineering processes as new systems are conceived and the capabilities of existing systems are exploited in new ways. In many cases, this is simply a matter of applying existing technical capabilities to the engineering challenges associated with the enhancement of existing systems, or the birthing of new systems. This may include requirements formulation, rather than requirements verification, or the examination of attributes of new technology developments, rather than conducting technology demonstrations. It may also include supplementing existing space architectures with new, cost-effective space payloads that are integrated with more affordable commercially available satellite buses or hosted on other satellite systems. Aerospace is now taking a step back to view the entire space enterprise and formulate concepts that support a sustainable future. This will involve leveraging the mission capability and development gains from the recent past. The lessons learned from the past decade are rich with guidance on the way forward.

In an effort to look toward the future and assess the best way forward, the Recasting Aerospace Support Team (RAST) has been formed at Aerospace to unite efforts already under way in program offices and within ETG to align and exploit existing Aerospace skills and products. RAST is one key means of implementing the corporation's strategic plan for innovative architectures and improved decision support, as well as providing guidance to program offices and ETG. The RAST membership has broad knowledge of technical skills, analytic tools, mission assurance activities, systems engineering design methods, acquisition processes, and lessons learned from across the corporation.

Interaction among RAST members provides a forum for sharing tools and processes that have been used in the past to successfully support Aerospace customers. RAST has already supported two SMC program offices where the government was in the process of formulating the right skills mix needed for existing and new acquisition programs. ETG has also developed a suite of powerful tools to evaluate space and ground system architecture concepts, including end-to-end system simulations, mission-level cost benefit trades, mission utility analysis, system-level concept of operations, enterprise decision support, and requirements impacts. These capabilities enable Aerospace to support SMC as it works to develop the next generation of resilient, affordable, and unrivaled space systems.

– Wayne H. Goodman, vice president, Space Program Operations

history of traditional transportation modes for gathering lessons for present and future regulatory action in commercial spaceflight.

Aerospace has contributed to a strategic plan adopted by the Office of Space Commercialization, Department of Commerce, and served the State Department during its engagement with an international committee on global satellite navigation systems.

Aerospace has applied policy expertise to its work on defense programs as well. In support of OSD and the Executive Agent for Space, Aerospace has provided a bridge for the technical/policy evaluations found in wargaming. In recent years, wargames across the military services and the intelligence community have incorporated space-related elements with strong policy implications. Aerospace has helped in areas where technical assistance must be coupled with policy and other nontechnical aspects to help develop a realistic future environment for the analysis and employment of new technology and systems. This assistance has included helping analyze the findings of wargames to better inform the intelligence community of the findings.

In general, the technical development of space and missile systems and experimental payloads cannot begin until certain questions are answered. These include: Is this action in conformity with policy and law? Does it involve international collaboration, and if so, are there export controls or other obstacles to overcome? Are there treaty implications? Aerospace has studied questions like these on behalf of various government customers, some of whom are formulating top-level policy. For example, Aerospace provided input and support during the development of the national space policies signed by Presidents Bush and Obama.

There will be no shortage of policy issues to address in the years ahead. As policy issues focused on partnering and capability sharing enter further into space architectures, and critical policy issues like protection and resilience move from concept to reality, the bridge Aerospace offers between policy and technology will only increase in importance.

All sectors of space activity are dynamic areas, offering promising applications and fascinating discoveries, alongside the risk of failure and frustration. Proper attention to policy and strategy helps to maximize the positive aspects of this dynamic climate and minimize the negative aspects. Aerospace will continue to be ready and able to help its customers bridge the gap between policy, strategy, and technology for space programs.

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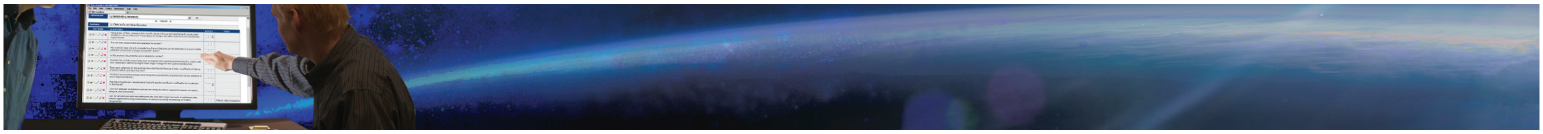
Jack Clarke, Systems Director, National Security Space Policy, Programs, and Oversight, joined Aerospace in 2008. He manages Aerospace support to the Office of the Under Secretary of Defense for Acquisition, Technology, and Logistics. He has supported the DOD executive agent for space; the deputy assistant secretary of defense for communications, command and control, and cyber; and the deputy assistant secretary of defense for systems engineering. He served for 20 years in the Air Force, working with space and missile operations, international military wargame facilitation, and defense space policy development. He has an M.S. in systems engineering from George Washington University.

James Vedda, Senior Project Engineer, National Security Space Programs, Policy, and Oversight, performs analyses on national security, civil, and commercial space issues. Before joining Aerospace in 2004, he worked at the Office of the Secretary of Defense in space policy and homeland defense, and as an associate professor in space studies at the University of North Dakota. He is the author of *Choice, Not Fate: Shaping a Sustainable Future in the Space Age* (December 2009) and *Becoming Spacefarers: Rescuing America's Space Program* (June 2012). He has an M.S. in science and technology policy from George Washington University and a Ph.D. in political science from the University of Florida.



Evaluating Software Architectures for National Security Space Systems

Alan Unell

A framework geared toward evaluating software architectures for national security space programs on the front end saves costs and minimizes schedule delays.

National security space programs rely on dependable and effective software for ground and space systems. Developing the software for these systems presents immense challenges. Ground systems software requires millions to tens of millions of lines of code. Spaceflight systems require far fewer lines of code; however, the complexity of working with real-time embedded systems and factors of mission criticality adds to the software development challenges. Historically, insufficient front-end work on software architecture and design has led to software acquisitions for ground and space systems that have incurred as much as 50–150 percent cost overruns and corresponding schedule delays, which can last for years.

In an effort to address software-related cost and schedule issues and also to reemphasize front-end engagement, The Aerospace Corporation has instituted a framework for evaluating its customers' software architectures. By developing a framework for evaluating software architectures designed for national security space systems, areas that demand attention can be identified, understood, and rectified earlier in a system's development lifecycle, thereby minimizing avoidable rework and operational deficiencies later in the process.

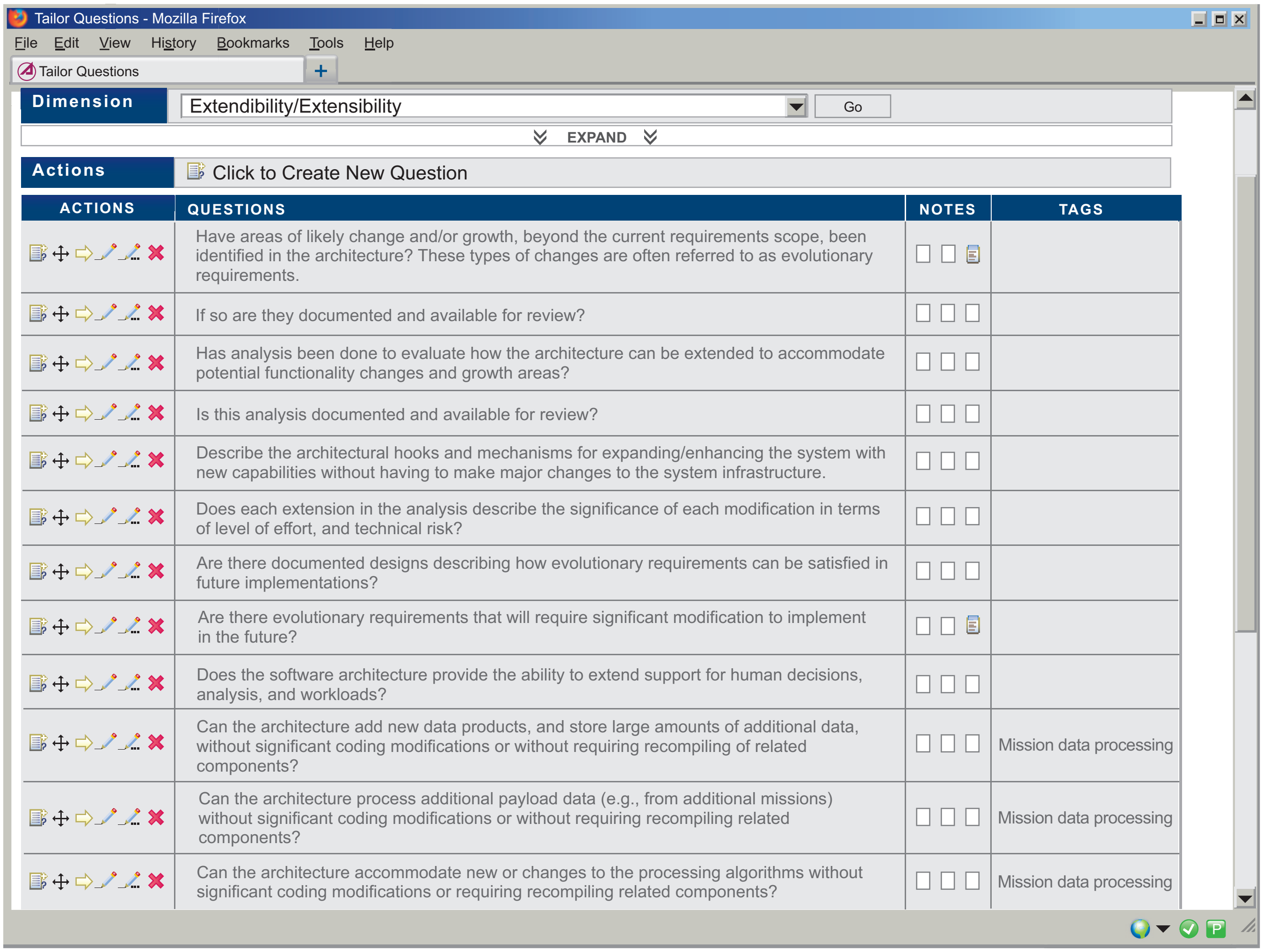
Software Architecture Fundamentals

Software architecture refers to a simplified representation, or model, of a software system and encompasses the significant decisions about a system's organization, including the structural elements and interfaces that constitute the system; the behavior, as shown by the interactions among the structural elements; the composition of the structural and behavioral elements into a larger subsystem; and the architectural style guiding the organization. The software architecture also accounts for a software system's features, such as usage, functionality, performance, resilience, reuse, comprehensibility, economic and technology trade-offs, and aesthetic concerns.

