Engineering the Solutions from Deep Ocean to Deep Space: Keys to 75 Years of Success

Conrad J. Grant

ABSTRACT

During the 75 years since it was established, the Johns Hopkins University Applied Physics Laboratory (APL) has been making critical contributions to the nation's most critical challenges in national security and space exploration, among other key areas. Underlying these innovations are essential ingredients for success: a talented, diverse, and motivated staff that has access to cutting-edge technical facilities and tools; trusted relationships with sponsors and partners; and a systems engineering process that not only embraces the invention of new technology and new ways to use it but ultimately leads to enduring capabilities of great value.

INTRODUCTION

Although much has changed since the Johns Hopkins University Applied Physics Laboratory (APL) was established in 1942 to meet a dire wartime need, much has remained the same. The fundamental ingredients are still evident in the Lab's work and culture today. These ingredients include APL's staff; its investment in facilities and tools; its trusted relationships with partners, especially government sponsors; and its systems engineering approach to solving tough challenges.

DISCIPLINED APPLICATION OF SYSTEMS ENGINEERING

The overarching ingredient in APL's success is its flexible systems engineering approach ranging from agile prototyping to rigorously developed space missions. The engineering performed within APL's mission areas is as diverse as their names would suggest: Air and Missile Defense, Civil Space, Cyber Operations, Homeland Protection, National Health, National Security Analysis, National Security Space, Precision Strike, Research and Exploratory Development, Sea Control, Special Operations, and Strategic Deterrence. In one sense, referring to this work simply as engineering does not do justice to the large number of technical and administrative disciplines within these mission areas.

Much of our traditional approach was first codified by early APL technical leaders like Alexander Kossiakoff,[1] and it has since been adapted to meet the specific requirements dictated by APL's many trusted roles for its government sponsors. In addition to practicing systems engineering throughout the Lab, many APL staff members teach these principles and processes to government, military, and industry leaders through a master of science curriculum in systems engineering offered by the Johns Hopkins University Whiting School of Engineering.

The systems engineering process can be represented as a life cycle loop (see Fig. 1). Two prior *Johns Hopkins APL Technical Digest* issues discuss this loop and describe how it has been applied to a number of different APL programs.[2,3] This representation focuses on the more traditional process for national security systems and does not reflect agile approaches such as for cyber capabilities. Further, it reflects APL's trusted role as a university-affiliated research center for which APL is designated a trusted advisor to government sponsors and does not itself manufacture production articles. (The exception is APL's fabrication of few-of-a-kind systems such as NASA spacecraft.) However, the activities identified in the loop are incorporated in various ways into the agile and NASA process variants. As a DoD university-affiliated research center, APL has various trusted roles with its different sponsors. We have typically used the expression *trusted agent* to refer to the spectrum of such trusted roles.

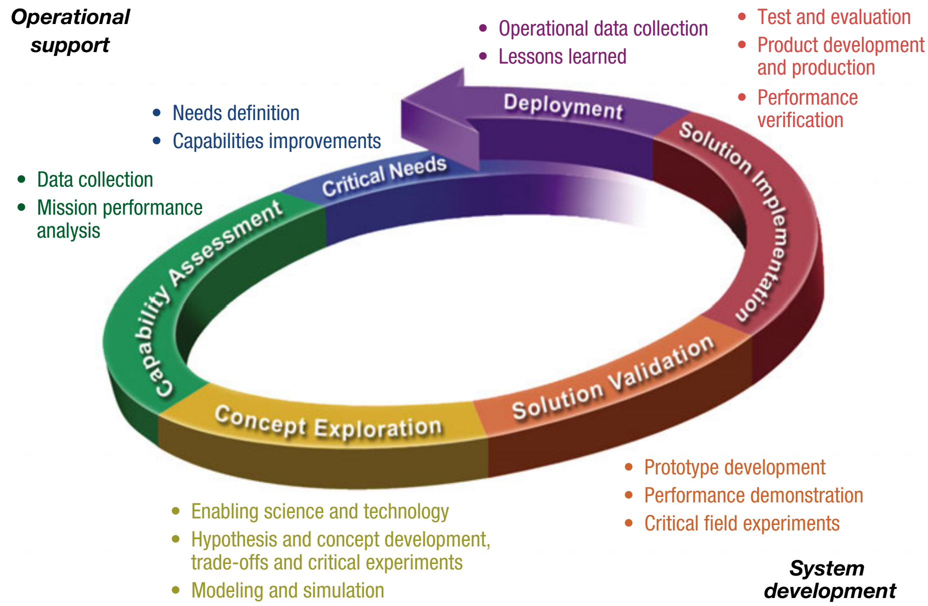

Figure 1. In the various trusted technical roles for its sponsors, APL performs systems engineering activities with government and industry partners throughout the life cycle of a system. APL often leads in defining mission needs; developing and validating requirements; and developing, prototyping, and testing critical technologies and system elements. This process starts with an assessment of the critical needs and continues through the eventual deployment of the system.

