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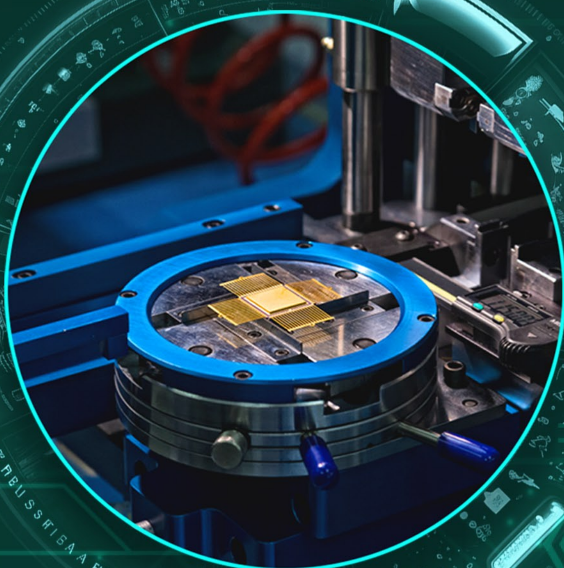
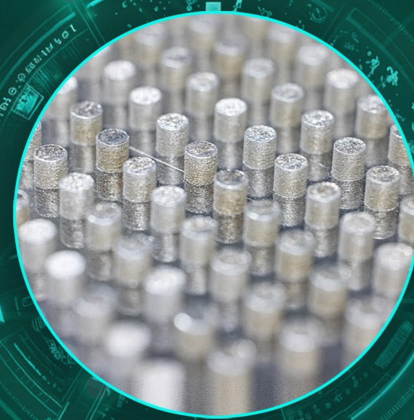
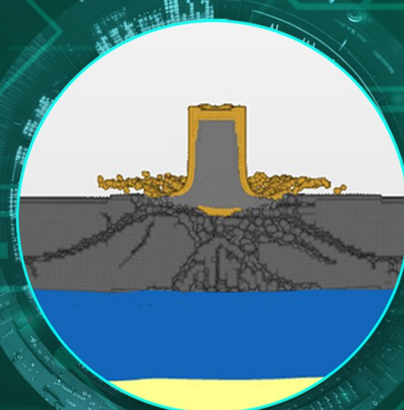
Concept Design and Realization Branch—Part II







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JOHNS HOPKINS
APPLIED PHYSICS LABORATORY

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Concept Design and Realization Branch—Part II: Guest Editors' Introduction

J. Todd Ramsburg and Danielle P. Hilliard

ABSTRACT

The Johns Hopkins University Applied Physics Laboratory (APL) Concept Design and Realization Branch offers an array of engineering, design, and fabrication capabilities that support the Laboratory's mission and broad sponsored work. Until 2023, the Johns Hopkins APL Technical Digest had not published a comprehensive review of the branch's work in more than two decades. During those years, manufacturing technologies and the Lab's capabilities have advanced significantly, as has the complexity of the challenges APL seeks to solve. This issue, the final in a series of two, further highlights APL's contributions in hardware design, mechanical and electrical fabrication, systems integration, and pioneering manufacturing science. This work not only benefits the Laboratory's programs and missions of today but also positions APL to contribute to solving the challenges of the future.

INTRODUCTION

The Concept Design and Realization Branch of APL's Research and Exploratory Development Department (REDD) is an enabling partner for diverse projects throughout the Laboratory. From modeling and analyzing multiscale systems to fabricating one-of-a-kind prototype systems and spacecraft, the branch has long been an essential contributor to APL's success and trusted relationships with its sponsors. The branch's more than 200 staff members, ranging from uniquely skilled machine operators and electronics technicians to multidisciplinary engineers and scientists, are embedded within projects across the Lab to develop innovative solutions to extraordinary challenges, fabricate and integrate complex systems, and lead pioneering research in manufacturing science. This issue, the second of two dedicated to showcasing the work of this branch, further explores many of the tools and technologies that make up this unique set of capabilities. In doing so, it highlights examples of the tremendous breadth and depth of contributions of staff members from across the branch. It is this collection of wide-ranging capabilities, exercised in concert with technical sectors focused on developing game-changing solutions to the nation's most pressing challenges, that enables APL to be a leader among its peers.

THE ARTICLES

This issue begins with "Microelectronics Packaging at APL: Delivering Custom Devices for Critical Missions," in which Rojas et al. survey APL's extensive array of microelectronics fabrication, packaging, and assembly capabilities and their multitude of unique applications. Distinctive from the large-scale worldwide industry supporting modern consumer electronics, APL's equipment- and facility-intensive set of laboratories enables highly specialized, one-of-a-kind tasking for Lab projects. In these laboratories, highly skilled staff members prototype and produce a broad range of devices such as sensors, detectors, and communications and computing hardware for projects supporting research and development, defense, near-Earth and deep-space missions, and medicine.

Next, in "Modeling Nonlinear and Dynamic Mechanical Behavior," Shanaman et al. review the state of the art in modeling and analyzing highly dynamic phenomenon, including impacts, blasts, and crashes. Specifically, this article focuses on techniques for achieving models with greater fidelity to real-world situations. Modern, highly specialized software packages running on very high-performance computing clusters enable greater understanding and more accurate characterization of these highly complex scenarios. Nonetheless, deep understanding of the physical mechanics involved, knowledge of the methodologies by which these tools solve for solutions, and the ability to tailor their use based on specific applications is key to superior results. Several case studies demonstrate how APL's expertise in this area contributes to the safety of our nation's warfighters and diplomatic personnel.

Guided by its role as a university-affiliated research center (UARC), APL must often rapidly develop and prototype novel complex systems. To meet the ever-increasing desire for compressed development (and ultimately fielding) schedules while pushing the boundaries of science and technology, the approaches and tools used to execute this work are also rapidly evolving, as described in two articles in this issue. Sharp et al., in "Rapid Prototyping: Accelerating the Design Process," describe several tool sets and methodologies that provide engineers quicker ways to iteratively modify designs of parts and systems with greater precision and at lower cost than ever before. They present three case studies that demonstrate how success is accelerated during the ideation, design, and integration phases of programs. Discussed in this article and also in "From Drafting Boards to Virtual Reality: The Evolution of Mechanical Engineering and Design" by Crane et al. is the role of augmented/virtual reality and how haptic feedback in demonstrations of systems such as future cockpits increasingly allows valuable capture of the human interaction element within systems, a critical component to their operational success. Also explored are related capabilities for reverse engineering from large-scale data, along with some key advanced capabilities embedded in modern computer-aided design tools for packaging complex electromechanical systems and communicating these designs.

The next few articles focus on realizing complex designs for proof of principle, demonstration, and often as a means of further accelerating iterative development. In "Advanced Development and Fabrication at APL: Machines, Components, and Processes," Walters et al. review several examples that illustrate the power of pairing state-of-the-art equipment with knowledgeable manufacturing personnel who directly interact with engineers, designers, and research scientists. As this article explores, the results are frequently groundbreaking, novel, and, in some cases, literally preserve expensive spacecraft missions.

Next, in "Composite Materials: Enabling APL to Meet Complex Requirements for Critical Systems," Quinn explores the role of composite materials in many systems developed by APL. While composites are a long-established material and construction method used widely throughout the aerospace industry, APL uniquely leverages the tailorable properties of these lightweight materials in rapid prototyping applications where the use of expensive tooling with long lead times is not an option. This article also discusses the challenges of engineering composite structures to withstand the extreme environments encountered by spacecraft exploring the solar system. A highly practical example detailed in the article is the development of composite radome covers for a deep-space antenna system situated in the southwestern United States. The material was chosen for its nonmetallic properties and because its thermal characteristics could be tailored to protect system performance, since the system's physical location meant that the antennas would need to survive environmental damage, including hail strikes. The discussion once again highlights the powerful, interdisciplinary nature of APL's manufacturing teams.

This issue closes with "Perspectives on Engineering Design and Fabrication at APL," a reflective discussion by Dr. James Schatz, the head of REDD. He looks back at the branch's first decade and a few of the successes made possible by the visionary strategy to position the design and fabrication capabilities alongside APL's traditional research and development corps, an organizational move that created REDD more than 10 years ago. Schatz highlights some of the emerging trends in fabrication and briefly discusses APL's contributions, including an educational outreach effort with a local skilled training facility. Throughout, he makes the case that the Concept Design and Realization Branch is well equipped to continue pursuing the department's vision of accelerating transformative innovation and inventing the future for APL.

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Microelectronics Packaging at APL: Delivering Custom Devices for Critical Missions

Vanessa O. Rojas, S. John Lehtonen, Nicholas M. Nowicki, and Khamphone Inboune

ABSTRACT

At the Johns Hopkins University Applied Physics Laboratory (APL), microelectronics packaging includes a wide range of microelectronics fabrication and assembly technologies. Conventional microelectronics packaging integrates electronics on a bare die level. At APL, microelectronics packaging has evolved to include packaging of customized miniature electrical, mechanical, and electromechanical devices. APL's engineers design, fabricate, assemble, inspect, screen, repair, and provide depackaging solutions for diverse projects and sponsors. Because of its technological capabilities and facilities, along with the skill sets of its staff members, APL is able to prototype and produce a broad range of devices, such as sensors, detectors, and communications and computing hardware, for mission-critical projects supporting research and development, defense, near-Earth and deep-space missions, and medicine. This article highlights microelectronics packaging capabilities at APL.

INTRODUCTION

Conventional electronics packaging begins with nanofabrication or microfabrication, where electronic circuits or electromechanical features are fabricated into wafers in the nanometer or micrometer scale. (Refer to the article by Currano et al.[1] for more on nanofabrication at APL.) These wafers are singulated into chips that then get assembled into single-chip or multi-chip microelectronics devices—this chip-level integration is the traditional scope of microelectronics packaging. These devices are then mounted onto boards or systems that get installed into enclosures.

Most devices packaged in APL's microelectronics cleanroom labs are high-reliability monolithic and hybrid microelectronic packages that require compliance with military and industry specifications and standards, such as MIL-PRF-38534,[2] MIL-PRF-38535,[3] MIL-STD-883,[4] NASA standards, IPC J standards, or similar. Consequently, APL teams have developed and established processes to comply with the Lab's quality management system or with industry standards, such as AS9100.[5] Commercial-class single-chip and multi-chip modules with newer substrate types, such as chip-on-laminate, comprise the second largest portion of microelectronic

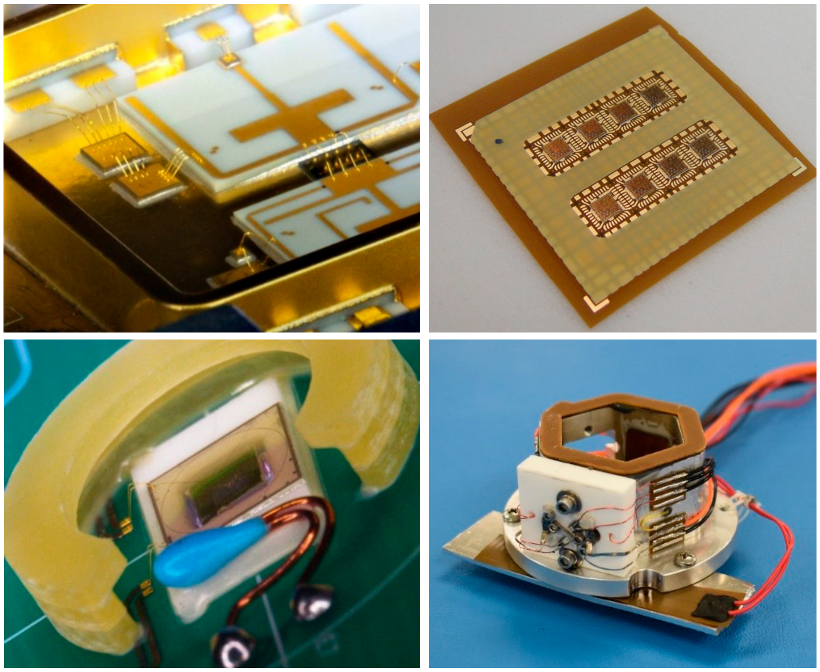

Figure 1. Diverse devices packaged at APL. Top left, a high-reliability hybrid microelectronics package assembled to comply with MIL-STD-883 Class H requirements.[6] Top right, silicon chips epoxy-attached to an eight-up laminate panel, then wire bonded with a 25-μm-diameter gold wire. The wire bonded chips were encapsulated and then singulated onto quad flat no-lead packages (QFNs). Bottom left, a thermistor soldered onto a printed circuit board (PCB). A die was mounted on laser-cut ceramic pieces using an optical adhesive. The stacked FR4 pieces serve as mechanical protection for gold ball wire bonds from die to PCB. This work was supported by the NASA Maturation of Instruments for Solar System Exploration (MatISSE) program under grant agreement 80NSSC17K0599 issued through the Science Mission Directorate. Bottom right, packaging of a miniature electromechanical device.

devices packaged at APL. The rest are a broad spectrum of prototypes and flight builds of custom miniaturized electromechanical hardware. Figure 1 shows a variety of devices packaged at APL.