When implemented correctly, the software architecture can demonstrate a software system's technical feasibility to its stakeholders. In DOD environments, it allows development and acquisition stakeholders to make more-accurate programmatic and technical decisions at each milestone in the development lifecycle. Key DOD stakeholders may include enterprise representatives, contractors, operators, commercial users, product vendors, and subject matter experts.

A major challenge in software architecting is to identify the mandatory attributes of a software system, which are determined by stakeholder and domain-specific concerns. For example, a software system may require several simultaneous capabilities specific to national security space, such as commanding a vehicle and processing sensor data while being resilient to attacks, scalability to meet peak and future usage, flexibility to incorporate new capabilities, and timeliness and reliability to support the warfighter.

During the preliminary software design phase, the architectural design principles, requirements, constraints, and assumptions provide formal guidance to the software development engineers. In this phase, engineers often discover initial design constraints and assumptions that must be revised so that detailed software designs and implementations will meet target system requirements. Such cases can emerge due to changes in existing requirements, or from the addition of new requirements. While revisions to architectural



The Aerospace Corporation has instituted a framework for evaluating its customers' software architectures. Here is a view of that framework, named Evalica, and its question browser and editor. Users can browse, reorganize, and edit questions in a common repository, sharing the information with other developers.

designs are ideally conducted quickly to remove software development roadblocks, they are sometimes done without fully regarding or understanding their impact on other areas of the software architecture. Conducting broad or even targeted software architecture evaluations at regular intervals during the preliminary design and implementation phases of software development assures stakeholders that the evolving architectural design will continue to meet all functional and nonfunctional system requirements.

Software Architecture Standards

An IEEE working group has developed IEEE Standard 1471-2000 ("Recommended Practice for Architectural Description of Software-Intensive Systems") with input from industry, academia, and other standards bodies. It provides a conceptual framework for architectural descriptions of software systems. Designed to be independent of other architectural description techniques, this standard establishes content requirements for a given software architecture description. These include identification of the stakeholders and their concerns, the views of the software system from the perspective of related concerns, templates for developing the views, consistencies among the views, and rationale. (A view is a representation of a set of software system components and the relationships among them.) The standard leaves the choice of views to the software architects, so there is no set depiction of software architecture.

According to the standard, a common language should be established during software design and evaluation, in which different program concerns can be expressed, negotiated, and resolved (e.g., creating a program-tailored DOD architecture framework or unified modeling language). The absence of such a language causes difficulties in sharing the program's design philosophy among the stakeholders and development team, which guides the day-to-day development decisions that influence the quality and utility of the final software product. An established communication medium facilitates regular software architecture evaluations, which ensure that evolving program and stakeholder needs continue to be satisfied. Such evaluations provide ongoing insight into the potential impact of new or changed requirements and design constraints.

Evalica: Supporting Software Evaluation Logistics

Supporting the logistics of a software architecture evaluation can be cumbersome and error-prone, especially as the depth of the evaluation and the number of participants grows. The Aerospace software architecture evaluation framework consists of more than one thousand questions that could be part of an evaluation. The software evaluation team must tailor the evaluation questions, assign questions to individual evaluators, capture the answers to those questions, and roll up the results for presentations to stakeholders. While these tasks can be done with ordinary office software (e.g., word processors, spreadsheets) and a shared document repository, these tools have little or no support for common evaluation tasks, such as tracking the evaluation's status, integrating responses from multiple evaluators, and modifying questions after the evaluation has begun.

To make supporting the logistics of a framework-based software architecture evaluation easier, Aerospace developed a tool called Evalica™. Evalica is a Web-based database-driven tool that provides a shared, collaborative space where evaluators and other stakeholders can work through the lifecycle of a software evaluation. It supports the following three common evaluation activities:

Tailoring. All software evaluation questions are loaded into the Evalica database. From there, the questions can be answered as-is, modified, or reorganized in Evalica. Questions can be annotated with metadata—guidance to evaluators indicating what to look for when answering questions or how to interpret questions in different circumstances. Questions can also be annotated with user-defined tags that can later be used in search queries, allowing users to more easily select subsets from the full question database. In addition, while collaborative tailoring can be done in Evalica, questions can be exported to and edited in Microsoft Excel or other spreadsheet software, and reimported into Evalica for users who prefer the spreadsheet interface.

Capturing Responses. Once a framework of questions is set up, questions are assigned to evaluators. The same question can be assigned to multiple evaluators if multiple responses (perhaps from different perspectives) are desired. Evaluators log into Evalica and respond to the questions as they perform their evaluations. Responses can include answers to the questions, what evidence was examined to reach the answers, and qualitative and quantitative assessments of the software architecture based on the answers. For users who want to work offline, response forms can be generated and filled out in Microsoft Word or other word-processing software, and reimported into Evalica. Evaluators can track their own progress, and software evaluation administrators can track each evaluator's progress or the evaluation as a whole through reporting screens.

Rolling Up Results. The answers to detailed questions about the software architecture are an intermediate, not final, product of an evaluation. Evalica allows users to create roll-up items such as conclusions, recommendations, and deficiencies, and link them back to the responses that prompted them. Users can export such findings directly into Microsoft PowerPoint.

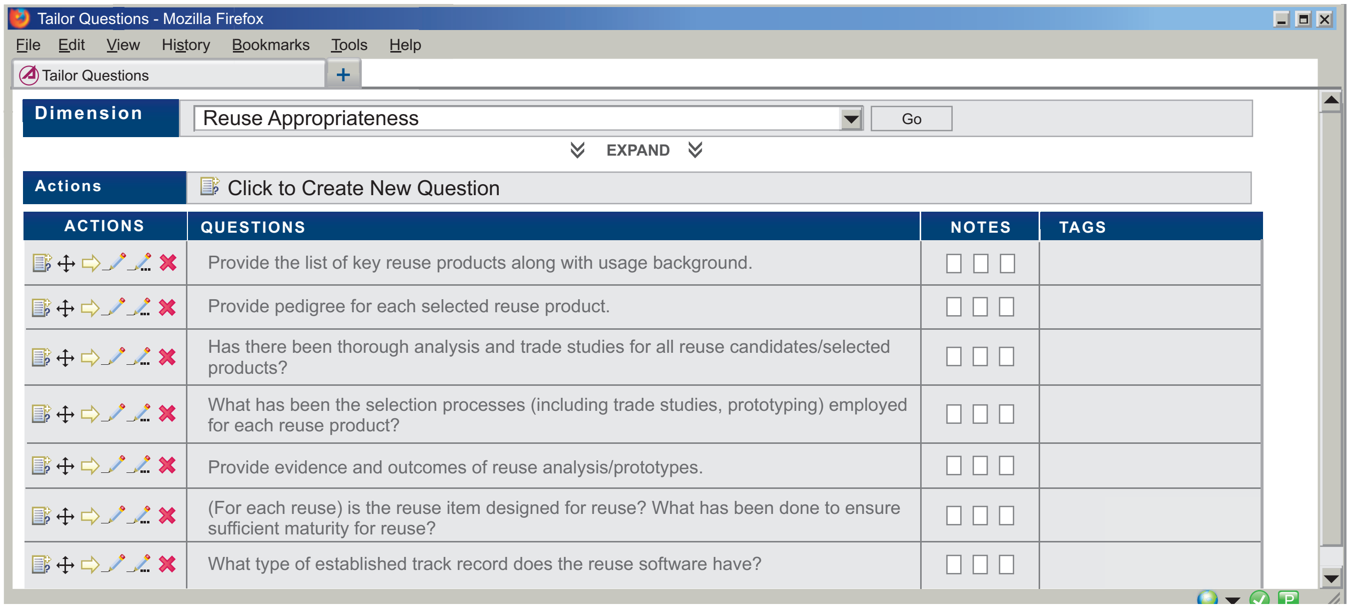
Evalica cannot do the hard work of a software evaluation: identifying what questions to ask and answering them. That work requires experienced evaluators and subject matter experts. However, Evalica can reduce the burden of supporting the coordination among all the evaluators and experts, freeing them up to focus on the software evaluation. Evalica has been used internally at Aerospace to support evaluations and has served as the primary mechanism through which the software architecture evaluation framework questions are managed. Beyond software architecture, Evalica can also be used to support the logistics of other question-and-answer-based evaluations. By loading the Evalica database with a different set of questions, Evalica can support various kinds of evaluations.