The first phase in the loop is an assessment of critical requirements based on deep awareness of the operational need. This assessment frequently involves working hand in hand with the system's eventual users and sometimes includes creation of a design reference mission, a descriptive set of operational situations, to provide APL technologists, operational forces, and the relevant community with an understanding of the mission's operational environment, potential threats, and ultimate measures of success. This first phase in the loop informs the second phase, capability assessment, when the team quantitatively identifies current gaps in performance and explores various ways to meet the need through technology, people, and process change.

This capability assessment phase frequently involves collecting data from current systems in the operational environment, allowing the team to characterize system performance and to develop or update the modeling and simulation that will be used throughout the rest of the life cycle. This activity results in one of the most important steps in the systems engineering process: generation of top-level requirements that delineate the functional performance of the system. For national security systems, APL staff members work closely with the intelligence community to understand threat trends, and then they use engineering modeling and simulation to predict future threat performance. This process ultimately drives the performance requirements for future systems. As a trusted agent, APL helps the government generate requirements that will be used to design and acquire capabilities needed to counter the threat based on data collections, analyses, experiments, and modeling and simulation.

Once the requirements are understood, concept exploration begins, with the team examining potential technology and process changes to meet the operational need. Working in partnership with government and industry, APL staff members often participate in top-level system design. This is the phase in which much of the recognized innovation takes place, capitalizing on the knowledge APL staff members have gained through their years of science and technology research, their knowledge of emerging technology development around the world, and the experience they have gained from working with operators at sea or in the field.

Medium- and high-fidelity modeling and simulation is another critical component of the concept exploration stage. The team must consider trade-offs among potential solutions and realistically predict how new technologies and processes would affect system performance and the outcome of the mission. For the fielded system design to succeed, these trade-off decisions must be based on realistic assumptions, and modeling and simulation reveals these assumptions.

It is not unusual for APL staff members, sometimes working with industry, to prototype select parts or the first article of a system as a means for proof of concept, especially in cases where modeling and simulation alone is not sufficient or where enabling technologies must be matured. The prototypes are tested in laboratories and field test sites or deployed to operational settings as part of the concept exploration or solution validation phases so that the team can verify design trade-offs and performance predictions prior to proceeding to production. The data collected from these tests are also used to validate models, which are then used for more extensive analysis of components or functions that cannot be readily tested in the field.

Prototypes also enable validation of system requirements and a preview of system behavior, allowing the user community to gain experience with the proposed system and to iteratively offer recommendations for system modifications that will help them achieve their mission. Prototypes are invaluable in early development of the user concept of operations, especially for more complex systems or when users will need to change their way of performing an operation to make best use of the new capability.

When proceeding to solution implementation, APL staff members partner with industry to offer insights gained from the previous phases (if the industry partner was not already involved), as well as with the government to evaluate industry proposals for the production system design. As a trusted agent, APL helps bridge the technical gap between government acquisition agents and industry partners. APL's goal is to help both government and industry succeed in producing an enduring capability.

With a system's detailed design and specifications complete, APL staff members typically engage with industry partners in refining production and manufacturing processes to improve the performance, yield, or cost of elements or components. Again, APL staff members' knowledge of emerging technologies and physics, together with their prototyping experience, helps them to create and evaluate production improvements.

When the industry partner has completed one or more production-representative units, APL staff members assist the government in system verification and validation through various forms of test and evaluation. Having contributed to the original concept of operations and top-level requirements, and given their experience working with the prototype in the field, APL staff members are well positioned as trusted agents in testing. In this role, they help design and execute the technical and operational tests, including the scenarios that will need to be executed to prove out the performance of the new system or capability.