APL staff members use many processing techniques (Table 1) to package these various kinds of devices in support of critical missions across the Lab. Because APL's microelectronics packaging teams are tasked with delivering highly customized devices, they do not always pursue industry trends geared toward commercial applications. Many of APL's packaging processes and applications are described in more detail in the sections that follow. APL's microelectronics packaging lab distinguishes itself from commercially available alternatives by supporting a very highly customized, low-volume mixture of prototype builds and high-reliability devices that are not designed to be scaled up for mass production—for instance, hardware for one spacecraft designed to crash into a celestial object and another designed to study the surface of Saturn's largest moon.

Table 1. Microelectronics packaging processes at APL

Fundamental Microelectronics Processes	Fabrication and Depackaging Processes
Eutectic die bonding	Decapsulation and depackaging
Thermocompression bonding	Extracted die plating
Epoxy bonding	Lapping and polishing
Wire bonding	Back-side processing
Underfill and encapsulation	Micromilling
Hermetic sealing	Laser cutting
Soldering	Chemical milling
Dicing	

APL'S MICROELECTRONICS PACKAGING FACILITY

Microelectronics packaging processes are performed in environment-controlled ISO Class 7[7] (FED-STD-209E Class 10,000[8]) cleanrooms in APL's microelectronics packaging lab. These rooms have hard-sided walls and high-efficiency particulate air (HEPA) filtration systems to ensure that air cleanliness levels do not exceed 10,000 particles (≥0.5 μm) per cubic foot. All workstations are configured to prevent and control electrostatic discharge.

The cleanrooms are outfitted with essential microelectronics assembly equipment enabling staff members to perform the various microelectronics packaging processes summarized below. An assortment of high-magnification and high-power microscopes are available to support visual inspections in the nanometer and micrometer scale. Wire pull and die shear testers are available to perform MIL-STD-883-compliant destruct and non-destruct tests. In addition, MIL-STD-compliant screening equipment is available in APL cleanrooms for performing fine and gross leak tests, temperature cycling, constant acceleration, particle impact noise detection (PIND) tests, and temperature and humidity tests.

MICROELECTRONICS PACKAGING, FABRICATION, AND DEPACKAGING PROCESSES AT APL

As mentioned, APL teams package a wide variety of devices using many processing techniques. These techniques include fundamental microelectronics processes, such as bonding, underfilling and encapsulation, hermetic sealing, soldering, screening, and dicing. APL staff

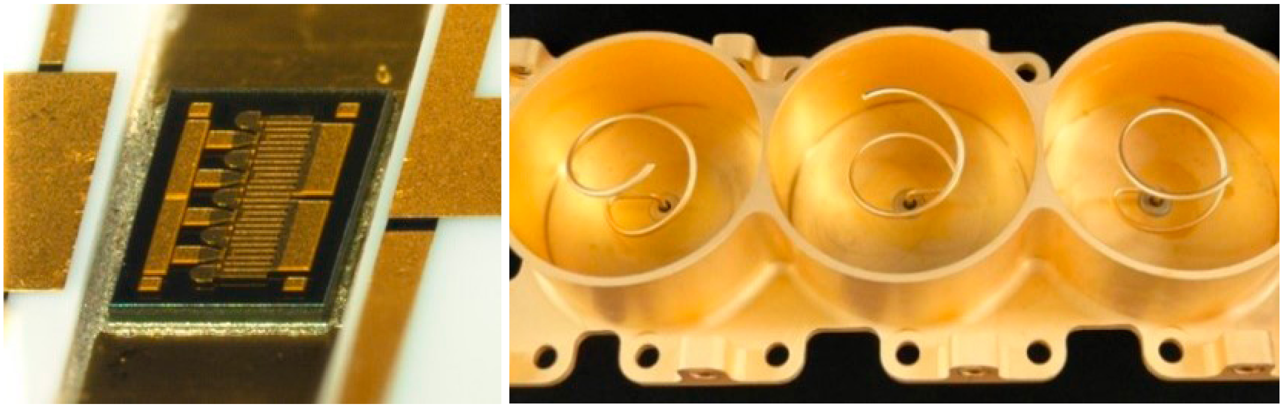

Figure 2. Eutectic die bonding examples. Left, a GaAs die eutectically mounted to a gold-plated copper-molybdenum-copper package using 80Au/20Sn solder preform for the IMAP mission. Right, hermetic feedthroughs eutectically mounted to gold-plated aluminum housing using 80Au/20Sn solder preform for the Europa Clipper fan beam antenna.

members also apply fabrication and depackaging techniques, such as decapsulation, die extraction and plating, lapping and polishing, micromilling, laser cutting, and chemical milling.

Eutectic die bonding using a solder preform, such as gold-tin, is the quintessential die mounting technique for attaching die elements, such as gallium arsenide (GaAs) and gallium nitride (GaN), to high-reliability hybrid microelectronics devices. Gold-tin eutectic solder, such as 80Au/20Sn, melts at 280°C and is typically used with a forming gas instead of flux. This eutectic die bonding technique is not limited to hybrid packages; it can also be used to attach components that require high-reliability seals, such as hermetic feedthroughs. Recent APL applications, shown in Figure 2, include packages for the Interstellar Mapping and Acceleration Probe (IMAP)[9] and Europa Clipper[10,11] missions.

Thermocompression bonding metallurgically bonds two metal surfaces by applying accurately controlled heat and bonding force onto mating components. An example application is thermocompression bonding a bottom termination leadless component onto a silicon chip with gold stud bumps acting as interconnects. The process temperature ranges from 300°C to 350°C for gold-to-gold interconnect.

Epoxy bonding is the most prevalent method of attaching components in microelectronics packages. The epoxy used varies depending on the device's integration requirements. Figure 3 shows an electrically and thermally conductive silver-filled epoxy used to attach a substrate onto a package. A nonconductive epoxy bonds glass onto a plastic housing, while a combination of conductive and nonconductive epoxies assembles an electromechanical device. Low-outgassing organic-based epoxies and optical adhesives are some other examples. Cure times vary depending on the bond line thicknesses and materials.

Wire bonding remains the most reliable, straightforward, and widely used interconnection method in many microelectronics packages. APL has a variety of manual

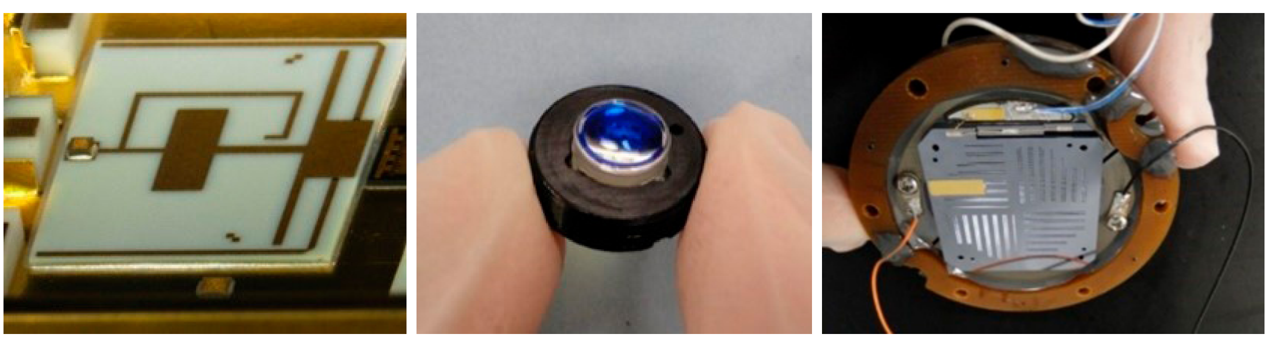

Figure 3. Epoxy bonding examples. Left, a hybrid package for the IMAP mission where a 0.005-in.-thick alumina substrate is epoxy-attached to a housing using a silver-filled conductive epoxy. A 0.015-in. square capacitor was epoxy-attached to a pad on the substrate. The attachments on this device must meet the MIL-STD-883 Test Method 2017 Class H requirements. Center, a glass bonded onto a plastic housing using a nonconductive epoxy that cures at room temperature. Right, a three-layer stack of etched silicon substrates bonded with nonconductive epoxy onto a titanium plate. Ribbon wires bonded with silver-filled conductive epoxy connect the stacked silicon layers to external terminals.

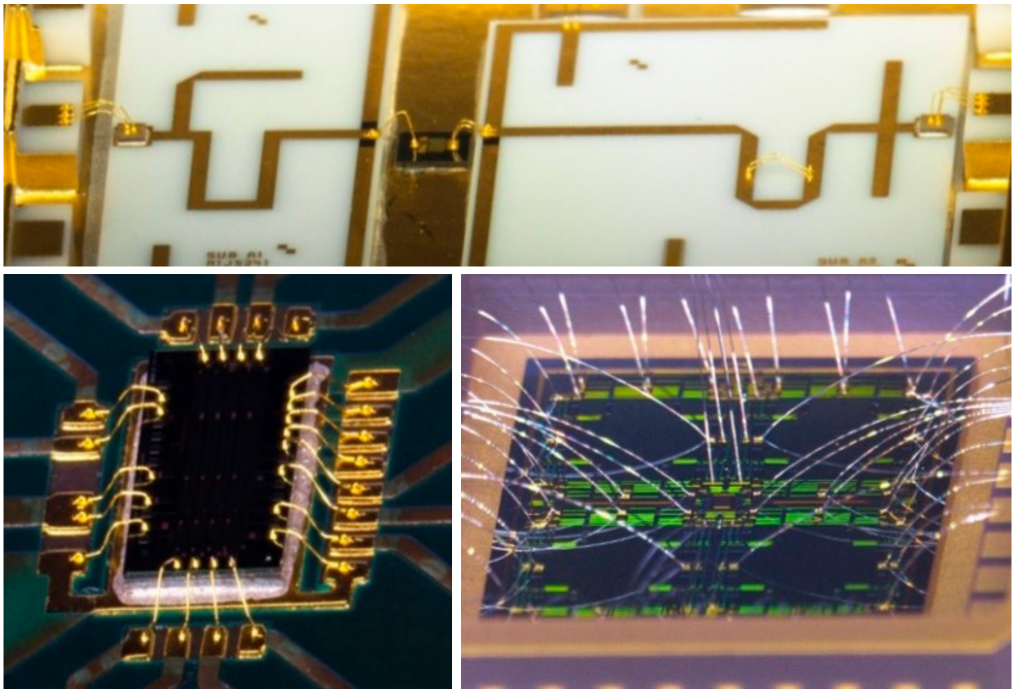

Figure 4. Top, gold ball wire bonding constant-length wires on an RF package. Bottom left, gold ball bonding a silicon chip on an organic substrate, a PCB. Bottom right, aluminum wedge bonding a microelectromechanical systems device on a leadless chip carrier (the package was wire bonded for the Army Research Laboratory).

and automated wire bonders for gold ball wire bonding, aluminum wedge bonding, and copper wire bonding. As expected, wire diameters have gotten smaller to adapt to smaller die bond pads and finer pitch. Gold wires as small as 12.5 μm in diameter have been used on die bond pads as small as 35 × 70 μm with pad pitch of 40 μm. Not only are wires getting smaller, but bond pad metallization also changes from traditional gold or aluminum pads to newer materials, such as niobium titanium nitride (NbTiN) thin films on silicon substrate. Wire bonding can be integrated into many applications, such as gold ball bonding constant-length wires on a radio frequency (RF) package, gold ball bonding a chip on organic substrate, and aluminum wedge bonding a microelectromechanical systems device on a leadless chip carrier (Figure 4).