Software Architecture Evaluations

The key factors contributing to software cost and schedule overruns are incomplete mapping and not fully understanding the software system requirements and system design attributes. Conducting early and regular software architecture evaluations ensures that early in a program lifecycle, the software system design is addressing all of the operational requirements and stakeholder needs. It also provides an early reality check of the program plans. Throughout the entire development lifecycle, understanding the software architecture provides a methodical approach for facilitating interactions among the structural and behavioral elements, enabling replacement of individual elements without breakage, and withstanding attacks on or failures of the system with minimal impact to ongoing operational activities.

Software assurance is the practice of focusing on enabling software that is created using methods that support good quality from the start, rather than testing for and implementing quality after the fact. Paying attention to compliance and quality assurance early in the software development lifecycle is important. Conducting software architecture evaluations is the best way to ensure that the software system scope is adequately and correctly defined at the front end, so as to avoid wasting software development efforts later in the process.

Software architecture evaluations that focus on thorough requirements analysis and design, early verification and validation, and up-front prototyping and simulation can avoid costly fixes downstream. Such software architectural practices can reduce cost escalations for large critical software systems.



Evalica's question response editor. Responses can include rich text and hyperlinks. By developing a framework for evaluating software architectures designed for national security space systems, areas that demand attention can be identified, understood, and rectified earlier in a systems development lifecycle.

Software architecture evaluations also assess the faithful derivation of the architecture and design from the software system's requirements and constraints. The software architecture must provide for, or at least not preclude, any of the functional capabilities defined in the software system's specifications, including capabilities that are anticipated for the future. Since the software architecture contains the blueprints for lower levels of design and implementation, it should describe all the software's requirements, functional capabilities, internal and external interfaces, significant algorithms, and usage constraints.

However, not all the software system's requirements must be determined before architectural design. In iterative software development lifecycles in which at any point some of the requirements definitions have not been fully addressed, the level of design detail only needs to be specified as is appropriate for those requirements. As software system uncertainties are removed through prototyping, analysis of available options, and other methods, the software architecture should evolve accordingly in scope and specificity. In this methodology, software architecture evaluations take into account the appropriate level of detail and the evolvable nature of the architecture.

Evaluation Methods

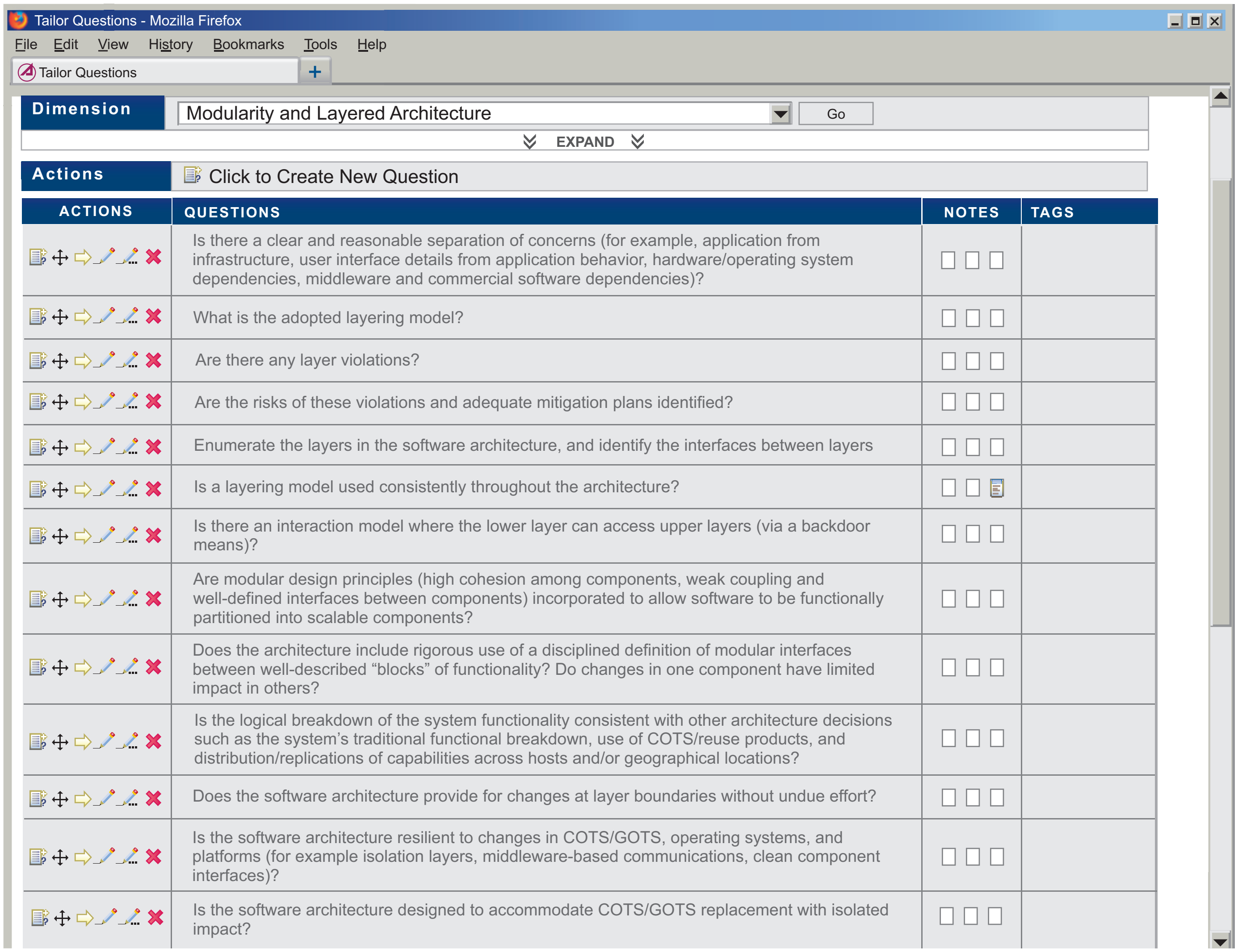
Software developers use a variety of methods to evaluate software architectures. One widely used technique is the Architectural Tradeoff Analysis Method (ATAM) that was developed by the Software Engineering Institute at Carnegie Mellon University (Pittsburgh). This method assesses the consequences of software architectural decisions as they relate to quality attribute requirements and business goals. The method provides a set of steps that help stakeholders ask appropriate questions to discover potentially problematic software architectural areas and use scenario-based assessments early in a software development program to address quality attributes (e.g., modifiability, performance, and availability). It is aimed at raising awareness of critical issues, localizing and analyzing trade-offs, and focusing on the highest risk areas.

ATAM and similar methods focus primarily on the process of doing software architecture evaluations and are not targeted to specific software applications. While complementary to ATAM, Aerospace has its own software architecture evaluation framework designed for space system development. It provides a set of questions and evaluation guidance that is tailored to national security space systems software.

The Aerospace Software Architecture Evaluation Framework

The Aerospace Corporation's software architecture evaluation framework questions are grouped into these top-level categories: architecture fundamentals, architecture documentation, architectural functionality and quality attributes, and architecture development and evolution methodology. Each category is then broken into dimensions that represent areas of concern and evaluation criteria. The dimensions include conventional software quality attributes (e.g., scalability and availability) and concerns specific to national security space programs such as reprogrammability, resilience to cyber attack, and appropriateness of commercial and government off-the-shelf products.

The framework questions are written to evaluate national security space systems software and are defined by three levels. Level one questions are nondomain specific and are applicable to most software systems. They provide a basis



Evalica's modularity and layered architecture dimension. Software architecture refers to a simplified representation or model of a software system's organization, including the structural elements and interfaces that constitute the system, as well as its behavior and composition, and the architectural style guiding the organization.

for discussions between subject matter experts and software experts to refine the generic questions into level two questions that pertain to national security space domains (e.g., command and control, mission planning). Based on the requirements of the software system being evaluated, the evaluation team can then tailor the level one and level two questions into national security space system-specific (level three) questions.

Space system software developers can support the front-end evaluation of software for such systems in a number of ways. One way is by interpreting the criteria for various national security space systems. For example, software developers might determine the scalability of a ground system and its capability to support a variety of different types of space vehicles. (This type of work differs from determining the scalability of an information technology system.)

Software developers can also work to improve the program evaluation of current and next-generation software systems by harnessing decades of Aerospace engineering and scientific experience in building national security space systems, along with the software development expertise that is built into the software architecture evaluation framework. Aerospace's evaluation framework development team consists of several software architects and engineers with many decades of experience in building or overseeing national security space systems.

The software architecture evaluation framework can be used at different phases or milestones throughout a program's lifecycle. The manner in which the evaluation framework is applied and the benefits gained from it will vary depending on the particular phase or milestone. For example, during the early project and presystems acquisition phase, software architecture design questions about the framework help to determine potential constraints on software system concepts. Asking the right questions up front ultimately serves as the foundation for the creation of system-level requirements.