The scenarios are based on the expected operational environment and predicted threat, whether natural or human-caused, so APL staff members carefully script them to make sure that the measures of performance embodied in the requirements can be demonstrated. Sometimes the test environment's limitations on scope, cost, or physical risk require that some of the verification be done through modeling and simulation. In this case, it is very important that the scenarios devised for the remaining physical tests provide the needed benchmark data to validate the models that will be used to "push the envelope" past stated requirements for sensitivity analysis and perform the number of iterations necessary to collect statistical data.

An example is in the development of a new missile. The U.S. Navy is able to budget, perhaps, only about a dozen live test flights at the cost of tens of millions of dollars each, because APL staff members use the data from the relatively few live tests to validate models that are then used in hundreds of thousands of simulated flights to prove out reliability and performance predictions.

APL's role in system development does not end with successful test and evaluation of the new capability or system. It comes full circle when the system is deployed to the operational user. APL staff members, building on their involvement with the user community from the very beginning in the definition of the system's requirements and the concept of operations, follow up with the final product. For new or complex capabilities, it is not unusual for APL to provide some form of user education or training, especially when the new capability has significant impact on how operations are performed. At the same time, APL staff members continue to gain insight into system performance and potential updates to improve operations.

The loop does not fully reflect NASA space mission development. As part of a science program, APL itself builds the operational one-of-a-kind mission systems. But there obviously can be no in-field testing prior to deployment, so additional rigorous system-in-the-loop, simulation, and environmental tests are exercised to compensate.

During long-term operation and maintenance of the system, APL staff members periodically review metrics associated with the system's performance and analyze gaps based on the evolution of the mission or the threat. These activities lead to recommended product improvements that should be incorporated into the capability. APL staff members start back through the systems engineering life cycle loop, again partnering with the government and industry to create the next iteration of capability.

APL'S STAFF

Without a doubt, the quality of APL's staff is the number-one ingredient for creating the practical, enduring capabilities APL is known for. Some key characteristics are summarized in this section.

Highly Qualified and Diverse

APL recruits talented professionals from many different technical disciplines and brings them together

Figure 2. Devon Goforth (left) and Brian Melchler work in the Counter Radio Controlled-IED Electronic Warfare (CREW) Lab. APL research contributed to the creation of methods to thwart the use of radio-controlled improvised explosive devices in conflict zones across the world.

in a collaborative environment that encourages cross-disciplinary exploration of potential solutions to unsolved technical challenges. The Laboratory's technical staff balances experienced scientists and engineers who have extensive accomplishments in the domains where the greatest technical challenges exist with new graduates from the nation's top scientific and engineering universities who are at the very forefront of the latest inventions and innovations. There is nothing more powerful for solving difficult problems than assembling a diverse team whose members represent a mix of disciplines and experiences.

Talent was brought together from across disciplines upon the very establishment of APL, which was created with the express purpose of developing the radio proximity fuze. As a more recent example, Lab staff members capitalized on their aptitude and diversity in efforts to defeat improvised explosive devices, when recent graduates with technical degrees in various disciplines and a penchant for hands-on prototyping skills teamed with more experienced staff members to conceive of and prototype potential triggering devices that our adversaries might use to detonate improvised explosive devices remotely. (See Fig. 2.) Incorporating new engineering talent led to some novel and innovative concepts. By postulating the various means by which improvised explosive devices could be triggered with commercially available technology, the team was then able to methodically address how to counter these devices. This is an example of agile systems prototyping.

Motivated and Persistent

The ethos of APL is its focus on the mission. Missions span from the deep ocean (projecting U.S. power under the sea) to deep space (exploring the outer reaches of our solar system) with challenges as varied as cyber operations and health care. This reflects the need for a very broad span of technology expertise. This mission focus attracts staff members who are dedicated to serving the needs of our nation and the world and who demonstrate their dedication by going to extremes to achieve the mission. Many APL staff members have dedicated their careers to contributing to one or more of APL's mission areas. Their dedication to the mission is the dominant motivation for their work.

Along with their mission-oriented motivation, APL staff members are driven to take on unsolved critical challenges within or across the Lab's mission areas. The harder the problem or the more extreme the threat, the more motivated staff members are to find the solution—enduring capabilities that fully satisfy the operational need.