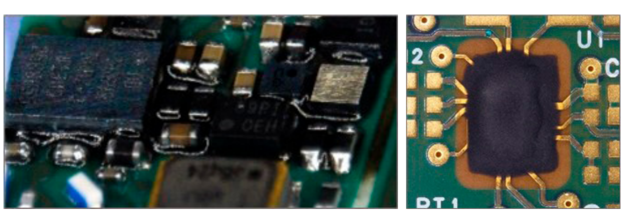

Figure 5. Left, an underfill material covering the solder joints of the components soldered onto the PCB. Right, an encapsulation material fully covers the die and all the wire bonds that connect it to the PCB.

The main objective of ***underfill*** and/or ***encapsulation*** is to protect interconnects or joints from damage during subsequent assembly processes or in the field. Underfill and encapsulation materials shown in Figure 5 are polymer materials dispensed onto specific locations of the circuit.

Hermetic sealing (Figure 6), also called seam sealing or seam welding, is typically performed on high-reliability microelectronics packages to create an airtight seal so the devices can survive harsh conditions in space, deep below Earth's surface, or in other extreme environments. APL has a seam welder to join similar or dissimilar materials along a continuous seam.

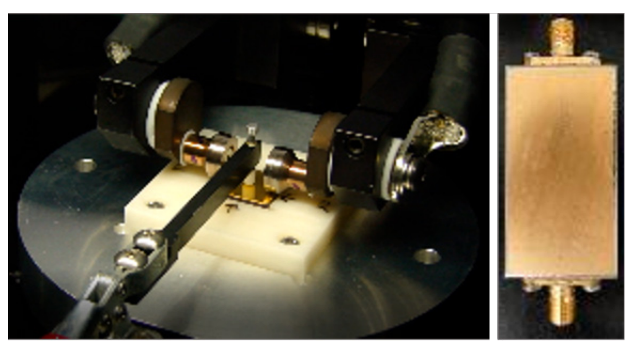

Figure 6. Hermetic sealing using special electrodes that weld the lid onto the package to create a continuous seam. This type of sealing is typically performed on high-reliability microelectronics packages that need to survive in harsh conditions.

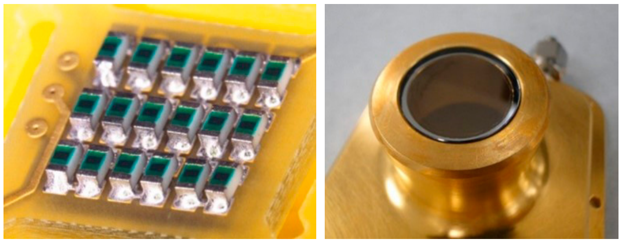

Figure 7. Soldering examples. Left, rows of 0402 chip resistors soldered onto FR4 board with 63Sn/37Pb solder paste, which melts at 183°C, and reflowed at peak temperature of ~220°C. Right, a glass window soldered onto a gold-plated aluminum housing using an In/Pb/Ag solder ribbon to form a vacuum seal.

Soldering is used on devices, like the one shown in Figure 7, that need solderable components mounted or wires soldered onto them using solder alloys, such as eutectic tin-lead 63Sn/37Pb with a melting point at 183°C or the lead-free alloy Sn/Ag/Cu with a melting point at 217°C. Soldering also applies to nonelectronic devices using alternative solder alloys, such as In/Pb/Ag with a melting point at 153°C. Soldering typically uses flux that is compatible with the materials and alloys to solder.

Dicing custom-made packages, like the one shown in Figure 8, was one of the enabling technologies for developing smaller and thinner QFNs. APL has the capability to dice many materials, from standard microelectronic materials to materials such as PCBs and metals.

Decapsulation is the process of removing packaging material from the front side of a packaged part to reveal the integrated circuit (IC) surface. The process uses a combination of sulfuric and nitric acids. Decapsulation does not damage package leads or wire bonds. The process allows the IC to be tested and evaluated in its original package. **Depackaging** is a destructive process by which the IC is completely removed from its original package to be evaluated. With the IC removed from its original package, it can be assembled into a new package.

Extracted die plating allows the reuse of die, like the one shown in Figure 9, that have been depackaged from a package or board. With this plating process, pads become once again wire bondable with good adhesion.

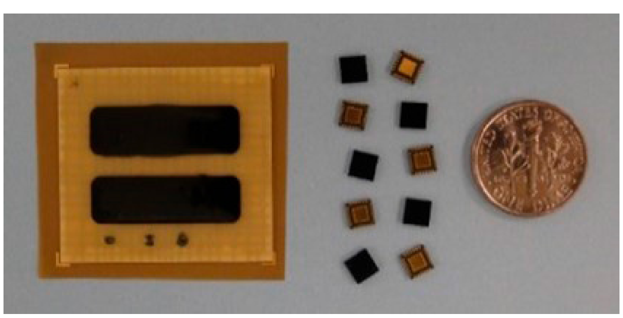

Figure 8. Dicing a custom-made package into QFNs. APL can dice many materials, from standard microelectronic materials to materials such as PCBs and metals.

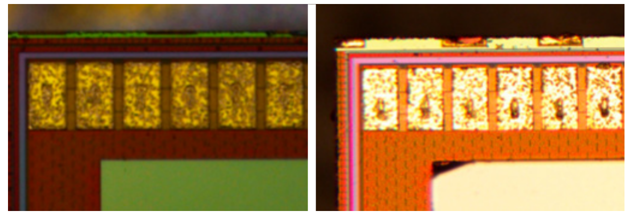

Figure 9. Replating of extracted die. With extracted die plating, pads become once again wire bondable with good adhesion, allowing depackaged die to be reused.

Lapping and polishing (Figure 10) is used when bulk material needs to be thinned or polished to a mirror-like state. This process has enabled significant reduction in the QFN footprint. APL can make a QFN just larger than the die itself and has used lapping and polishing to thin stacked die to as thin as ~50 µm.

A small milling bit ranging in diameter from 3 to 0.4 mm is used to create cavities in package material. The milling bit can also be used remove package lids without damaging the package.

Laser cutting (Figure 11) is the process of cutting features through materials, like ceramic plate, aluminum sheets, laminate materials, and flexible substrates, such as Kapton. Laser cutting is useful for cutting oddly shaped or custom-shaped features.

Chemical milling etches out or mills parts, such as the beryllium copper sheet shown in Figure 12, that

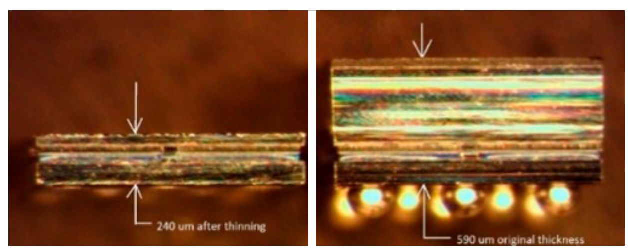

Figure 10. Lapping and polishing to thin die. Left, side view of a commercial die after it is thinned. Right, original die thickness. APL has used lapping and polishing to thin stacked die to as thin as ~50 µm.

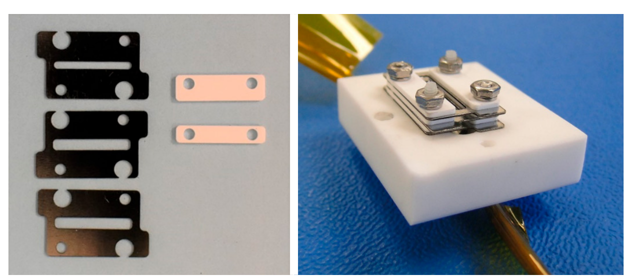

Figure 11. Laser cutting. Molybdenum sheets and alumina laser-cut and stacked onto an electromechanical device.

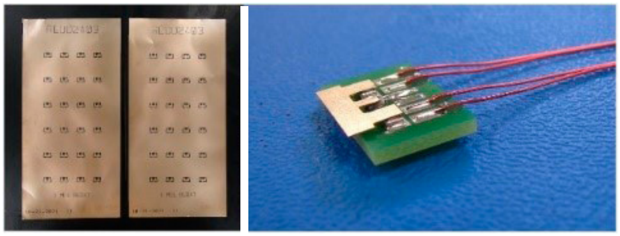

Figure 12. Chemical milling. A singulated chemically milled 0.005-in.-thick beryllium copper is bonded onto a PCB using a thermally conductive, electrically insulative epoxy.

are otherwise difficult or impossible to fabricate using mechanical milling or machining methods. Chemically milled parts are generally made using material thinner than 1.0 mm. APL can chemically mill parts out of copper, copper alloy, aluminum, and stainless steel.

SELECTED EXAMPLES

DART Camera

APL developed a high-resolution telescopic camera, Didymos Reconnaissance and Asteroid Camera for Optical Navigation (DRACO),[12] for the DART spacecraft[13] (Figure 13). This camera consisted of an optical imaging chip assembled on a custom PCB. The PCB and mechanical parts—heat sink, frame, and cover—were designed and fabricated at APL. The multilayer rigid-flex PCB was plated with nickel palladium and gold (ENEPIG). This special-purpose surface finish allows for both soldering surface-mount devices and wire bonding onto the PCB. The heat sink was attached to the PCB, and the imaging chip package was mounted onto the heat sink. Electrical connections to the optical chip were made using ultrasonic wedge bonding technology to attach 32-μm (0.00125 in.)-diameter aluminum wires.

DART Radial Line Slot Antenna

APL also fabricated the Radial Line Slot Antenna (RLSA)[14] for the DART spacecraft (Figure 14). The design called for a small cone-shaped radiating element to be attached to the center conductor pin of a connector to feed the microwave signal to the antenna. An important consideration for the radiator cone is that it can heat up to over 200°C during operation. Standard tin-lead alloy solders melt at these temperatures. The solution was to use a high-temperature solder, such as gold-tin, which melts around 300°C, to reflow attach the cone. In addition, the insulation and center pin lengths of the original connector were modified to dimensions specified by the design engineer. The small cone was machined in APL's machine shop and gold-plated in the

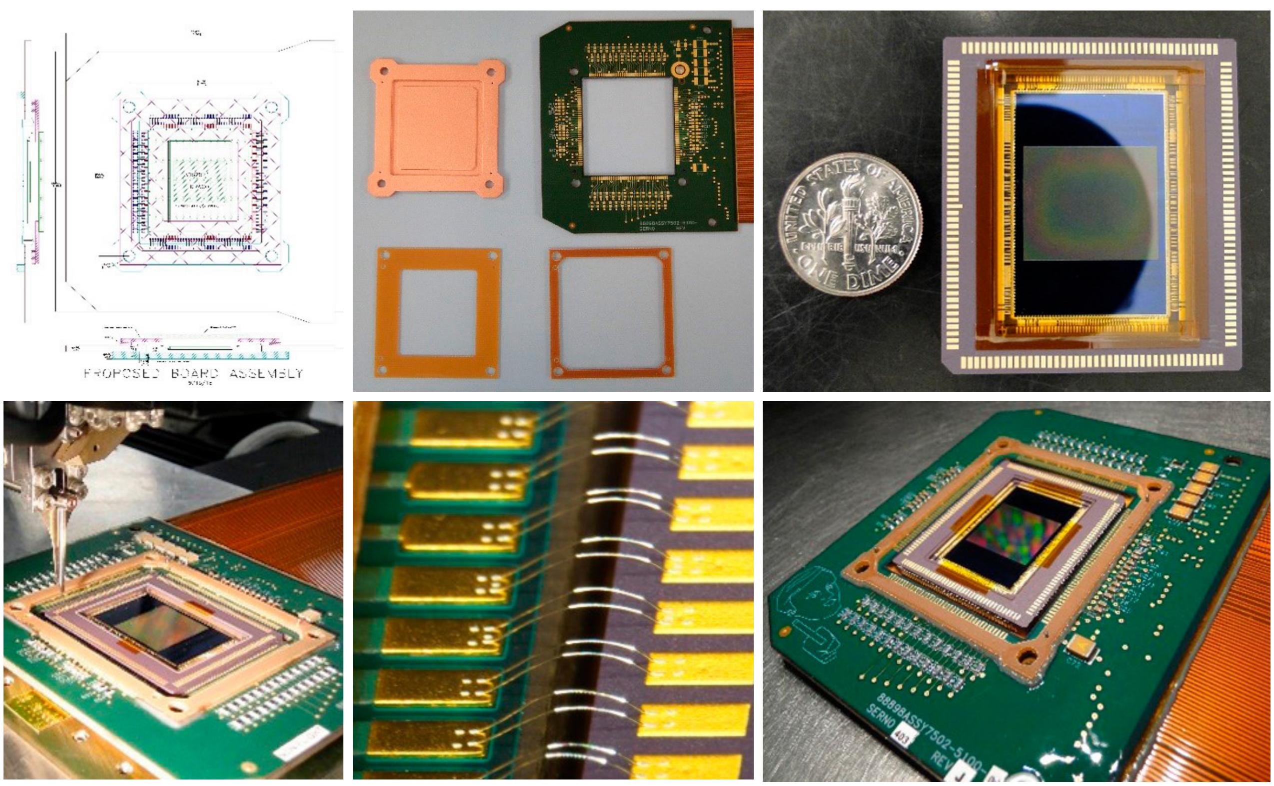

Figure 13. Microelectronics assembly of the micro-imager chip for DRACO, a high-resolution telescopic camera for the DART mission. The micro-imager chip is wire bonded to the circuit board. This design was a joint effort by engineers in APL's microelectronics area and its Space Exploration Sector. The circuit board, heat sink, frame, and cover are also shown.