The Aerospace software evaluation framework offers capabilities that enable full evaluations of complete and existing operational software systems. The framework can also be tailored to address the specific level of software architectural design detail that is commonly expected at a particular review milestone (e.g., system, preliminary, and/or critical design review). Using the software architecture evaluation framework at a preliminary design review milestone is invaluable in providing a detailed picture of the contractor's architectural design and allows for supplemental input into the formal review process.

Applying the Aerospace Evaluation Framework

Several national security space programs have implemented the Aerospace software architecture evaluation framework since its inception in 2010. For example, a ground system's software architecture that is currently under development was evaluated using the framework as part of the preliminary design review. The Aerospace framework more thoroughly examined the risks and opportunities that an earlier ATAM-based evaluation of the software system had identified. While determining the scope of the Aerospace evaluation, the ATAM-identified risks were used to select the evaluation criteria. This program illustrated the complementary nature of the Aerospace framework with general, scenario-based evaluation methods such as ATAM.

In another program evaluation, the Aerospace framework analyzed performance issues on a software system for a national security space system. The framework's methodical analysis of the software system was instrumental in identifying the sources of the performance issues, which would not have been possible using any ad hoc software design technique.

The Aerospace framework has also been used to identify potential software architecture and design areas that needed evaluation during the source selection process.

These examples have helped Aerospace software evaluation development teams validate the utility of the Aerospace software architecture evaluation framework for various software architecture and design evaluation purposes. The work has also enhanced the overall framework by adding previous lessons learned to the database.

Software architecture evaluations have not historically been recognized as useful tools for effective technical oversight of programs. That has changed, and today Aerospace has developed relevant guidance and specific language for drafting requests for proposals and subsequent contracts. Part of this guidance is the recommendation that Aerospace's customers should include software architecture evaluations as part of the front-end development process.

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About the Author

Alan Unell, Senior Project Leader, Software Engineering Subdivision, joined Aerospace in 2008 and led the team that developed the software architecture evaluation framework. His 30 years in the aerospace industry include experience at Hughes Aircraft/Raytheon as a programmer, program manager, chief engineer, and mission assurance director. He has a Ph.D. in mathematics from Northwestern University.

Simplified Spacecraft Design Tools For Evaluating Architecture Concepts

As space system architecture capabilities mature, the tools used to analyze them must be modified and enhanced. The Aerospace Corporation is placing an increasing emphasis on its corporate architecture and systems-of-systems capabilities, which supports its customers in the analysis of options as they decide how best to spend their limited resources.

Current corporate tools include the decision support framework and the concurrent program definition environment. The Air Force Space and Missile Systems Center's (SMC) cross-enterprise architecting tool is another method used in the analysis of options. These tools support activities such as the current spaced-based environmental monitoring assessment of alternatives, and the NavSat study (a satellite navigation system demonstration) for the SMC commander.

A research effort is under way at Aerospace to address updating, completing, and expanding some of these existing tools, as well as developing new ones. Investigating or generating spacecraft concepts inevitably becomes part of the architecture analysis process, and the tools that support these activities also need updating. Spacecraft concepts and designs are developed to gather a basic understanding of the required capabilities (i.e., size, weight, and power) for the mission. While Aerospace's Modular Concurrent Engineering Methodology (ModCEM) (system-level fidelity) and the Concept Design Center's (subsystem-level fidelity) capabilities are well-suited to generating tens of discrete point designs within a few hours to a few days, neither is conducive to rapid exploration of vast trade spaces (perhaps hundreds of thousands of point designs).

The team updating and creating these architecture analysis and spacecraft design tools includes Richard Gong, systems director, Developmental Planning and Projects, along with coinvestigators Joseph Aguilar, O'brian Rossi, and Dan Judnick, Vehicle Concept Department; Daniel Nigg, Concept Design Center Office; and John Evans, Space Architecture Department.

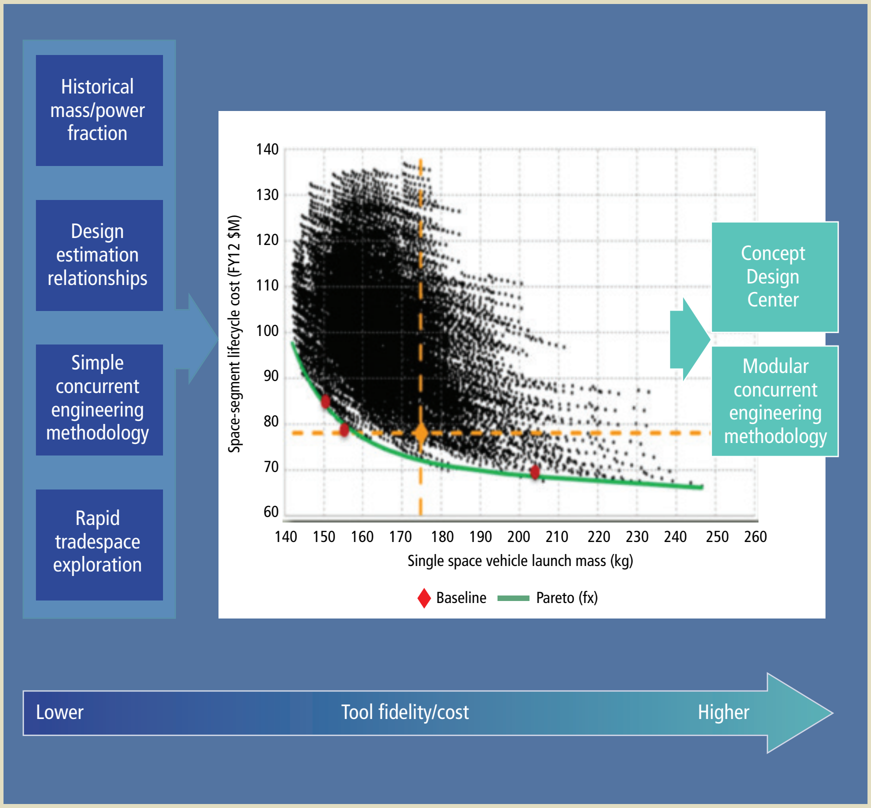
Four existing corporate tools are being upgraded and enhanced: historical mass/power fractions (HMPF), design estimation relationship (DER), simplified concurrent engineering methodology (CEM), and rapid tradespace exploration (RTE). These spacecraft design tools each employ a different approach to generating data. "These domains often have large uncertainties associated with them, making high-fidelity modeling fruitless. With these tools, thousands of spacecraft designs can be quickly created, making efficient exploration of large solutions spaces possible," Gong said.

HMPF generates mass and power fractions from Aerospace's small satellite database by retrieving historical information on design life, orbit, stabilization type, and propulsion systems. The size of the supporting spacecraft bus can be determined using historical data about a particular payload's mass and power. "The usefulness of this tool lies in its ability to calculate mass and power fractions based on satellites in the database. For example, a three-year, low Earth orbit mission will use only 44 of the 139 spacecraft available in the database to calculate the mass and power of the supporting spacecraft bus because those are the only spacecraft with attributes that are applicable to the mission," said Rossi. The tool allows engineers to easily compare newly proposed space vehicle designs to those that have historically worked for similar payloads. Having such a reference allows engineers to better identify high-risk subsystems too. This is particularly relevant for conceptual designs where subsystems such as structures, thermal, and harness masses are often estimated and therefore susceptible to miscalculation.

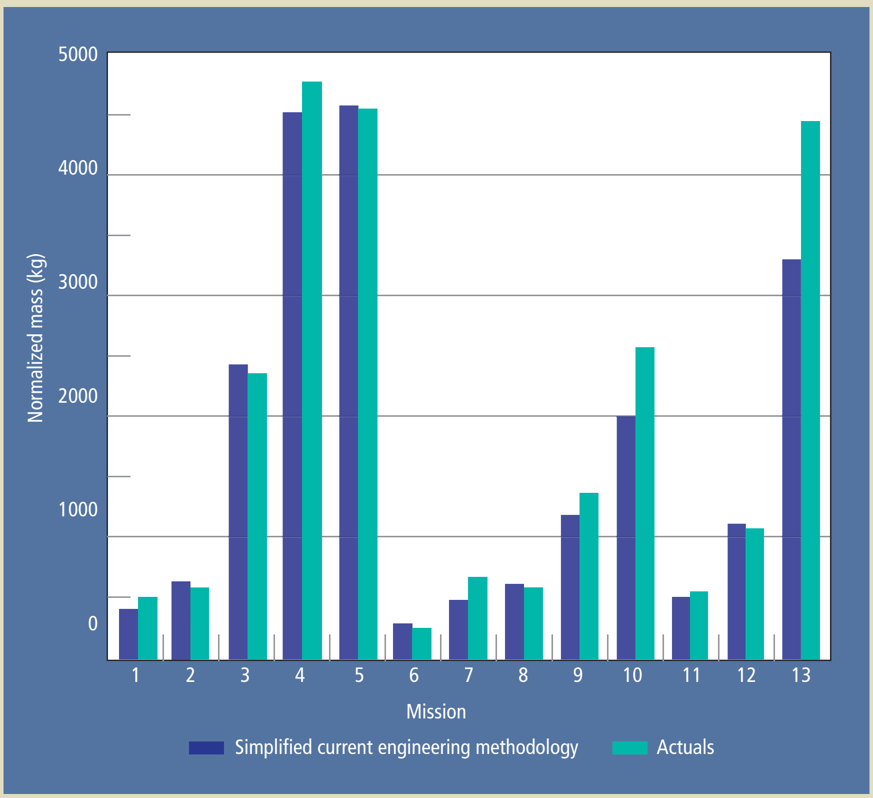
The DER tool creates spacecraft mass and power using estimation relationships. It generates information similar to what is calculated by the cost-estimation relationships used in costing, but is based on design parameters such as design life, data rate, and pointing knowledge stored in Aerospace's small satellite database. "Significant effort was devoted to developing unique mass and power design estimation relationships for each subsystem and the total spacecraft. As with the HMPF tool, this tool helps to identify out-of-family subsystems for further study and review," Rossi said.