As an example, in 2008, APL staff quickly responded to the potential threat facing our nation, and the world, from an inoperable satellite carrying 1000 pounds of highly toxic hydrazine in an uncontrolled decaying orbit. In a very short period of just weeks, APL staff, with partners from government, industry, and other laboratories, conceived of changes that needed to be made to the operational Aegis Ballistic Missile System and Standard Missile-3 so that they could be employed to intercept the satellite and vaporize the hydrazine tank before it had the chance to reenter the atmosphere and threaten population centers. During this intense period, APL staff and its industry and government partners worked around the clock to model all aspects of the mission, showing that the intercept could be performed successfully, proposing modified algorithms, testing the interceptor's key elements to ensure its performance, and deploying across the country to key sites to execute the mission. If not for their dedication, the mission to successfully intercept the satellite would not have been possible (Fig. 3).

Deeply Aware of Operational Needs

Understanding is gained only through close and persistent interaction with users and observation of how they perform their missions. This knowledge is invaluable in creating systems approaches to improving the user's capability and performance, sometimes by enhancing current operations and other times by creating a whole new way to achieve a given mission.

APL staff members have a rich heritage in working in the field, developing relationships with the user community, and creating a shared understanding of how systems can be engineered to meet the users' needs. With the first versions of the radio proximity fuze complete, five APL staff members became commissioned officers in the U.S. Navy so that they could accompany the highly classified fuzes to the South Pacific and support verification of their performance in the operational

Figure 3. Left, During Operation Burnt Frost, U.S. Navy Petty Officer Second Class Andrew Jackson activates a modified tactical Standard Missile-3 from the Combat Information Center of the Aegis cruiser USS *Lake Erie* (CG 70), on station in the Pacific Ocean on February 20, 2008. The missile struck a nonfunctioning U.S. satellite as it traveled in space at more than 17,000 miles per hour over the Pacific Ocean (U.S. Navy photo). Right, On the bridge of USS *Lake Erie* after the successful intercept of the satellite are Captain Randall M. Hendrickson (now Rear Admiral, retired), commanding officer of USS *Lake Erie*; Rear Admiral Alan B. Hicks (now retired), program director of Aegis Ballistic Missile Defense; and (then) APL Air and Missile Defense Sector Head Conrad Grant, now APL chief engineer.

setting. This direct on-site involvement continues in many of the Lab's subsequent programs, with APL staff traveling around the world to work hand in hand with U.S. service members, helping to create capabilities that translate to immediate operational utility.

The systems engineering of the key elements Cooperative Engagement Capability (CEC), Aegis, and Standard Missile-6 into Naval Integrated Fire Control – Counter Air (NIFC-CA) was achieved through a disciplined process of prototyping, testing, and refining. Its success is attributable to the many years of dedication of the individuals who spent significant amounts of time at sea and in the field.[4]

Deeply Knowledgeable

APL staff members have a current, fundamental, and detailed understanding of the physical, chemical, electrical, biological, and other principles underlying the technical challenges they are working to solve and the capabilities they are attempting to create. This knowledge enables them to explore a wide range of possibilities when considering the trade-offs among different approaches or the application of various emerging technologies in countering a national security threat or creating new scientific theories.

Deep understanding of science is the foundation on which APL staff members innovate and conceive of different ways to solve challenges with the technology available. Combining broad and deep fundamental knowledge with awareness of operational needs leads to an environment in which innovation can flourish.

Such fundamental understanding also enables APL staff members to develop detailed, high-fidelity models of the environment (including security threat) behavior and current and projected system performance; with these models, they can make engineering decisions associated with early proof of principle, prototyping, final design, manufacturing, and ultimately test and evaluation of a complex system design. Creating and fielding a complex system is generally unaffordable without these high-fidelity models to assist in all phases of the engineering development process. These tools allow APL staff members to make a significant number of trade-off assessments before reaching design decisions at each phase of development and to ultimately use predictive analysis to assess the end-to-end performance of a complex system.

High-fidelity predictive analysis with requisite error-estimation models is essential in determining and maintaining the performance of a system like our nation's submarine-launched ballistic missiles.

Familiar with Applicable Emerging Technologies

APL performs a significant amount of applied science and technology research through both internal and sponsor funding. This work explores essential, seminal concepts and technologies for future solutions to our nation's most critical challenges. In addition to its own research, the Lab appreciates the need to remain aware of worldwide science and technology research that might become key to a critical contribution. Maintaining familiarity with the significant number of applicable emerging technologies is a challenge, given the rapidly accelerating pace of worldwide discovery, but APL is committed to keeping abreast of developments.

For example, APL has formed partnerships with the government, industry, and other laboratories to maintain awareness of science and technology research within the community. Several recent initiatives, like the Janney program described by Jerry Krill in this issue, encourage APL staff members to better connect with researchers at universities around the world who are doing fundamental research on the technologies that may be critical to creating the next generation of enduring capabilities for our nation.