Figure 14. RLSA for the DART mission. The radiator cone can heat up to over 200°C during operation, requiring a high-temperature solder to reflow attach the cone. In addition, the insulation and center pin lengths of the original connector were modified. The small cone was machined in APL's machine shop and gold-plated in the microelectronics fabrication lab. Special mechanical fixtures were also made to facilitate the modification and solder reflow attachment of the cone to the center pin.

microelectronics fabrication lab. Special mechanical fixtures were also made to facilitate the modification and solder reflow attachment of the cone to the center pin.

Dragonfly DragonCam Light-Emitting Diode Array

Dragonfly's[15] DragonCam light-emitting diode (LED) array (Figure 15) is designed to image Titan's surface. The LED array will illuminate sampling sites over multiple wavelengths, including ultraviolet, visible, and near infrared, using nine multispectral LEDs. The array consists of 180 individual LEDs on a multilayer PCB fabricated at APL. To keep the array small and lightweight, the board includes bare LED die spaced 2.5 mm apart. The LEDs are attached with a silver-filled conductive adhesive and electrically connected with 25-µm-diameter gold wire using a thermosonic wire bonding process.

CONCLUSION

Electronic systems continue to demand more miniaturization.[16] Devices that were traditionally designed for board-level and even system-level electronics are being miniaturized. Microelectronics packaging will always be the bridge from microfabricated chips to board-level electronics. APL has the unique combination of technological capabilities, state-of-the-art facilities, and expertise

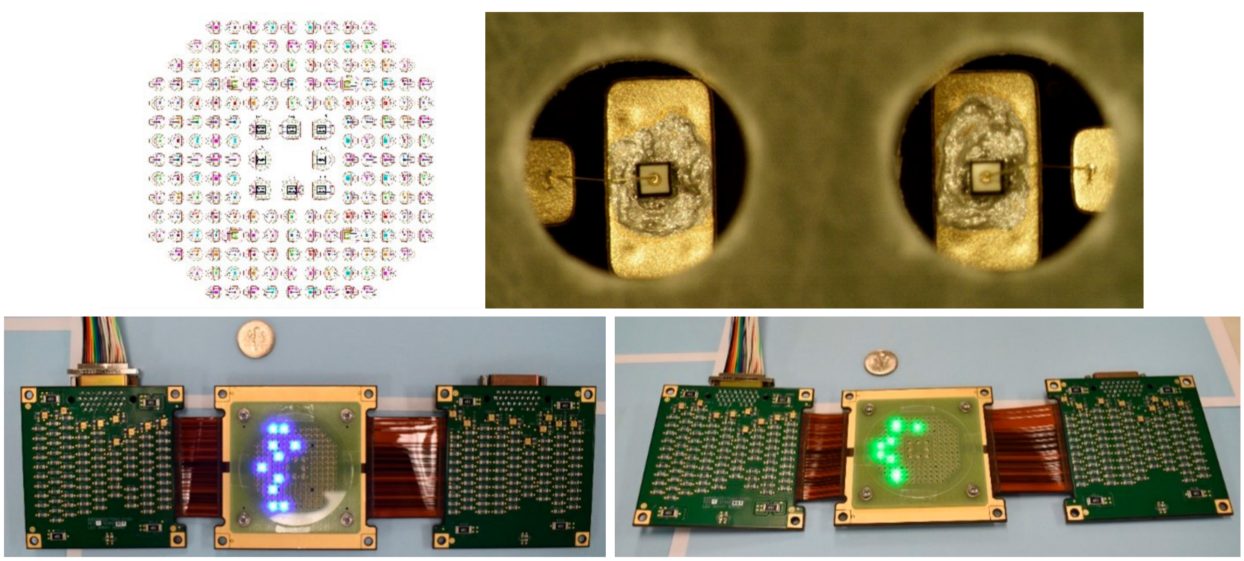

Figure 15. DragonCam LED array for the Dragonfly mission. The array, consisting of 180 individual LEDs on a multilayer PCB, was fabricated at APL. Bare LED die are spaced 2.5 mm apart and attached with a silver-filled conductive adhesive and electrically connected with 25-µm-diameter gold wire using a thermosonic wire bonding process.

to prototype and produce a broad range of devices for diverse applications in support of critical missions.

APL will continue to expand its capabilities to remain at the forefront of technological advances and to meet its sponsors' requirements. The Lab is advancing its processes and technologies to support finer-pitch wire bonding and high-accuracy flip chip bonding to enable packaging of multi-stack devices. The areas of growth are 3-D assembly and photonics packaging.

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Modeling Nonlinear and Dynamic Mechanical Behavior

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ABSTRACT

Highly nonlinear and dynamic mechanical behavior involving impact, crash, and blast is common in some of the work done at the Johns Hopkins University Applied Physics Laboratory (APL). Modeling these behaviors involves finite element analysis (FEA) that reaches beyond typical static analyses. APL researchers are able to model complex nonlinear dynamic behavior without oversimplifying or converting the problem to a so-called equivalent static problem. Presented here is an overview of dynamics and nonlinearity and a brief summary of the options available for modeling these behaviors. The article concludes with several case studies that demonstrate how APL's expertise in this area contributes to the safety of our nation's warfighters and diplomatic personnel.

INTRODUCTION

Blast, impact, and ballistics are the legacies and the poster children of nonlinear dynamic finite element analysis (FEA). Sometimes termed *hydrocodes* because of their original uses for solving hydrodynamic problems[1] such as those researched in the Department of Energy labs, nonlinear dynamics FEA software programs, as well as the challenges in using them, are often associated with specialty users at national laboratories or in academia. In fact, researchers in APL's Research and Exploratory Development Department (REDD) and its progenitors have been tackling problems like these for years on projects that span the entire Laboratory. The field has earned a reputation for being difficult and expensive and requiring long lead times because of the resources required to set up, debug, and run the simulations. However, REDD researchers have combined advances in software and hardware with their extensive experience to open the door to incorporating nonlinear dynamic FEA into the normal design and evaluation process.

BACKGROUND

Dealing with Dynamics

FEA has become ingrained in engineering design, especially with the advent of graphical user interface (GUI)-driven model development in legacy FEA software packages like ANSYS, which streamlined analyses for the average user. Most engineers and analysts with experience in structural FEA are familiar with static problems, and possibly even problems with a small degree of nonlinearity. However, most of these same analysts are just as unfamiliar with dynamic FEA. In fact, many will seemingly go the extra mile to convert a dynamic problem into a static one, or come up with static-equivalent loads to avoid a dynamic problem. (Refer to Box 1 for more detail on statics, dynamics, linearity, and nonlinearity.)

Strictly speaking, all loads could be considered "dynamic" in the sense that any load on a structure must have been applied over time. All structural FEM codes are built from the same set of physical conservation equations: mass, momentum, and energy. The momentum relation ends up being the equation on which much of the code pivots since it controls the movement of the nodes, and it is here that the distinction between a static and a dynamic problem is made. The momentum balance in its typical forms can be manipulated and finally expressed for finite elements in a simple balance of forces as functions of displacement and time[2]:

$$Ma + f^{int}(d,t) = f^{ext}(d,t)$$

inertial forces + internal forces = external forces.

It is an intuitive concept: when a force acts on a body, it is going to manifest as both movement and deformation of the body. Deformation results in stresses, or internal force built up inside the body. Viewing structural problems in the light of conservation of momentum is important because it forces the mindful analyst to observe that static and dynamic problems are not two separate entities. Instead, a static problem is actually a special case in which an analyst has decided that inertial effects are so small that both time and mass can be neglected from the system for the sake of a simpler problem.

Many engineers try to avoid dynamic problems because highly dynamic situations get complicated and highly nonlinear very quickly. With this greater complexity comes a need for more detailed information, a tendency toward longer model solve times, and a higher likelihood that the model might fail to solve or that it might solve incorrectly. The best remedy to these issues is not to avoid the difficulties, but to leverage specialized and experienced modelers along with advanced software and hardware. Fortunately, REDD is able to supply all these assets.

BOX 1. STATICS, DYNAMICS, LINEARITY, AND NONLINEARITY

In the field of continuum mechanics, a static problem is one in which the system does not change over time. A dynamic problem is therefore one in which the system does change over time. The broader implication is that in static finite element method (FEM) problems, the concept of time is neglected, along with mass, since inertial forces exist only in a system in which an object is moving.

Linearity and nonlinearity, in the context of FEM, refer to the mathematical relationship between the forces and the displacements in the system. A linear mechanics problem's output will scale proportionally with its input. Analysts and programmers care about this distinction mostly because linear problems are very easy for computers to solve, while problems with increasing nonlinearity generally require iterative calculations and special algorithms to solve, which increases the computer resources, the time, and the detail required for a correct solution, as well as the chances that the solver will fail to find a solution.

Under the Hood of Dynamic FEA Software

Dynamic FEA software uses one of two methods to integrate differential equations in time: explicit and implicit. Explicit methods are a class of numerical integration algorithms that drive the solution forward in time by using information known in the present to calculate future values. Using the classic forward Euler method as an example,[3] position in the future is calculated by using the velocity known in the present:

$$x_{future} = x_{present} + \Delta t v_{present}.$$

The advantages of explicit methods are that they are computationally easy to solve and do not require iteration and convergence because they use values that are already known to step forward. There is also no need to build and then invert a large stiffness matrix, as is the case with static and implicit methods. The major disadvantage of explicit methods is that they are termed *conditionally stable*. This means that the solution can remain stable only if the time step is smaller than a critical value, known as the Courant–Friedrichs–Lewy condition.[2] For first-order structural finite elements, this critical time step is the characteristic length of the smallest element divided by the sound speed of the material within that element. If a single element of steel with a sound speed of 3,200 m/s is 1 mm across, then the maximum time step would be 0.3125 μs, requiring 3,200 time steps to solve 1 ms of simulation time!

Explicit methods trade time step size for ease of computation and are therefore best suited to events happening at small timescales on the order of a few milliseconds or fewer (crash, impact, blast). This means that explicit methods are usually confined to problems in which stress wave propagation is important and the area of interest is local to the applied loading. Additionally, since the solver does not require iteration and convergence, explicit methods are the best solution for solving problems that change suddenly and are highly nonlinear.

Implicit methods differ from explicit ones in that they drive the solution forward in time by using information from the future. This is exemplified by the classic backward Euler method,[3] in which position in the future is calculated using the velocity from the future also:

$$x_{future} = x_{present} + \Delta t v_{future}.$$

The glaring difference between this and the forward Euler method is that there are unknown terms from the future on both sides of the equation, which at the least requires a system of equations to solve (a matrix equation) and, because it is nonlinear, will require an iterative solution to solve. In FEA, this requires a large stiffness matrix to be built (a square matrix the size of the number of degrees of freedom in the system) and then factored to invert the matrix and solve for forces. In an iterative solution, this has to be done many times.

The consequence of the implicit solver is that it is more computationally expensive to compile and invert a large stiffness matrix and iterate toward a solution. This consequence can manifest itself in the form of long solving time, but it may also have repercussions derived from hardware or software license limitations. Large matrices require a lot of computer memory. If a user does not have sufficient computational resources or their available software licensing does not support the additional computational resources required, they may be restricted in terms of the size of the model they are able to run. The huge advantage, however, is that an implicit solver is termed *unconditionally stable*, meaning that the solution remains *mathematically* stable for virtually any time step size. However, exceedingly large time steps could skip over a potentially significant dynamic event in time or change the behavior of a material that is path dependent, so it is important to remain cognizant of the time step size, even if it is unconditionally stable. If an iterative solver has trouble converging on a solution, usually because of high nonlinearity, the best course of action is usually to take smaller time steps. In some cases, the required time steps for convergence can become so small that the value of the implicit solver is completely lost.