The CEM tool is derived from the ModCEM tool and requires 23 high-level inputs such as payload mass, design life, and orbit. The tool was compared to 13 different satellites as it was updated. Judnick, a senior member of the technical staff, said that good agreement (error under 26 percent) was achieved between actual missions and the simplified CEM tool. "It is interesting to note that while the subsystem masses may vary widely, the overall space vehicle mass matches rather well," he said. The tool has been used to support a number of national security space programs. It is increasingly used in areas that do not require the level of fidelity of the ModCEM tool, or for those conducted by the Concept Design Center, but do require more fidelity than the HMPF or DER tools.

The RTE tool is used to quickly create zeroth-order (coarse approximation) spacecraft designs and has produced suitable results comparable to other more complex capabilities. "The tool is flexible enough to accommodate a variety of mission types in numerous operational orbit regimes with some attention to coarse and fine interaction between subsystem sizing algorithms," Nigg said. "All candidate point



The simplified spacecraft design suite applied to architecture development and tradespace exploration. The tool helps to identify thousands of spacecraft concepts to explore. Typically, engineers select a limited number of concepts along the pareto frontier (green line) for further refinement using high-fidelity tools like the Concept Design Center and the modular concurrent engineering methodology.



A comparison of results between the simplified concurrent engineering methodology and actual programs, including those for the Air Force, NASA, and Earth-orbiting commercial use.

designs presented are capable of meeting their respective mission requirements; trades are made only with respect to the application of technology development in each spacecraft subsystem and result in numerous aggregate system solutions," he said.

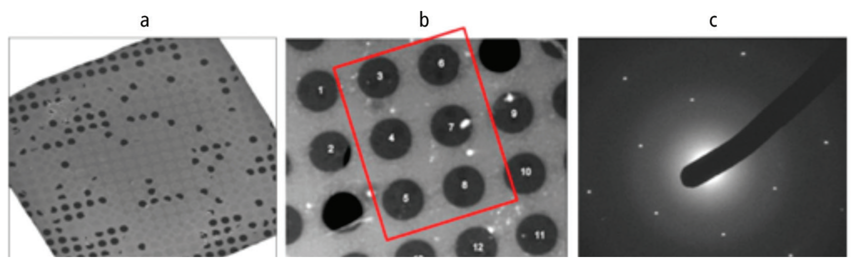
"Ultimately, the goal is to offer engineering tools that allow the exploration of a wide variety of alternatives leading to better, more capable architectures at a reduced cost," Gong said. Being able to quickly generate first-order spacecraft designs based on limited mission and payload information can help to better focus time and resources on those designs that warrant further examination. "For example, thousands of potential solutions were created in RTE in a few minutes and mapped against lifecycle costs during one recent study," Nigg said.

"The tools we are developing provide a means to generate efficiently and quickly thousands of spacecraft designs, helping engineers eliminate alternatives that do not meet a particular set of criteria, such as low cost or high agility," Gong said. "Further refinement using the CDC or the Mod-CEM can then be used to focus on fewer alternatives, saving resources and allowing a deeper exploration of those culled alternatives," he said.

This independent research and development work attempts to identify areas within these tradespaces where rigorous, high-fidelity modeling activities should be investigated to determine optimal solutions. Trend information based on subsystem technology and mass-cost relationships, which determine system-level impacts, can also be developed for any modeled space mission with these tools. Studying these trends helps to identify opportunities to lower development costs and launch mass, and offers information on how to increase design life or optimize any combination of these characteristics.

Graphene Growth, Characterization, and Applications

Considered the building block for graphite, graphene is a single layer of carbon atoms and consists of a two-dimensional, hexagonal lattice of sp^2-bonded carbon. In addition to its one-atom thickness, graphene's unique properties are extraordinary electron mobility, high electrical current carrying capacity, high thermal conductivity, high optical transparency, mechanical strength, and large specific surface area. Based on such properties, applications for graphene include electronic and photonic devices, solar cells, and energy storage devices.

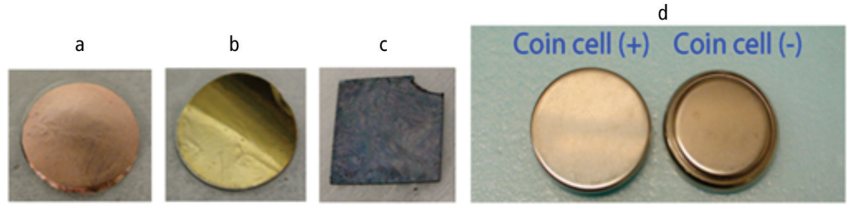


A low-magnification scanning electron microscopy image taken in the transmission electron microscope (TEM) showed areas of graphene coverage up to 60 percent in individual TEM grid squares (a). Selected area electron diffraction patterns were recorded from graphene on individual TEM grid holes shown in (b). A hexagonal spot pattern shown in (c) is due to the hexagonal carbon lattice in graphene. Areas over which the spot pattern was identical and nonrotated were mapped out and found to be 10–30 μm^2.

These diverse applications are driving the need for large, high-quality graphene films. The need to produce large areas of graphene as well as large single-crystal grains of graphene has propelled the development of new deposition techniques. Various methods for graphene growth have been established, such as annealing silicon carbide, reduction of graphene oxide, and growth on metal substrates using ethylene and methane with hydrogen as gas-phase precursors.

Gouri Radhakrishnan, senior scientist, Materials Science Department, is the principal investigator of an independent research and development project at The Aerospace Corporation. The goals are to develop novel and scalable techniques for the growth of single-layer graphene and the full characterization of the material. In addition, there is an interest in understanding the electrochemical performance of graphene to examine its potential application as an anode for lithium ion batteries. The research team includes coinvestigators Paul Adams, Materials Science Department, and Joanna Cardema, Electronics and Photonics Laboratory. Collaborators include Brendan Foran, Hyun Kim, Heinrich Muller, Andrew Stapleton, Miles Brodie, Michael Meshishnek, Martin Ciofalo, and Matthew Mecklenburg.

A novel process for the growth of monolayer graphene has been developed at Aerospace, in which methanol is decomposed on copper at 1050°C in a flow of pure argon gas. This method offers an alternate synthesis route for making high-quality graphene without using hydrogen as a process gas. Eliminating hydrogen as a process gas offers increased safety and facilitates fabrication scaling. This method produces monolayer graphene films with large, single-crystal areas that are 10–30 square microns. "While our process is typically carried out using copper as the underlying substrate for depositing the graphene, we have also developed a process for growing multilayer graphene at the same temperature on other substrates," Radhakrishnan said. Aerospace was recently awarded a patent on this subject by the USPTO.



Optical images of anodes: single layer graphene on Cu (a), multilayer graphene on Ni (b), and highly oriented pyrolitic graphite (c). Shown in (d) is a coin cell.

One of the challenges involved in graphene growth is applying sophisticated diagnostic tools in-house to confirm that single-layer graphene has actually been produced. An established diagnostic is Raman spectroscopy, a nondestructive technique that measures laser light scattered by phonon modes in a material. Graphene has a very characteristic Raman spectrum that allows a clear distinction between a single layer, two-to-three layers, and multiple layers of graphene, which would comprise bulk graphite. "We were able to identify the growth of single-layer graphene from the specific peaks in the Raman spectrum of our graphene films as well as the ratio of peak intensities," Radhakrishnan said.

In addition to establishing that a single layer of graphene has been deposited, it is important to determine the grain structure of graphene. To investigate graphene's grain structure, the Aerospace research team used transmission electron microscopy (TEM) to examine very thin electron transparent samples. The team carefully transferred the single layer of graphene from the copper substrate to a special grid (typically three millimeters in diameter) that comprised an extremely thin amorphous carbon membrane. This allows high-energy electrons to be transmitted through the graphene film placed on the grid membrane. The transmitted electrons create an image on a viewing screen or detector, and provide signatures representing the crystal structure of graphene with very high spatial resolution.

To study the graphene film's crystalline grain structure, the research team obtained selected area electron diffraction (SAED) patterns, which are an array of hexagonal spots that reflect the graphene sample's internal crystal structure. The simple hexagonal spot pattern is due to the hexagonal carbon lattice from a single crystal of graphene. Changes in the graphene lattice's orientation cause rotations in the hexagonal SAED pattern, and multiple grains of graphene produce multiple hexagonal SAED patterns. The areas with identical diffraction patterns were determined by measuring the SAED patterns across all the grid hole locations covered by graphene. The areas in which the spot pattern was identical and nonrotated indicate a single crystal of graphene.

A specific area of research currently being pursued is the application of graphene to lithium ion batteries. Based on its insignificant mass, strong electrical conductivity, and extremely high specific surface area, graphene is a promising candidate for supercapacitor electrodes and an anode material for the uptake of lithium in lithium ion batteries. Compared to the commonly used powder graphite electrodes, graphene electrodes can offer high specific capacity (i.e., capacity per unit mass).