SIGNIFICANT INVESTMENT IN TECHNICAL FACILITIES AND TOOLS

APL staff members would not be able to perform their work without the Lab's extensive set of technical facilities, designed by the staff members themselves, where they can perform the research, exploration, experimentation, testing, and analysis associated with the complex problems they are solving. A significant financial investment is required to keep these laboratories and facilities current with the cutting-edge technology and technical tools needed for scientific discovery and the system-of-systems engineering of large-scale, sophisticated capabilities.

Particularly important are the resources needed to perform data analysis, environmental and system-specific modeling and simulation, and test and evaluation analysis. Meeting the great increases in demand for these resources is challenging, and APL has continued to invest in computing resources that support the diverse needs of its staff. APL staff members have also contributed to the design of massively parallel processing and cloud architectures to support the advanced data processing needs of the current and future systems they are creating.

APL has combined sophisticated hardware-in-the-loop capabilities with tailored data processing in unique technical facilities. These facilities enable users to test advanced systems in high-fidelity synthetic environments representing the operational environment in which a system will eventually be used. A number of sophisticated laboratories and facilities support APL's mission areas. In the 1970s, for example, APL built facilities to develop and test the advanced guidance and control needed to enable the Tomahawk missile. In these facilities, APL staff members created and refined the midcourse TERCOM (terrain-contour matching) and terminal-approach DSMAC (Digital Scene Matching Area Correlator) technologies.[5] These innovations were essential to Tomahawk's ability to achieve the targeting accuracies needed for operational uses.