Implicit solvers trade ease of computation for a larger time step size and are therefore best suited to problems with moderate nonlinearity, moderate size, and relatively long simulation time on the order of tens of milliseconds or more. Problems that do not need to capture wave propagation, but rather the overall dynamic structural response of a system, fall into this category.

Another dividing line in dynamic FEA implementation is reference frame. What most imagine as classic FEA is from the Lagrangian perspective: element boundaries and nodes describe the deformation of a material. This is a very natural way to describe solid materials and their deformation. Unfortunately, under high deformation, elements can become overly stretched or even tangled; if this deformation does not crash the simulation, it both reduces the accuracy of the elements and drives the time step in explicit simulations to become smaller as the distance across some dimensions of the stretched elements becomes very small. Popular Lagrangian finite element codes include most of the industry-recognized names, such as ANSYS, NASTRAN, Abaqus, LS-DYNA, COMSOL, and many others.

The other perspective from which finite elements can be viewed is Eulerian. In this finite element scheme, a grid of elements and nodes is fixed in space while material moves through the fixed grid. This is a very natural way to describe fluid materials and how they flow. This description is convenient in terms of large deformation because the mesh cannot severely distort or tangle. The primary disadvantage is that Eulerian methods often require a very large number of elements since they must be defined at any point in which material might flow; it is also more difficult to visualize hard boundary lines between disparate materials or empty space. Another difficulty is that material history variables must be advected, or passed between elements, rather than being fully contained within an individual element over time, and this presents its own numerical challenges.[2] An example illustrating the differences between the Lagrangian and Eulerian modeling techniques is found in Figure 1, where the high-speed testing technique known as Taylor bar impact testing is simulated using both methods.

In an effort to combine the best of both worlds, a method called Arbitrary Lagrangian Eulerian (ALE) was developed.[4] An ALE solver allows a user-defined mix of Lagrangian and Eulerian descriptions. This method takes the form of a multistep process where a full

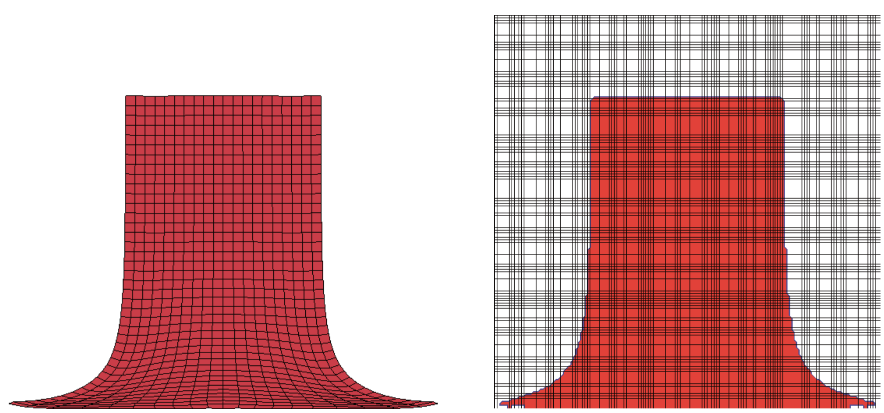

Figure 1. Comparison of Lagrangian and Eulerian methods for a 200-m/s Taylor impact test of a copper cylinder. The Lagrangian method (left) shows a clear deformed shape at the element boundaries and requires relatively few elements but displays severe element distortion in the highly deformed region, degrading accuracy and causing eventual stability issues. The Eulerian method (right) maintains a fixed element grid and thus maintains computational stability through extreme deformation, but at the cost of an unclear material boundary using over 50 times more elements that are 4 times smaller than their Lagrangian counterparts.

Lagrangian step is taken and then followed by a mesh remapping step where the mesh is pushed back an arbitrary amount toward its initial position, and material is appropriately advected through the mesh.[2] The user can go so far as to use an ALE code as purely Lagrangian or purely Eulerian if they wish.

Relevant to the discussion of dynamic FEA are the so-called meshless methods, in which elements are avoided completely in favor of particles so that large deformation or even fluid flow is possible in the Lagrangian description. An example often used at APL is smoothed particle hydrodynamics (SPH), in which particles interact with each other via kernel functions that describe continuum mechanics in similar ways to classic finite elements.[5] SPH is well suited to extremely fast problems involving very high deformation, like those involving explosives and hypervelocity impact. The advantage is a model capable of achieving massive deformation while maintaining a Lagrangian reference frame. However, a common disadvantage, similar to Eulerian methods, is that boundaries and continuity are more difficult to observe because of the particle representation. Advances in SPH post-processing have helped to relieve this problem.

BOX 2. CURRENT SOFTWARE CAPABILITIES USED IN APL'S REDD

With all of the different types of solvers, length scales, timescales, and problem sizes, it isn't surprising that a single software package would be inadequate to handle all of them. For this reason, REDD employs an entire suite of software applications whose combined capabilities allow researchers to tackle a broad range of problems. The following is a list of the most commonly used software packages in REDD:

- ANSYS LS-DYNA: A finite element solver whose progenitor, DYNA3D, was created at Lawrence Livermore National Laboratory (LLNL) in 1976. The software is capable of both explicit and implicit nonlinear dynamics and has Lagrangian, ALE, and SPH modules. It is most widely associated with Lagrangian nonlinear explicit dynamics simulations.
- IMPETUS: A finite element solver with similar capabilities to LS-DYNA, but without the ALE or implicit capabilities. Its major difference from LS-DYNA is that it was written to be run on graphics processing units (GPUs) rather than standard central processing unit (CPU) machines. Its GPU capabilities allow for very large models and extreme deformation of Lagrangian elements without computational failure.
- ALE3D: LLNL's modern ALE finite element solver available to the Department of Defense and associated contractors for work related to national defense.[6] Its main use is as an explicit hydrodynamics code, but it also has multiphysics, implicit, and SPH capabilities as well.
- Abaqus FEA: A finite element solver capable of both explicit and implicit nonlinear dynamics with Lagrangian, ALE, and SPH modules. The software has a long legacy reaching back to 1978, is very well known, and is most widely associated with Lagrangian nonlinear implicit simulations.

CASE STUDIES

Simulation of the Warrior Injury Assessment Manikin (WIAMan)

Improvised explosive devices (IEDs) quickly became a problem in the Iraq and Afghanistan wars of the 2000s when they introduced a new loading mechanism that vehicles had to protect against—underbody blast (UBB). To better protect the warfighter in such scenarios, the Army used the Hybrid-III crash test dummy to understand the human response to the UBB loading scenario. Because the Hybrid-III was designed by the automotive industry for frontal crash testing, it was discovered to be an inadequate surrogate for the human in UBB conditions. Its physical response did not match that of a human, and it was not sufficiently durable in UBB conditions. The Army decided to develop a crash test dummy specifically designed for UBB, called the Warrior Injury Assessment Manikin (WIAMan). The WIAMan needed to withstand the severe loading of UBB while still exhibiting the physical response of a human. On top of this challenge, the Army needed a solution fast, but crash test dummies are often developed over the course of decades with necessary refinement to their predictions of human injury. Since the Army did not have decades to develop the WIAMan, dynamic FEA was used to help speed up the design process.

With nearly a decade of expertise in both biomechanics and LS-DYNA modeling, REDD's Biomechanics and Injury Mitigation Systems (BIMS) program modeling team developed an LS-DYNA model of the manikin (the WIAMan FEM) and validated it against the response of the physical test device.[7,8] This development effort was performed in conjunction with government engineers from the WIAMan Project Office, the Army Research Laboratory, and the Combat Capabilities Development Command (DEVCOM) Analysis Center (DAC). The WIAMan FEM team had particular expertise in validating large-scale dynamic models of this nature. Further, the team was composed of a mix of mechanical engineers and biomechanical engineers who brought unique perspectives from both the mechanical design side and the human response relationship side. For this kind of modeling, software solutions must offer a number of capabilities: a vast library of nonlinear material models, the ability to simulate short-duration events (~100 ms) using explicit FEA, the ability to solve very large models, and a long history of use for blast simulation. Inherent in blast simulations is the need for very large deformations and motion over a short period of time, which requires that stress wave propagation is tracked appropriately. This, combined with hundreds of parts coming into contact and the use of advanced material models for both polymers and metals, demands the use of an explicit dynamic nonlinear FEA solver.

Model development was no small undertaking: on the order of 1,000 parts had to be modeled for the WIAMan (Figure 2). The team took a hierarchical approach to validation, where material characterization fed into component and subsystem models that were ultimately assembled into the whole-body model. Subsystem models were validated against test data in addition to the full system-level validation of the whole-body model. The current whole-body model typically runs on a high-performance computing cluster on 60–100 CPU cores and can simulate 50 ms in roughly 6 h.

The validated model was used in several ways to enhance the physical test device and the understanding of human injury in UBB. A large-scale design-of-experiments study was conducted using about 50 simulations to help the WIAMan designers understand which design aspects would have the greatest effect on the biofidelity (WIAMan's ability to respond like a human). This study revealed that while some design parameters yielded minor improvements to the biofidelity scores in close proximity to the changed parameter, they were often at the detriment of other scores, with a net-zero gain. The WIAMan test device is now in the production phase, but the WIAMan FEM will live on as a long-term complement to the physical test device. While the physical test device was being outfitted with injury prediction capabilities through the research of a collection of universities and APL, the WIAMan FEM team was concurrently developing the same capabilities for the model. This will give Army engineers an additional tool for predicting human injury in vertical loading scenarios to complement expensive blast tests. Ultimately, the WIAMan FEM affords two benefits: it is a design tool for rapidly developing a physical device and is a stand-alone injury prediction capability for the Army. The WIAMan FEM is owned and managed by DAC.

Simulation of the Swaging Process on an Elastomer Hose

For another project, the design team requested simulation to help them design a metal collar to be swaged on to the end of an elastomer (rubber-like) hose. The swaging process involved drawing a mandrel through the inner collar part while holding the outer collar part fixed with the rubber hose sandwiched between the two parts. The drawn mandrel then forced the inner collar part outward, plastically deforming the metal and clamping the rubber tightly between the inner and outer collars.

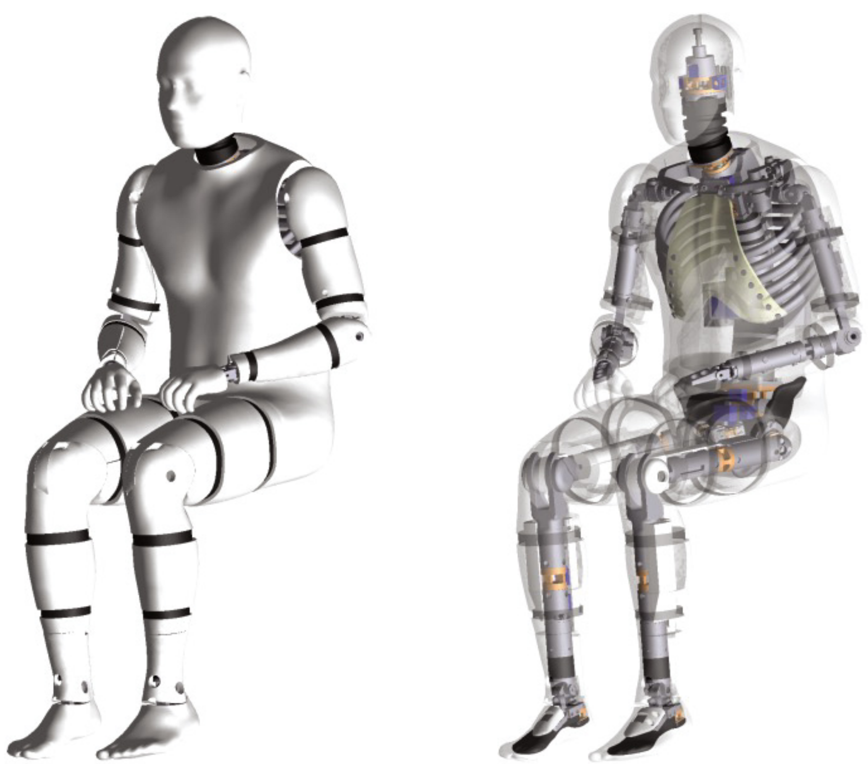

Figure 2. The whole-body WIAMan FEM. The model, with flesh (left) and interior parts exposed (right), was developed using LS-DYNA. It can simulate the response of the physical test device and predict the likelihood of human injury in the dynamic UBB environment.