The Aerospace research team compared the electrochemical performance of anodes fabricated from three well-characterized systems with an increasing number of graphene layers. These systems contained single-layer graphene, multilayer graphene with approximately 50 atomic layers of graphene, and well-ordered bulk graphite in the form of highly oriented pyrolytic graphite (HOPG) with a thickness of about 200,000 layers of graphene. For purposes of establishing the electrochemical effects specifically resulting from graphene, the anodes were assembled without the use of a binder. "Not only does a binder-free electrode provide further weight reduction, it also allows us to test the fundamental electrochemical properties of the active graphene layers," Radhakrishnan said. "In addition, we performed extensive pre- and post-cycling characterizations that have provided insights into the electrochemical performance of these three systems, which also offers valuable diagnostics for failure analysis."

The research team has also successfully measured the electrochemical capacity from a single atomic layer of carbon. While the capacity is small, the graphene weight that is needed to obtain a capacity similar to commercial graphite would still be 200 times less. The results provide new insights into the mechanism of lithium uptake in a single graphene layer, which is different from the intercalation of lithium between adjacent layers in multilayer graphene. The results also suggest new designs for improving the capacity and performance of these graphene anodes. In contrast to one graphene layer or a few layers, the electrochemical performance of the thicker HOPG layers becomes diffusion limited, and the lithium ions are not able to access all the graphene layers. Work is ongoing to understand the applications of these very novel nanocarbon material systems.

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Patents

R. P. Patera, "Systems and Methods for Attitude Propagation for a Slewing Angular Rate Vector," U.S. Patent No. 8,185,261, July 2009

The attitude propagation of a vehicle can be determined accurately and easily if the angular rate vector points in a fixed direction with respect to the vehicle. However, most cases of interest involve angular rate vectors that change direction as a function of time. This invention is directed to computer-based systems and methods for propagating attitude for a moveable object (e.g., a space vehicle, a terrain vehicle, or other types of moveable objects). Since the slew rate of the angular rate vector causes attitude propagation error, this invention overcomes this problem by employing an additional coordinate frame that slews with the angular rate vector. In this new intermediate frame, the angular rate vector does not change direction and improves attitude propagation accuracy compared to prior attitude propagation techniques. For pure coning motion, this invention completely eliminates attitude propagation error.

H. G. Muller, H. I. Kim, and B. J. Foran, "Stable Lithium Niobate Waveguides, and Methods of Making and Using Same," U.S. Patent No. 8,189,981, November 2009

Electrooptically active devices have conventionally been prepared using lithium niobate. However, lithium niobate waveguides prepared using conventional proton exchange techniques are vulnerable to performance degradation, limiting their application. The resulting waveguide may also be unstable due to stresses caused by the ion exchange process. This invention provides stable lithium niobate waveguides with improved stability and methods for making and using them. Specifically, the waveguides may be fabricated using a plurality of steps, each of which inhibits the formation of performance-degrading defects. For example, a high-refractive index layer may be prepared using a soft proton exchange on a lithium ion substrate, in which an excess of lithium ions are provided to slow the proton exchange reaction, allowing more time for the protons to diffuse into the substrate and thus reducing defect-inducing stress. Such a proton exchange step may be followed by an annealing step during which a predetermined vapor pressure of water is applied over the substrate. The vapor pressure of water may be selected to inhibit dehydration of the substrate, reducing the formation of defects, and provide a specified stoichiometric ratio of niobium to oxygen in the proton-exchanged layer.

D. S. Kun and N. Morgan, "Constant False Alarm Rate Robust Adaptive Detection Using the Fast Fourier Transform," U.S. Patent No. 8,194,766, May 2009

Many conventional detectors are deficient in that their detection functionality depends on having an accurate estimate of the noise power. For example, some conventional detectors, under certain environments in which the signal-to-noise power ratio can change abruptly (e.g., wireless channels), cannot change their detection threshold without having to restart their numerical algorithm to estimate the noise power. This invention relates generally to signal detection and, in particular, to receivers and techniques that use the fast Fourier transform (FFT) to detect the presence of man-made signals and achieve a constant false alarm rate (CFAR) when only noise is present within a predetermined frequency band. The invention involves signal-detection techniques using FFT that instantaneously react to rapid changes in the signal while achieving a CFAR without resorting to calibration or collection methods to estimate the key statistical parameters of the environment in which the signal resides. The invention employs a decision rule that immediately adjusts to power fluctuations, which overcomes the disadvantage of prior signal-detection techniques of being unable to adapt immediately to abrupt changes in the environment. The invention derives the probability distribution of the decision statistic that results in a detection threshold that is independent of the noise variance, FFT window type, and the statistics of the environment.

R. B. Dybdal, S. J. Curry, F. Lorenzelli, et al., "Systems and Methods for Increasing Communications Bandwidth Using Non-Orthogonal Polarizations," U.S. Patent No. 8,199,851, July 2011

Dual polarization system designs allow two independent signals to be communicated in the same bandwidth, thus doubling the signal throughput. Example applications include direct broadcast satellite TV that allows twice the number of channels to be sent to subscribers. Mutual interference between the independent signals is avoided by design attention to passively and actively maintaining polarization orthogonality. Further increases in communication throughput require communicating independent signals on nonorthogonal polarizations. Mutual interference in this case is avoided by joint signal separation techniques that allow the separation of the independent signals from the composite signals used in their communication. An example embodiment referred to as quadrapol communicates four independent signals using four nonorthogonal polarizations to increase the throughput by a factor of four, compared to the conventional dual polarization designs that double the communication throughput.

S. La Lumondiere and T. Yeoh, "Refraction Assisted Illumination for Imaging," U.S. Patent No. 8,212,215, February 2012

One method of imaging through substrate material is conventional bright field microscopy. While this technique can be relatively inexpensive, the resolution of the resulting images is often disappointing. This invention is directed to systems and methods of imaging subsurface features of objects such as semiconductor devices. An illumination source may be directed toward a surface of an object comprising subsurface features, wherein the illumination from the source is directed at a first angle relative to the normal of the surface. The object may have a portion between the subsurface features and the surface, which has an index of refraction that is greater than the index of refraction of a surrounding medium that surrounds the object. An imaging device may be placed with an objective lens oriented substantially normal to the surface. The first angle may be larger than an acceptance angle of the objective lens.

T. S. Yeoh and N. A. Ives, "Isosurfacial Three-Dimensional Imaging System and Method," U.S. Patent No. 8,217,937, March 2007

Isosurfacial reconstruction methods reconstruct exterior surfaces of objects. However, a limitation of the isosurfacial technique is the lack of information of interior surfaces underneath exterior surfaces and exterior structures. This invention is directed to a three-dimensional isosurfacial imaging system and method for imaging objects that may have obscure interior surfaces hidden from exterior views. The system captures a series of tilt images that are used to reconstruct an isosurface of the object that is a three-dimensional model image. The system then processes the series of tilt images using enhanced tomographic computations. The system can apply a special case in computer-aided tomography that assumes complete transmission or complete absorption in order to compute the density micrograph.

F. Lorenzelli, "Signal Separator," U.S. Patent No. 8,218,692, December 2009

Techniques modifying transmitted signals to aid subsequent separation are the workhorses of modern-day communications, and it is their improvement that has dominated signal separation research and development. This invention relates to a device and process for separating digital signals embedded in a single received signal. The signal separation device and method of the invention include embodiments for separating uncoordinated cochannel signals of comparable power from a single received signal impaired by intersymbol interference, mutual interference, and additive noise. The method comprises the following steps: implementing an initial channel estimator, a blind maximum likelihood symbol detector, and a least-squares channel estimator in one or more digital processors; converting the received signal in an analog-to-digital converter, the sample rate of the converter exceeding the symbol rate by a factor greater than or equal to two; utilizing the initial channel estimator to make an initial set of channel estimates from the converted received signal; producing a data block by decimating the converted received signal; detecting symbols from the data block in a multisignal trellis of the maximum likelihood symbol detector using the most recent channel estimates; utilizing the least-squares channel estimator to make another set of channel estimates from the detected symbols; returning to the detecting step if the channel estimates have not converged; comparing the trellis end survivors' metrics to determine if the detected symbols should be accepted; returning to the first utilizing step and revising the initial channel state information if the detected symbols are not accepted; and accepting the detected symbols and returning to the producing step if data remains.

J. K. Fuller, "Stereolithographic Rocket Motor Manufacturing Method," U.S. Patent No. 8,225,507, February 2008

Hybrid rocket motors use reactants of different physical phase states, usually a solid fuel such as rubber and a gaseous oxidizer such as nitrous oxide. While hybrid motors do not generally deliver the performance of liquid motors, they are safer and simpler to build and operate. Ideally, hybrid motors can have very good performance, but the real-world problems of maintaining an optimal oxidizer-to-fuel ratio and slow-burning fuels have limited their use to niche applications. This invention is directed to a hybrid rocket motor, including a fuel grain, that is created by printing a fuel material using rapid-prototyping techniques. A grain can be manufactured by photopolymerizing the solid fuel in a stereolithography rapid-prototyping type machine. Fuel grains made with rapid-prototyping techniques can be made of almost any shape. These grains can have improved performance by including port shapes and features that promote mixing and increase the amount of burning surface. Many of these port shapes could not be produced with traditional fabrication techniques.