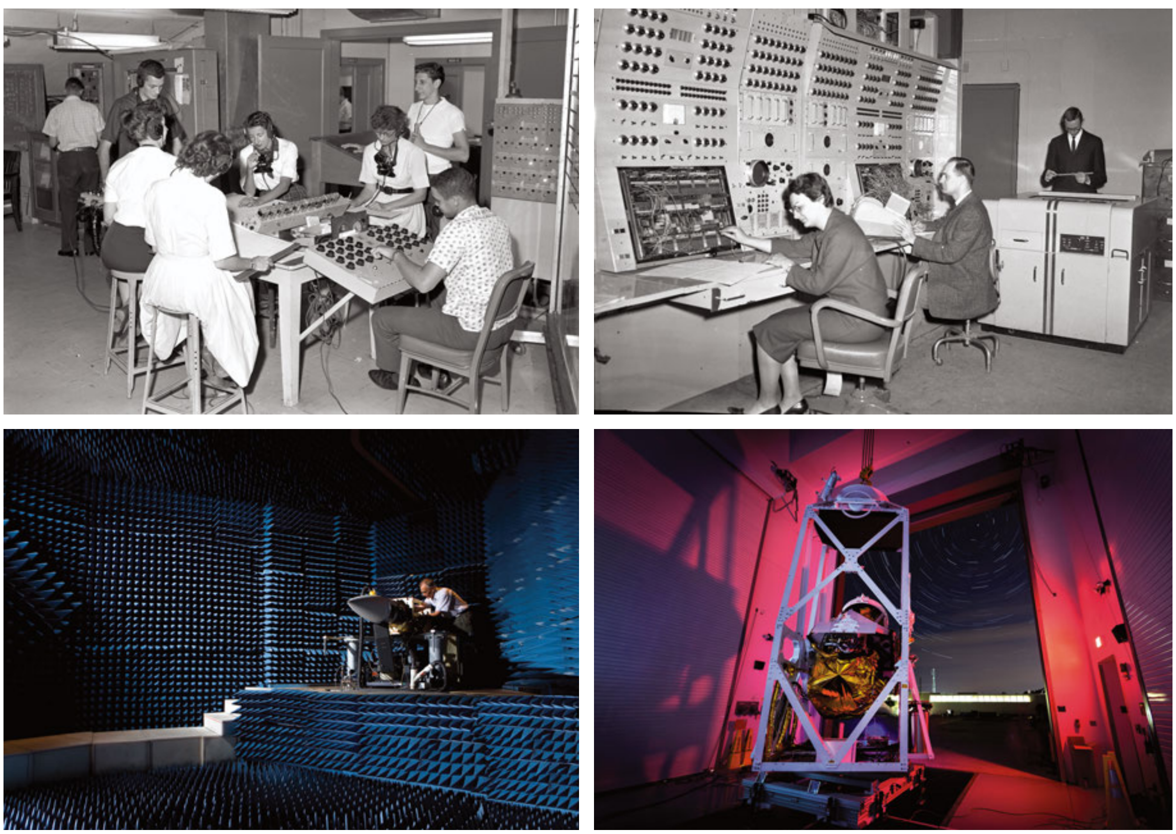

Figure 4. Some of APL's facilities. Top left, The Battle Simulator Facility in the 1960s, an engineering tool to test computer-aided decision-making in combat situations. Top right, An early computing facility. APL acquired a Reeves electronic analog computer in 1948, becoming one of the few institutions outside NASA to do so. Bottom left, APL has two GSEL facilities, one for missile defense and one for air defense. The GSEL facility shown here is for air defense. Bottom right, The APL-built Balloon Observation Platform for Planetary Science (BOPPS) in the APL space integration facility being readied for its mission in 2014.

The Guidance Systems Evaluation Laboratory (GSEL), another major APL facility, currently supports realistic high-fidelity testing of the U.S. Navy Standard Missile-3 kill vehicle seeker and guidance systems. The U.S. Navy uses the Standard Missile-3 to intercept threat ballistic missiles during their exo-atmospheric phase of flight. It is difficult to prove out the combined seeker and guidance system in the kill vehicle without actually flying the missile and kill vehicle in an operational setting. Because this *in situ* testing is expensive, the Navy can conduct it only sparingly. The GSEL uses a vacuum chamber with a complex scene generator to represent the seeker's view in cold space as it searches for the threat reentry vehicle. At the same time, it captures commands from the guidance system and feeds them to a high-fidelity simulation process that is able to alter the scene in near real time, mimicking what would happen in space when the kill vehicle maneuvers. This high-fidelity test environment allows closed-loop evaluation of the seeker and guidance systems' performance.[6]

Similarly, APL's significant space integration and test facilities allow staff members to build and test complete spacecraft or scientific instruments developed for NASA or national security sponsors. These facilities complement those available at other centers, like the nearby Goddard Space Flight Center, and allow APL to develop new space mission capabilities rapidly and inexpensively.

Finally, as APL moves into new technology areas, like additive manufacturing, it has made strategic investments in facilities and equipment to enable its staff to remain on the cutting edge of the development and use of these capabilities.

TRUSTED RELATIONSHIPS

APL's invaluable partnerships are another important contributor to its success. As mentioned throughout this article and issue, APL staff members partner with government, industry, other laboratories, research and technology development centers, and academia to develop and field critical systems to meet various national challenges, including those related to security, space exploration, and, most recently, health care.

With its designated trusted roles from many of the traditional national security sponsors, APL staff members assist the government in establishing requirements for system solutions, evaluating potential technology applications, and working with industry to design and produce these capabilities.

APL staff members also partner with industry, carefully guarding their industry partners' proprietary information while assisting them in successfully meeting government-specified system performance requirements. The relationship is special: APL staff members, as the government's trusted agents, are responsible for helping industry partners achieve success while at the same time independently assessing their products for the government.

CONCLUSION

APL continues to meet emerging critical challenges in national security, space exploration, and other areas. Although the Laboratory faces new challenges and new missions, its fundamental characteristics remain unchanged. These ingredients position APL for success in its current and future missions.

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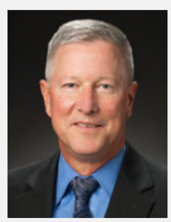

Conrad J. Grant, Chief Engineer, Johns Hopkins University Applied Physics Laboratory, Laurel, MD

Conrad J. Grant is APL's chief engineer. He earned a B.S. in physics from the University of Maryland, College Park, and an M.S. in applied physics and an M.S. in computer science from Johns Hopkins University. He served for over a decade as the head of the APL Air and Missile Defense Sector, where he led 1100 staff members developing advanced air and missile defense systems for the U.S. Navy and the Missile Defense Agency. He has extensive experience in the application of systems engineering to the design, development, test and evaluation, and fielding of complex systems involving multi-sensor integration, command and control, human–machine interfaces, and guidance and control systems. His engineering leadership in APL prototype systems for the Navy is now evidenced by capabilities on board over 100 cruisers, destroyers, and aircraft carriers of the U.S. Navy and its allies. His e-mail address is conrad.grant@jhuapl.edu.