Modeling this process required advanced material models for both the titanium metal collar and the rubber tubing. Because the metal was plastically deformed, the material model had to capture this phenomenon accurately. Titanium, a commonly used structural metal, is just as commonly used in FEA and is well characterized in the literature, so the team easily found and applied a Johnson–Cook plasticity material model for the swaging simulations.

The hose underwent very rapid, large deformation during the swaging process. Although elastomers have a reputation for springing back to shape, they generally have varying degrees of nonlinear, plastic, and time-dependent properties, so proper material model selection and intelligently designed material testing is required in order to calibrate the material models.[1] In addition to the material modeling, complexity is added to the simulation since the swaging process and the nature of the parts involved require multiple time scales, small mesh sizes, and accurate contact interfaces between the parts. This complexity created a difficult choice between explicit and implicit methods: the nonlinearity of the problem due to the materials and contacts made it a good candidate for explicit methods, while the mesh size and timescales on the order of seconds made the problem a good candidate for implicit methods. The team used Abaqus, which offers a robust library of material models for elastomers and the ability to use both explicit and implicit methods, to carry out the simulation.

The first step was to test the elastomer materials and calibrate them to a representative material model. The elastomer material needed to respond correctly to large deformations at a relatively high rate, and then relax appropriately after the swaging process was finished. This behavior was captured with two tests: a standard ASTM D395 compression set test[9] and a customized cyclic tension test with stress relaxation holds.[10] The compression set test, sometimes called "permanent set," compresses rubber samples to a defined strain and holds them for a long period of time before releasing them. The residual strain in the compression samples is then measured after samples have rested for an appropriate period of time. The custom cyclic tension test consisted of five tensile iterations in which the sample was pulled to a finite strain, held at this strain for 10 s to allow observation of stress relaxation, and then released back to zero strain. With each new cycle, the maximum strain was increased from an initial 5% strain to a final 60% strain to capture nonlinear viscous effects in the stress relaxation. With these test data in hand, a polymer material fitting software was used to calibrate an advanced polymer material model in Abaqus, called the Parallel Rheological Framework (PRF) model, using three viscoplastic networks and Mullins damage to achieve a nearly perfect fit to the experimental data (Figure 3).

Along with the PRF models built for the rubber layers, orthotropic material properties were introduced and assigned to "skins" (shell layers) within the rubber layers to capture the additional radial stiffness of the hose imparted by the layers of wrapped nylon cord reinforcement. These properties were calculated by applying a series of stiffness matrix transformations to test and published data to appropriately capture the micromechanics of this specific material system. These material properties were assigned to their respective rubber hose and reinforcement and applied to an axisymmetric geometric representation of the configuration-built Abaqus CAE. A rigid surface representing the mandrel was aligned axially and prescribed a constant velocity so that it made contact with the inner swage fitting surface. The mandrel caused the inner swage fitting to plastically deform and crimp the inner hose material.

The team used the Abaqus explicit solver to solve the mechanics of the mandrel swaging process, and then imported results into the Abaqus implicit solver to investigate the coupling's springback behavior. A springback analysis (implicit) allows for efficient assessment of the effects of stored elastic energy on a part that has been plastically deformed, providing an "equilibrium" state for the swage fitting so that its final deformed dimensions can be realized. Once the amount of springback was determined, tie constraints were applied to the inner surface of the coupling and outer surface of the hose, thereby fixing the hose within the coupling. This approximated the epoxy that is injected into the coupling fitting before the fitting is inserted and the hose is swaged. Once these constraints had been applied, a vertical load was applied to the top of the swage fitting to assess the stresses and strains within the various hose materials as part of a preliminary analysis of the pull test qualification required for the final system. By combining these Abaqus analyses and the test data generated from APL's tear test experiments, the team investigated several criteria as candidates for predicting the onset of material failure.

Modeling contact interactions between very stiff and very compliant materials is one of the toughest challenges encountered in FEM. Each solver's design of its elements is proprietary, and various material model options are available for use in the modeling of hyperelastic materials, so element failures and errors are common. In the case of this analysis, the Abaqus explicit solver offered robust axisymmetric element formulations and a built-in ability

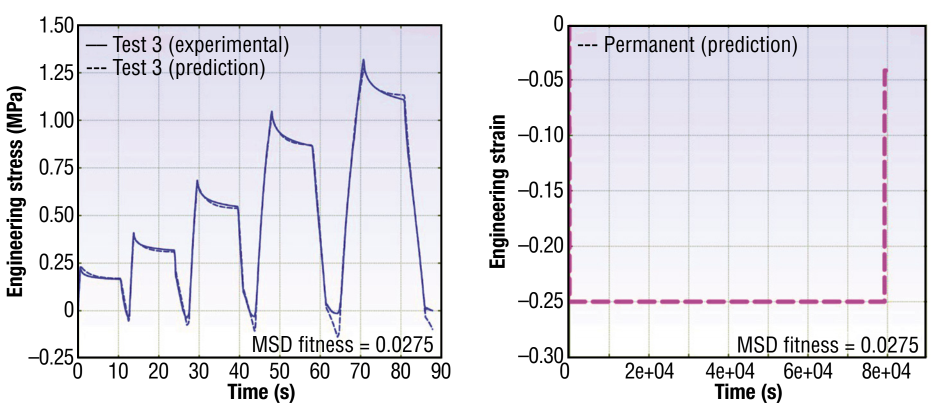

Figure 3. Swaging simulation test data. Abaqus PRF material model calibration to cyclic tensile test data (left) and permanent set data (right). The permanent set graph does not show experimental data, but the predicted permanent strain value of 4% matches the experimentally measured value.

to export explicit solutions to the implicit solver for a restart analysis, which facilitated very efficient sequential, multistep analyses where use of the explicit solver was not necessarily required.

Simulation of Bullet Impact on Armor

For another project, a REDD team was asked to provide whatever information it could on the rear face of personal body armor after it was struck by a rifle bullet—and the team was asked to do it on a short schedule of just 40 hours. The colloquial term for this phenomenon is *backface deformation* (BFD) of armor. Understanding BFD is important because, while armor may protect wearers from some ballistic threats penetrating into their bodies, the large energy of the impact is still a problem when it transfers through the armor and into the wearer, causing injury. The goal of the project was to develop a new system for measuring BFD, including selecting a material that could rest against an unbacked armor system and provide an accurate and consistent visual representation of the BFD. Because of the short schedule and the need for some very advanced modeling, the solver had to offer a fast and easy modeling process.

The armor system consists of a hard armor plate, which is represented in the model as a layer of ceramic armor in front of several layers of a thermoplastic composite (Figure 4). In practice, several layers of Kevlar are the next line of defense behind the armor plate, and these layers are also represented in the model. Finally, the deformation measurement material, which was originally specified to be a rubber material, backs the armor system. A rifle bullet traveling at several hundred meters per second impacts the hard armor plate and transfers its energy through the system, resulting in deformation, which is tracked and measured in the model.

The bullet is modeled using IMPETUS's advanced SPH package to capture its extreme deformation. The materials included in the bullet are Johnson–Cook plasticity models of lead and brass that are referenced to experimental work. The ceramic layer is represented by SPH and a Johnson–Holmquist material model lifted from the literature, specifically intended to characterize ceramic material strength and failure under impact loads. The thermoplastic is represented in several bonded layers by another tuned model for Dyneema, an ultra-high-molecular-weight polyethylene composite that is often used in armor panels.[11] The Kevlar is modeled with layers of an orthotropic fabric material model with typical stiffness and strength of Kevlar KM2 fabric. The initial trial material model for the backing material was a Bergström–Boyce elastomer model of moderately soft rubber that had been tuned in a previous project for air cannon impacts. High-order elements were used to ensure good deformation and good performance for high-aspect-ratio elements.

For partial validation, since full experimental data were not available in the time allowed for the simulations, the team was able to confirm that the simulated hard armor BFD depth matched average observations of APL-conducted experiments on unbacked hard armor plates. The simulated ceramic layer is fully penetrated by the bullet and stopped by the composite layer, which is also corroborated by the experiments.

Initial simulations that included the elastomer backing layer showed that it separated from the Kevlar backing layer and deformed to a much greater depth, very local to the bullet impact area. Because the intent was to observe the backing layer as a representative of armor BFD, extremely different deformation characteristics were not preferred. The behavior of the simulated rubber is reasonable, given that its material properties are drastically different from both the hard armor and the Kevlar layer. Since it is so soft compared with both the Kevlar and the hard armor, stress waves cannot travel nearly as quickly in the soft material, which forces material local to the impact to absorb and respond to all the impact energy, rather than spread it out further into more mass as stiffer materials tend to do. When testing this observation, the team was able to show that a theoretical soft material reinforced with directional strands of a stiffer material (which is the same idea as a tire using nylon fibers to reinforce the rubber directionally) would respond in a way that was more suitable to the designers' goals.

This quick evaluation of the impact event steered the experimental team toward a few subsets of material choices that would

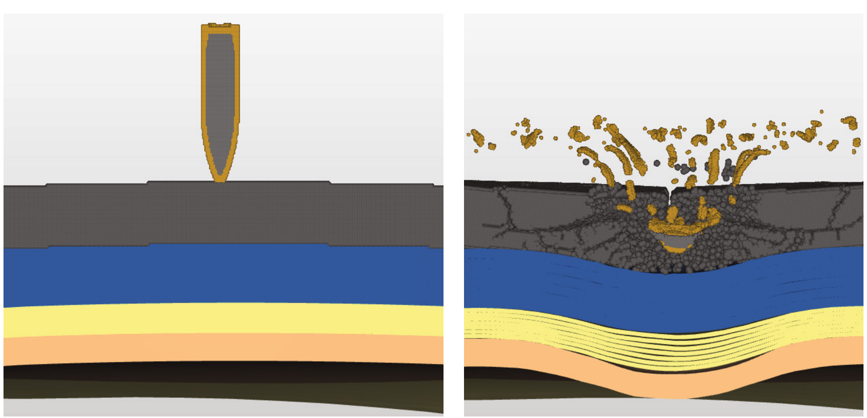

Figure 4. Simulation of a bullet strike on a layered armor system. The modeled system consists of (from top to bottom) ceramic, thermoplastic, Kevlar, and an elastomer backing material. The bullet and ceramic are modeled using the SPH method to capture the extreme deformation of the bullet, as well as the cracking and crushing mechanisms of the ceramic failure.

help them accomplish their ultimate goals. This also helped to guide the design of the clamping fixture that secured the backing material to the armor system. If the designers had not consulted the modeling team, a costly series of design iterations involving prototyping and experiment would have been required. This is a prime example of how physics simulation can drastically shorten the design process, even without a full suite of materials testing and validation efforts. While extra tests are certainly preferred or required in many cases where simulated response needs to be exact, when guidance and an understanding of how a system is likely to respond are needed, models such as the one presented here are still highly valuable.

Simulation of Shaped Charge Jet Generation and Fragmentation

Several APL programs are exploring the effects of shaped charges and warhead fragmentation, but much of this work cannot be discussed in open forums. In the interest of presenting an example of this work, a generic shaped charge warhead, with no link to current APL programs, is discussed.

Shaped charge jet formation and warhead fragmentation occur on the microsecond timescale. This timescale, along with the massive deformation of the materials, tends to place these phenomena fully in the camp of explicit FEA methods. In our experience, ALE and SPH methods accurately simulate explosive detonation, metal fragmentation and deformation, and ceramic cracking for a variety of problems.