R. P. Welle, "Phase-Change Valve Apparatuses," U.S. Patent No. 8,240,336, April 2010

Developments in miniaturization and large-scale integration in fluidics have led to the concept of creating an entire chemistry or biology laboratory on integrated microfluidic devices. However, producing reliable valves has proven to be problematic with these devices. Thus, there has remained a need for a bistable phase-change valve that can remain in either an open or closed position, and in which there is a very low probability of phase-change material being lost from the valve. This invention relates generally to valves for controlling fluid flow and, in particular, to valves for microfluidic devices. The invention is an electrically actuated bistable valve (e.g., microvalve) that uses a phase-change control fluid to alternately block and unblock the flow of a working fluid through the valve. The control fluid is introduced from a side channel and is pumped into or out of a main flow channel when the control fluid is in a liquid state. The valve apparatus includes the following elements: a substrate, a main flow channel, a control channel, a biphase material within the control channel, a heating element adjacent the control channel and the junction, and a pumping mechanism.

N. A. Ives, C. Suen, M. S. Leung, et al., “Adaptive Membrane Shape Deformation System,” U.S. Patent No. 8,244,066, March 2008

The use of a lightweight antenna system is a desirable goal for space-based communication systems. A system that uses a lightweight polymeric material configured as a large sheet that may be greater than thirty meters in diameter has been proposed as a suitable candidate for such applications. However, there is a need to shape and maintain the sheet to reflect directed signals to act as an antenna. This invention is directed to a method for determining the shape of a flexible membrane and deforming a flexible deployable membrane. The method first captures three-dimensional shape data of a membrane that may be a flexible, deployable, space-based adaptive membrane antenna, and then determines the shape of the membrane. The determined membrane shape is compared to a desired shape and altered by actuation so that the membrane shape is deformed into the desired shape. The method can be applied to a system for maintaining the shape of the membrane to a desired shape. The system and method would include image capturing, image data processing, and activation beams for deforming the membrane shape into the desired shape.

R. P. Welle, “Microfluidic Devices with Separable Actuation and Fluid-Bearing Modules,” U.S. Patent No. 8,245,731, July 2010

A microfluidic device should be fully capable of manipulating multiple fluids, which includes a number of functions such as storage, transport, heating, cooling, and mixing. Although all these functions have been demonstrated with varying degrees of success on microfluidic devices, valves and pumps have typically been complex devices that are difficult to manufacture. Unfortunately, this leads to high fabrication costs, which generally make it impractical to manufacture the devices to be disposable. Thus, a need has existed for a microfluidic device that is capable of performing various manipulations on fluids while also being manufacturable in a manner suitable for the devices to be disposable. This invention is a microfluidic device that is provided by two operatively interfaced modules, namely a fluid-bearing module and an actuator module. The fluid-bearing module incorporates fluid transport and containment elements as well as other elements that may come into contact with fluids. The actuator module incorporates actuation mechanisms for fluid transport and control. The two modules are brought together into contact for use. The modules are detachably secured to each other, thereby allowing the fluid-bearing module to be separated from the actuator module and disposed of. On the other hand, the actuator module is reusable with another fluid-bearing module, eliminating in many instances the possibility of cross-contamination between fluids in the two fluid-bearing modules.

M. J. Lange, “High Power Waveguide Polarizer with Broad Bandwidth and Low Loss, and Methods of Making and Using Same,” U.S. Patent No. 8,248,178, December 2009

Guided-wave polarizer technology converts a circularly polarized wave into a linear-polarized wave while maintaining orthogonality of the two possible senses of each polarized wave. However, prior art polarizers suffer from a number of deficiencies, including low bandwidth, high loss, low power-handling capability, and large size. This invention provides a compact waveguide polarizer that includes a hollow waveguide body and at least one ridge disposed along the interior of the waveguide body. Each ridge includes on its upper surface a plurality of spaced projections (e.g., cylindrical or rectangular posts) or serrations. The ridges and spaced projections together produce a broadband differential phase shift between two orthogonal modes propagating through the waveguide body. Specifically, the spaced projections provide a small capacitive reactance that offsets the inductive loading of the lower portions of the ridges. As a result, a mode propagating parallel to the ridges accumulates a phase delay relative to a mode propagating orthogonal to the ridges that is substantially independent of wavelength over a relatively wide bandwidth. The differential phase delay may easily be tuned by adjusting the length of the projections. The bandwidth of the polarizer may be enhanced by configuring the projections such that they are narrower than the ridges on which they are disposed. Additionally, the polarizers may be inexpensively fabricated, are compact, have no dielectric losses, may accept high power fields, and may be used in a wide variety of environmental conditions.

M. P. Ferringer, R. S. Clifton, and T. G. Thompson, “Systems and Methods for Parallel Processing Optimization for an Evolutionary Algorithm,” U.S. Patent No. 8,255,344, August 2009

The goal of multiple-objective optimization is to maximize or minimize multiple measures of performance simultaneously while maintaining a diverse set of Pareto-optimal solutions. Classical multiple-objective optimization techniques are advantageous if the decision maker has some prior knowledge of the relative importance of each objective. Because classical methods reduce the multiple-objective problem to a single objective, convergence proofs exist assuming traditional techniques are employed. But despite these advantages, real-world problems, such as satellite constellation design optimization, challenge the effectiveness of classical methods. According to this invention, the systems and methods for parallel-processing optimization may include the following: receiving an initial population of parent chromosome data structures; selecting pairs of parent chromosome data structures; applying at least one evolutionary operator to the genes of the selected pairs to generate a plurality of child chromosome data structures;

allocating the generated plurality of child chromosome structures to a plurality of slave processors; receiving objective function values for a portion of the plurality of allocated child chromosome data structures; merging the parent chromosome data structures with the received portion of the child chromosome data structures; and identifying a portion of the merged set of chromosome data structures as an elite set of chromosome data structures.

R. B. Dybdal, F. Lorenzelli, and S. J. Curry, "Methods and Systems for Increased Communication Throughput," U.S. Patent No. 8,259,857, September 2012

Various technical and economic factors have led to a desire to increase communication throughput within a given frequency bandwidth. One approach, for example, utilizes higher-order signal modulation formats such as eight-phase shift keying and quadrature amplitude modulation to obtain greater bandwidth efficiency. Such modulation formats maximize the data transmitted in a given bandwidth, resulting in increased bandwidth efficiency. But one limitation of higher-order modulation is increased stringency on transmitter linearity resulting in transmitter power backoff requirements that reduce signal power for receiver detection and prompt the development of linearizers to allow operation closer to transmitter-saturated output levels. This invention is directed to systems and methods that use signal processing techniques to allow the frequency bandwidth to be shared among two or more independent data streams as a means to increase communication throughput. This invention allows the separation of the independent data streams from a composite signal comprised of the multiple independent data streams negating what would normally be unacceptable levels of cochannel interference or other interference for conventional receiving systems. In this way, multiple signal components may partially or completely share the same frequency bandwidth by applying signal separation techniques to obtain acceptable communication performance for each of the multiple signals. Several applications described in the patent describe potential increases in communication throughput that are achieved by applying signal processing techniques to a composite signal to communicate multiple independent data streams without the constraint imposed by passive design techniques to isolate the individual signal components.

J. Y. Kim, "Systems and Methods for Concurrently Emulating Multiple Channel Impairments," U.S. Patent No. 8,265,921, September 2012

Wireless communications links are sometimes characterized by relatively high bit error rates, large delay-bandwidth products, variable round-trip times, asymmetric channels, and impairments caused by various expected and unexpected events such as weather, fading, blockage, or jamming. In order to test the functionality and performance of next-generation wireless networks, it is important to have the ability to emulate communication applications in real time over communications links with similar characteristics. Thus, there is a need for systems and methods for concurrently emulating multiple channel impairments. This invention describes a multichannel emulator system. The system may include a memory that stores a plurality of channel impairment profiles, where each channel impairment profile corresponds to a respective channel impairment type, a real-time clock that generates timing data, and a processor in communication with the memory and the real time clock. The processor may be configured to: receive a selection of two or more of the plurality of channel impairment profiles; generate a composite impairment profile by combining the selected two or more channel profiles, specifying time-variant impairments, or reflecting a combination of the respective impairment types of the selected channel profiles; and apply the time-variant impairments specified by the composite impairment profile to an input real-time data stream to generate an impaired real-time data stream, where a timing of the application of the time-variant impairments is based at least in part upon the timing data from the real-time clock.

M. T. Presley, "System and Method for Distributing Processing of a Single-Process Application Having First and Second Objects in a Network Having Local and Remote Processes," U.S. Patent No. 8,266,201, September 2012

An object-oriented computer program contains interacting objects that carry out specific program logic. Single process programming techniques assume that all objects reside within the same process hosted on a single computer system. Distributed programming systems, on the other hand, are designed to support objects across multiple processes, usually hosted on separate computers. This invention overcomes the shortcomings of previous systems and methods of adapting single-process legacy systems and distributed applications by modifying object classes during load time. The systems and methods of this invention provide a computer method for distributive processing of an object on a plurality of processes. A computer system and method are provided for making modifications to run-time coding of object-oriented software that enables distributed execution. The method automatically modifies object class definitions as the objects are loaded into the executing process. More particularly, the code modifications cause instances of the classes to interact with a distributed run-time system that allows all objects to be migrated between processes. Because the class definitions are modified at run time, a programmer does not need to add any code for application distribution. Thus, no programmer expertise in distributed systems is necessary, or any a priori knowledge of the program flow.