The case study presented here and shown in Figure 5 is of a basic shaped charge jet penetrator that uses a waveshaper to reduce its footprint. A basic shaped charge is a high explosive shaped to direct and concentrate its energy in a particular direction. Colloquially in the discussion of warheads, the term *shaped charge* generally indicates an explosive whose detonation collapses a liner metal into an extremely high-velocity jet that is used as an armor penetrator. Rather than relying on the strength or hardness of a penetrator to defeat armor, shaped charge jets rely almost purely on kinetic energy and momentum driven by extremely high velocities.[12] The basic shaped charge can be described as a cylinder of high explosive into which a cone of liner material is pressed. When the charge is ignited at the opposite side from the liner, the detonation wave advances through the explosive toward the liner, impacting the tip of the cone first and gradually enveloping the rest of the liner. The explosive pressures cause the liner to collapse on its symmetric axis, resulting in the liner accelerating and stretching into a very fast and thin jet.[11,12]

Almost any material or geometric aspect of the full charge can affect the resulting jet's performance and shape. One way to increase jet performance while using less explosive is to change how the detonation wave reaches the liner via a waveshaper.[13] A waveshaper is an inert material that is placed between the ignition point of the explosive and the liner such that the detonation wave must travel around or through this material to detonate the explosive material on the other side. This shapes the detonation wave before it reaches the liner. In the example described here, a syntactic foam disk is embedded in the explosive charge such that the detonation wave is impeded from advancing directly into the liner tip, and instead must travel around the outside of the waveshaper, creating a shock wave that converges on the tip from the outside of the cylinder to the central axis. The model uses a polymer-bonded explosive, modeled with a tuned Jones–Wilkins–Lee explosive equation of state (EOS), to accelerate a metal liner modeled with a Steinberg–Guinan material strength law and Mie–Grüneisen EOS specifically tuned for very high velocities, temperatures, and pressures. The waveshaper is modeled with pore-compaction strength law and EOS. For completeness, the warhead liner jet is shown penetrating steel.

Placing a case around the sides of the explosive can also affect the jet, but it can also serve as additional fragments for the explosive. By applying appropriate material strength, EOS, and damage laws, the fragmentation characteristics of the case can also be modeled and tracked in the software. In the case of this model,

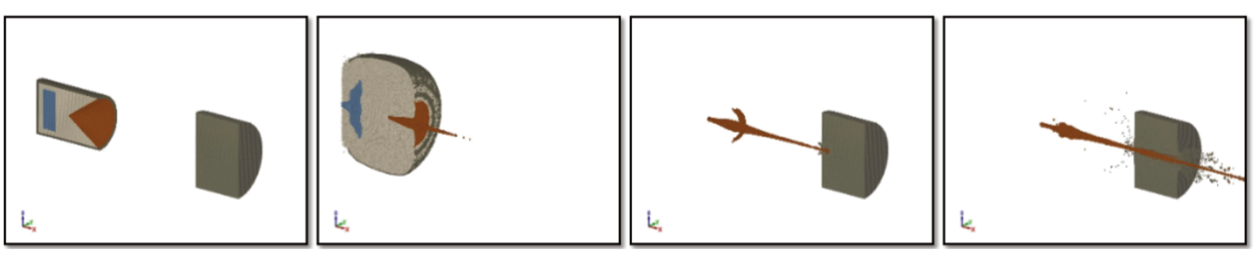

Figure 5. Simulation of a generic shaped charge generating a jet to penetrate steel. The detonation wave begins at the rear of the warhead, traveling through the explosive (white) and around the waveshaper (blue). As the explosive detonates, it converts to rapidly expanding detonation products, both fragmenting the metal body and forming the liner into a jet. The jet strikes and easily penetrates the cylinder of steel because of its extremely concentrated kinetic energy. The simulation is built for efficiency, turning parts on and off as needed throughout the simulation.

Johnson–Cook strength and damage laws are combined with a Mie–Grüneisen EOS to appropriately fracture the steel material into fragments. A built-in fragment tracker catalogs unique free bodies of all nonexplosive parts over the course of the simulation such that individual fragments can be identified and even exported with information, including their material, mass, velocity, size, and spin properties. This information is easily converted to standard ZDATA fragment files or paired directly with in-house codes such as the Ray-tracing Endgame Computational Tool (RECT) for future fragment dispersal and lethality assessments.

APL's ability to quickly analyze the detonation process, the effects of the explosion on both near and far-field material, and the fragmentation of materials—all while avoiding an extremely large Eulerian element grid or tangled Lagrangian elements—has significantly boosted its ability to support multiple programs. Future work in this field could contribute to warfighter injury mitigation, explosive ordnance disposal, future conventional weapons advancement, novel armor concepts, and sympathetic detonation assessment.

CONCLUSION

For over a decade, REDD staff members have been amassing experience and making critical contributions to projects across APL using nonlinear dynamic FEA. Along with the experience, software capabilities have also grown, both in product updates to existing solvers and the advent of new products. All of this, combined with powerful computing clusters, gives REDD a robust and advanced set of tools to solve difficult problems across the entire Lab. By solving nonlinear and dynamic problems in their natural state, instead of resorting to the old practice of oversimplifying or converting from dynamics to statics, we can significantly reduce over-engineered products, solve harder problems more accurately, and make critical contributions to our national defense.

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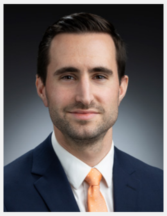

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Rapid Prototyping: Accelerating the Design Process

Jacalynn O. Sharp, Kelles D. Gordge, Edna S. Wong, Gregory L. Merboth, and Nicholas W. Houriet

ABSTRACT

Prototyping techniques have significantly advanced in the last decade, providing engineers with quick ways to iteratively modify designs of parts and systems with greater precision and at lower cost than ever before. The Research and Exploratory Development Department (REDD) at the Johns Hopkins University Applied Physics Laboratory (APL) has made the most of these advancements, using rapid prototyping tools and quick-turn manufacturing that was not possible a decade ago to achieve success in many applications. Examples highlighted in this article include human–machine interfaces conceived through a Navy program called Tactical Advancements for the Next Generation (TANG), confined-area autonomous mapping devices like the Enhanced Mapping and Positioning System (EMAPS), and personal protective equipment to help prevent the spread of COVID-19 during the unprecedented and uncertain times of the early pandemic. These three case studies demonstrate the benefits of rapid prototyping.

INTRODUCTION

Sponsors rely on APL engineers and scientists to produce high-quality, intelligent solutions to complex problems, even when projects have incredibly short timelines. Although some projects require years of intricate planning and testing for one final hardware deliverable, other projects need to go from concept to reality in a matter of weeks. Regardless of design needs and schedules, by relying on rapid prototyping (RP) hardware, APL teams can decrease the cost of design and shorten the time to deliver.

Prototyping hardware to develop novel and innovative designs is not a new concept. For centuries, humans have employed prototypes to convey design intent or provide an initial model of an object to test a design. Thomas Edison was said to have built more than 3,000 light bulb prototypes before arriving at the right design.[1] The Wright brothers tested more than 200 wing and airfoil models to optimize their design.[2] APL's founder, Merle A. Tuve, went through dozens of prototype iterations to ensure that the inner radio tube component in the famous VT fuze would not shatter under high forces when deployed.[3] Since its beginning, APL has successfully employed prototyping methods in its design and research process. Recent advances in RP methodologies, such as the use of additive manufacturing, metal additive manufacturing, quick-turn machining, and artificial intelligence in developing G-code, have changed the landscape of concept generation and project timelines for APL teams.

This article highlights how APL has leveraged mechanical RP and early-concept design methodology and used advanced design and fabrication methods not previously possible to rapidly develop prototype hardware that can meet or exceed sponsor expectations. It also provides examples of how design thinking and the application of iterative design and RP have enabled the creation of innovative solutions to sponsors' problems.

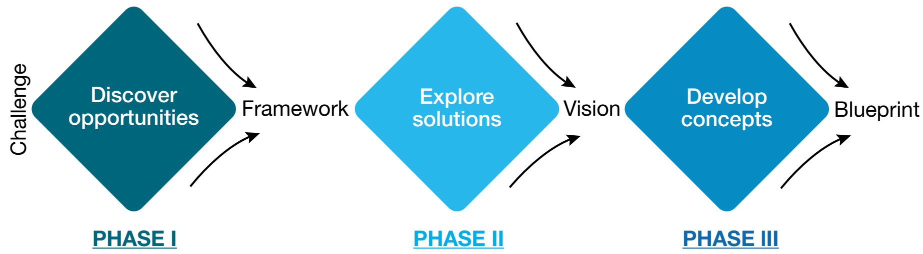

Figure 1. TANG's three-phased approach.

TANG: DEMONSTRATING IDEATION THROUGH EARLY PROTOTYPING

In 2011, the US Navy established the TANG Program (Tactical Advancements for the Next Generation) to leverage design and systems thinking methodologies to tackle human-centered and mission-focused challenges across the Department of Defense. The TANG Program is a multi-organizational program, led by APL, that aims to bring together diverse perspectives across end users, stakeholders, and subject-matter experts to create impactful solutions that address pain points across those communities.

The TANG Program focuses on challenges in the early stages of development, delivering front-end innovation solutions to sponsors. Through empathizing with the end user and developing a comprehensive understanding of the challenges and opportunity space, project teams work with end users, stakeholders, and subject-matter experts to design different human-centered solutions and prototype concepts rapidly. This RP enables sponsors to buy down risk in the long run, ensuring the right concept is being built before focusing on higher-fidelity and costly systems. The TANG methodology offers a unique capability to turn nascent ideas into reality by delivering high-quality "pretotypes" (a pretotype is a low-cost early prototype, as coined by Google's Alberto Savoia[4]). The example discussed below illustrates how pretotyping was injected into the process for creating a futuristic helicopter cockpit.

Putting the TANG Approach to Work

Upon learning about the benefits of human-centered design to inform future requirements, a sponsor approached the TANG Program to charter a project to explore the cockpit experience of a future rotary wing aircraft. After framing the challenge with the sponsor, the team launched into Phase I of the process (Figure 1): discovering opportunities. The team conducted immersive ethnographic research with the user community, interviewing and observing pilots in the field in order to identify pain points and opportunity areas in the current cockpit. This was the first step of a three-phased design approach: discover opportunities, explore solutions, and develop concepts (Figure 1). In Phase II, the team explored the technology space and took inspiration from analogous human–machine pairings, such as NASCAR and video game interfaces. This inspiration was fed into a workshop with end users, stakeholders, and subject-matter experts during which over 40 concepts were designed in the following future technology areas:

- Controls
- Haptics
- Artificial intelligence
- Virtual and augmented reality (VR/AR)
- User interface and user experience (UI/UX)
- Modularity

This approach ultimately led to a cross-Laboratory and multi-organizational collaborative Phase III effort to develop different concepts, relying on the technical experts in each technology area to contribute to various prototyping efforts. Prototyping has been used extensively for every aspect of the project, including creating life-size virtual test environments for demonstrations and creating real tactile devices and visual interface concepts for users to quickly test. The article by Crane et al., in this issue, expands on these capabilities.

Virtual and Augmented Reality

One aspect of envisioning the future flight experience was understanding physical constraints and space within the cockpit, ranging from overall dimensions to visibility to the number of operators it would accommodate. Through research, synthesis of user needs, and brainstorming on the vision for the future cockpit, the team identified initial design parameters. Engineers quickly developed solid models of the cockpit that could be 3-D-printed for handheld demonstration. However, this approach was not very immersive and did not provide operators with a way to "step into" the cockpit for themselves.

Figure 2. Example VR/AR environment for user experience testing of current cockpits. Haptics creates a greater sense of immersion, enabling the user to feel the elevation changes throughout the experience.[5]

To enhance the user experience, the team created a first-iteration flight simulator using gaming chairs, commercial off-the-shelf (COTS) projectors, and perforated foam to create a panoramic view of the external environment. They then overlaid the solid 3-D model of the cockpit airframe into the environment.

With a COTS AR headset, pilots were able to sit in their virtual cockpit and look around to provide feedback on how they imagined themselves working in the space, considering factors such as field of view, position of equipment, and digital information layout, to make the experience more intuitive. Since the software model is highly modifiable in digital space, engineers can quickly implement design changes in the software to instantaneously provide operators with updated concepts. By using commercially available software and readily accessible materials, interested parties can easily make their own virtual environment to test without traveling long distances, reducing travel costs.

Haptics

The Cockpit Experience team also researched how to enhance operators' situational awareness using haptic feedback. In pursuit of a rapid hardware solution and a low-fidelity proof of concept, they leveraged COTS hardware and software to prototype concepts such as enemy threat tracking, horizon line indicators, and elevation alerts using active haptic feedback. For example, they created a virtual experience that placed the user within a cockpit flying over a simulated environment (Figure 2). The addition of haptics created a greater sense of immersion, allowing the user to feel the changes in elevation throughout the experience (for more details, see the article by Crane et al., in this issue).