In Memoriam: Sally K. Ride

THE FIRST AMERICAN WOMAN IN SPACE

"The nation has lost one of its finest leaders, teachers, and explorers."

—Charles Bolden, NASA administrator

Richard K. Park

Sally K. Ride, a member of The Aerospace Corporation's board of trustees for eight years, died in July 2012 at the age of 61. At the time of her death, Ride had endured a 17-month battle with pancreatic cancer.

Ride was best known as the first American woman to fly in space and, at age 32, was the youngest person to travel in space when she flew as an astronaut on the space shuttle Challenger in June 1983 (STS-7). She also flew aboard the Challenger in October 1984 (STS-41). NASA had decided that it needed astronauts with more education in the sciences when Ride was picked as one of only 35 out of 8300 applicants for the astronaut training position. Ride had an extensive science education, having earned a bachelor's degree in physics in 1973 from Stanford University, as well as a master's in 1975 and a doctorate in 1978, both in astrophysics from Stanford. In later years, following the shuttle disasters, Ride was the only person to serve on both of the panels investigating the 1986 Challenger accident and the 2003 shuttle Columbia disaster.

In the presentation "Reach for the Stars," which Ride gave at Aerospace in August 2010, Ride recollected the moment she lifted off into space on her first shuttle mission. "I didn't know whether I was going to be terrified or exhilarated or some combination of those things. I was really surprised by my emotional reaction. When the solid rockets ignited, I was instantly washed over by this incredible feeling of helplessness, because it was so obvious there was nothing I could do to change what was happening. It actually took me a few seconds to fight through that feeling." She had also told reporters after her first shuttle launch, "I'm sure it was the most fun that I'll ever have in my life."

While the public will primarily remember Ride for her participation on the space shuttle flights, her vast accomplishments did not end there. Ride worked at NASA's Washington headquarters, where she wrote "Leadership and America's Future in Space." There, she also founded the Office of Exploration, before resigning in 1987 to work at Stanford University's Center for International Security and Arms Control. In 1989, she became director of the California Space Institute at the Scripps Institution of Oceanography and a professor of physics at UC San Diego.

Ride was elected to The Aerospace Corporation's board of trustees in June 2004 and served on the audit and finance, technical, awards, strategic planning, compensation and personnel, and executive committees. She was the technical committee chair from December 2009 to December 2010.

"As an astronaut, I'm a true believer in the value and importance of mission assurance—the need for an important process; vigilance that the process is well maintained and understood; objectivity, tenacity, and, probably most important of all, integrity about the technical details that you're studying and working on. When I realized that that was what Aerospace stood for, I thought I couldn't be prouder to be a member of any board of trustees or directors in the country," said Ride.

Aerospace President and CEO Wanda Austin, one of Ride's fellow trustees and a member of the technical committee, recalled working with her and the many contributions she made.

"Everyone knows Sally Ride as the first American woman in space and as a technical powerhouse," said Austin. "What made Sally Ride so special was her strength of personality and strength of character. I had an opportunity to see her magic in action when we both served on the Augustine Commission." That commission was also known by its formal title, the Review of United States Human Space Flight Plans Committee.

Later in her life, Ride became passionate about developing and encouraging young people's interests in science. She wrote several books for children, including *Exploring Our Solar System*, *The Mystery of Mars*, and *Voyager*. In 2001, she founded Sally Ride Science, a science education company dedicated to supporting girls' and young women's interests in science, math, and technology. The organization's mission is to bring science to life by strengthening teachers' skills in science and math through training and professional development and by offering real science investigations for students in grades 4–8. Aerospace is a corporate partner of Sally Ride Science and has sponsored several Sally Ride Science festivals. These are held at college campuses throughout the United States and bring together hundreds of young girls for a day of science, hands-on workshops, and guest speakers.

"It is important to give every child the opportunity to succeed and achieve their potential, no matter what that potential might be in. You do not want a 10-year-old to foreclose their options to be a scientist or an engineer because they do not know anything about science; they do not know how cool it is, and they can't see themselves going into that. You want them to keep their options open so that they can achieve their potential," said Ride.

Ride was also a founding member of Change the Equation, a nonprofit, nonpartisan, CEO-led initiative that is mobilizing the business community to improve the quality of science, technology, engineering, and math (STEM) learning in the United States. Aerospace is a member of this coalition, and Wanda Austin was among the first to commit to the initiative when it launched in September 2010.

"My first job was to call CEOs to get them to commit themselves and their companies to this concept and join the initiative. My first call was to Wanda Austin, because I knew that this wasn't going to be a difficult phone call, and that I did not need to convince her about the importance of science and math education both to Aerospace and the nation in general," said Ride.

"Sally was a dedicated, committed role model for the next generation of kids, especially girls. She spent countless hours in her quest to inspire them to study engineering and the sciences," said Austin.

Ride received numerous awards in her lifetime, including twice being awarded the NASA Space Flight Medal. She has been inducted into the National Women's Hall of Fame and the Astronaut Hall of Fame.

Courtesy of NASA

Space shuttle Challenger launches on STS-7 in June 1983 with Ride aboard.

NASA astronaut Sally Ride on her first space shuttle mission.

Courtesy of NASA

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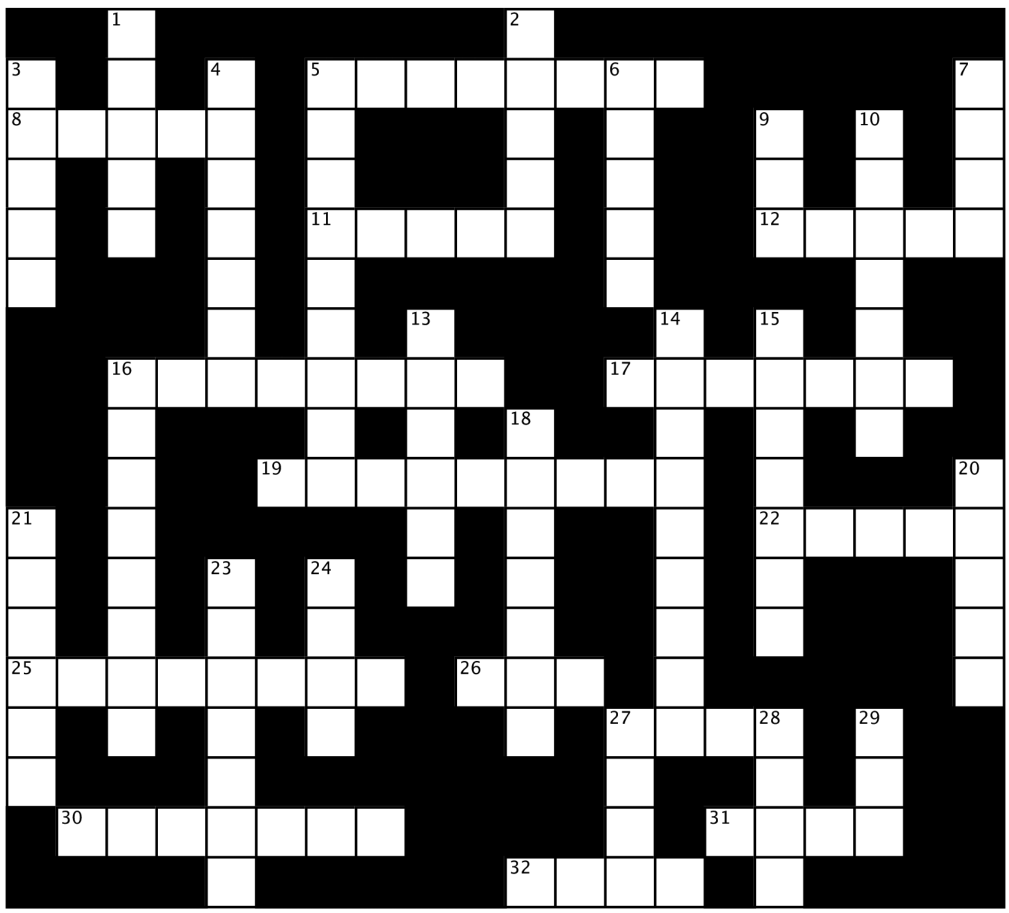

Across

5. Acquire (poison ivy, for example)
8. Baseball team transaction
11. Literary iteration
12. Leave no ______, hiker's credo
16. Screenplay abstract
17. Kind of freak
19. Can spring back
22. Back ______, last week's Time
25. Bent-knee offer
26. One governs gravity
27. It's stored in box, kit, or chest
30. ______ time, undisturbed attention
31. Chicago hood?
32. Type of freeze

Down

1. Linked stores
2. Lead a band
3. Cram, maybe
4. Bar of song
5. One who runs
6. Washer spin time
7. Sleazy joint?
9. Experienced one
10. Wading water depth
13. 20/20 is normal
14. Stock pile
15. Water or power
16. Lens bath
18. How-to picture
20. Profundity
21. What demand requires
23. Someone's outline
24. Jazz or Heat
27. Genealogy template
28. Old Life rival?
29. Flattened Earth

Most puzzle words and clues are from articles in this issue. The solution is on the Crosslink Web site: http://www.aerospace.org/publications/crosslink/.