These examples of prototyping hardware solutions are just a few used in TANG projects. Without the use of quick, low-cost prototyping, realizing the TANG vision to develop various human-centered designs would not be possible. With its main goal to reduce cost while providing an all-immersive experience, the future cockpit project is no exception, and the use of low-fidelity, high-quality prototyping hardware is critical to the validity of user and expert feedback studies.

EMAPS: ITERATIVE DESIGN FOR A GROWING PROJECT

During research and development, evaluation kits or stock electronics obtained from equipment manufacturers are often used to develop platforms to complete novel tasks. As the design grows, so does the hardware, and engineering teams are forced to reengineer and integrate the parts they must use. Using an iterative RP design process allows for faster and more cost-effective modification and integration.

The Enhanced Mapping and Positioning System (EMAPS)[6,7] is an example of a successful program that continued to grow and change for several years. Developed for the Defense Threat Reduction Agency, EMAPS is a portable device that can be used to automatically create annotated maps in tight spaces where GPS is not readily available, such as in underground areas and on ships. This system, worn in a backpack, greatly improves range, maneuverability, and mapping ability compared with mapping-robot counterparts. The mapper's main objective is to measure, analyze, and capture a continuous detailed survey of the operator's surroundings and interpret these data to build a comprehensive map through the use of point clouds and photographs.

The form-fitting outer protective enclosure was made of acrylonitrile butadiene styrene (ABS) via the fused

Figure 3. EMAPS backpack-mounted mapping sensor head version 1. Initial prototypes incorporated quick-turn sheet metal components and heatsinking plates to support and dissipate heat from the COTS electronics and imaging systems.

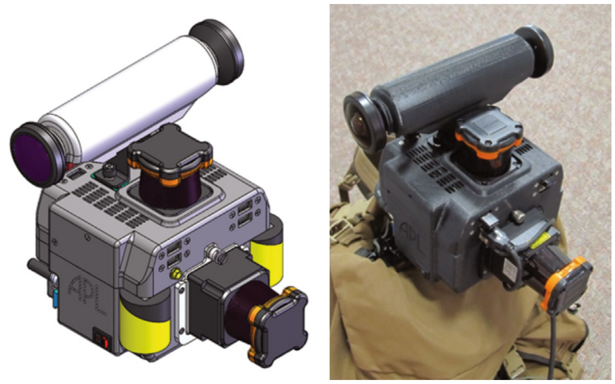

Figure 4. EMAPS backpack-mounted mapping sensor head versions 2 and 3. The design evolved to include different lidar modules and cameras, as well as antennas and other sensors.

deposition modeling additive manufacturing process to provide a compact and lightweight device. Initial prototypes for the unit incorporated quick-turn sheet metal components and heatsinking plates to support and dissipate heat from the COTS electronics and imaging systems (Figure 3).

Unsurprisingly, the design continued to evolve, using different light detection and ranging (lidar) modules and cameras, as well as antennas and various other sensors (Figure 4). Each design iteration added requirements, such as electromagnetic interference shielding and increased mechanical robustness. As APL's additive capabilities continued to expand, a different additive manufacturing method was used for the fourth- and fifth-generation housings. These final two versions used selective laser sintering (SLS) nylon for its ability to serve as both the primary structural support and the protective housing for the electronics. The final housing included both a plated lower section for electromagnetic interference shielding and an unplated upper section for radio frequency transparency, as shown in Figure 5. APL's continual investment in emerging manufacturing technology, such as laser sintering additive manufacturing, allowed for improved precision and resolution in fabricated parts.

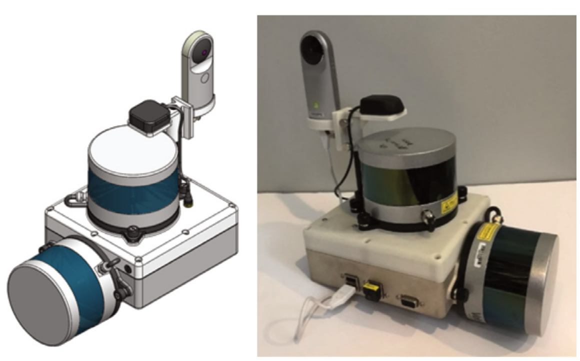

Figure 5. EMAPS backpack-mounted mapping sensor head version 5. This final version included both a plated lower section for electromagnetic interference shielding and an unplated upper section for radio frequency transparency.

As the overall system design progressed, so did the need to rapidly accommodate more capable sensors and user convenience features. The design was upgraded to include two lidar units and two ultra-wide-lens cameras, as well as several ports for external sensors. The enclosure was quickly redesigned to accommodate the new hardware and connector interfaces, so it remained composed of ABS 3-D-printed plastic for several iterations.

After creating five EMAPS backpack devices, the APL team reached its final product. Using EMAPS, nontechnical operators can capture environmental information while they carry the ~6-in., 4-lb cube in a backpack. Lidar sensors scan an area with narrow beams of light coming from every angle. The distances between objects are quickly recognized and translated into detailed views of the area being scanned while providing real-time graphical feedback to the operator through a handheld tablet. The basic system has a 270° laser scanner that measures distances to environmental elements, such as walls. A second laser scanner enables the capture of 3-D data, and an inertial sensor enables detection of the user's steps by measuring the system's roll, pitch, and yaw. The unit can also house a removable camera to obtain omnidirectional images, a GPS receiver to geo-register collected data, and a solid-state hard drive to process and store data in real time.[6]

EMAPS has generated maps of APL office buildings, ship engine rooms, and museums. By using RP parts and off-the-shelf components, the team was able to focus the design and associated costs on the electronics prototyping hardware, allowing for further and faster development of usable prototypes. APL's Tech Transfer Office recently licensed EMAPS to an external company to be mass-produced for government use.

POWERED AIR-PURIFYING RESPIRATOR REDESIGN: PROTOTYPING IN A RACE FOR A CRITICAL INVENTION

March 2020, the onset of the COVID-19 pandemic, was unlike any other March: work-from-home mandates began, materials shortages for manufacturing loomed, and hospitals quickly hit maximum capacity. Soon thereafter, the shortages affected production of medical personal protective equipment, and supplies trended toward a dangerously low inventory.

A Johns Hopkins radiology nurse—who also happened to be married to an APL engineer—mentioned to her husband that medical facilities were close to having no powered air-purifying respirator (PAPR) hoods left. PAPR hoods protect health care personnel who are directly exposed to aerosolized pathogens that cause acute respiratory conditions.[8] In late March, because

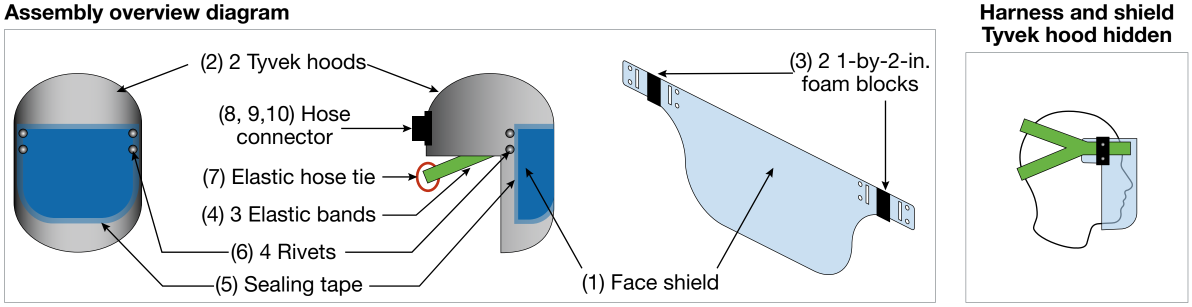

Figure 6. Final design concepts for the PAPR hood. The APL team explored may design concepts and materials before landing on this final design.

of material sourcing limitations, health care personnel were already being forced to sanitize and share hoods. A small APL team formed to develop a design using an alternative material for PAPRs, as well as an agnostic hook-up nozzle design so that the newly designed PAPR could be used in any health care setting.

The team collaborated with a local engineering company, which worked on the air filtration portion. Members met virtually since in-person meetings risked virus transmission. The team swiftly defined the parameters to drive design efforts remotely (see Zinn et al.[9] for more on how APL staff members adapted to a rapidly changing work environment). First, the hood had to be made of a soft material that needed no additional sewing so that anyone could construct the PAPR. Second, a connector for the back of the PAPR needed to connect to certain air circulation blowers. There are several different blowers with different connector interfaces, and ideally, the new PAPR could serve as a host connector that could attach to various types of systems and therefore work in any hospital, anywhere.

Using online video conferencing and slideshow software, the team drew initial concepts on human heads. They then convened to collaboratively decide on design paths, and after reaching consensus, they worked on their design ideas independently. They conducted market searches on state-of-the-art PAPR technology to inform their design decisions and collected and shared information using cloud platforms. The APL team then split into two subteams, each focusing on a specific subtask: (1) the hood and shield assembly and (2) the agnostic connector.

To design the hood, the team searched for materials similar to those used in current PAPR hoods. They began by exploring COTS materials, but traditional Tyvek materials for PAPRs were sold out everywhere. They found Tyvek house wrap and tried sewing and taping it in their first design iteration, but the design was unsuccessful because of the material's stiffness. The team continued searching, trying several materials they were able to source from retailers, when they happened upon Tyvek-based hairnets. Although this material prevented them from producing PAPRs in large quantities, it did allow them to make individual hoods at a significantly low cost. After successfully developing the hood, they moved on to developing the shield. Relying on other open-source RP part design that was being developed, the team was able to quickly create shield holders that were adaptable to the hood. These were connected to a thin polycarbonate shield that was selected after they had ordered many extremely inexpensive materials of different textures and thicknesses (acrylic, polyvinyl chloride film, perfluoroalkoxy, polyester, and polycarbonate) to reduce design time. The final design concept is shown in Figure 6.

The connector design was not as straightforward: it required knowledge of the blower interface dimensions, and this information was not available. As a result, it took several iterations to correctly create the curvatures and surface interfaces. The team turned to 3-D-printed RP as a manufacturing method in lieu of traditional injection molded parts because the traditional method, with a mold manufactured and parts produced, can require a lead time of weeks to months. In addition, specific features for the air blower connection required geometries that were too complex for

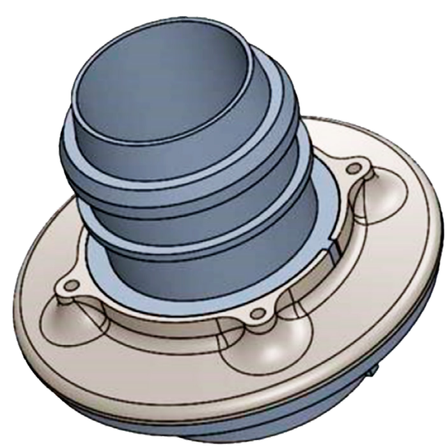

Figure 7. Final design of agnostic PAPR connector. The connector design was not straightforward. The team used 3-D-printed RP as its manufacturing method, saving both time and cost.

injection molding. The approach to 3-D-print multiple individual test designs reduced the design iteration time by several months and reduced cost by several orders of magnitude. The team was able to bypass significant delays from external 3-D printing vendors by using APL's in-house 3-D printers. Each design iteration was drafted via computer-aided design (CAD) at night, 3-D-printed overnight, and hand-delivered by the next day between designers' houses to avoid contact between workers. Each design iteration was completed and tested within 2 days. Figure 7 shows the final design.

Integrating the device had its challenges, an all the team members worked in parallel during the integration phase: one dropping off the valve iterations, one dropping off COTS supplies, and one constructing the hood. The pieces were then integrated, and the hood was delivered to Johns Hopkins Hospital for testing. After working many late nights, the team developed a deployable prototype within 6 weeks by relying on RP technologies and using virtual environments to ideate and collaborate. Not only was the design readily usable and easy to make, but this work resulted in an intellectual property disclosure for the hood design and a patent application for the connector.

CONCLUSION

Prototyping hardware is a powerful tool to bring a product to life. From conceiving ideas and concepts to producing full-fledged designs, prototyping can be used throughout the design process to ensure success. Recent advances in RP and quick-turn part manufacturing have allowed APL researchers to meet sponsor needs by iteratively designing systems at lower cost. Using RP parts and COTS technologies and ideating with low-cost materials allows teams to work faster than was imagined possible a decade ago. These advances in prototyping parts development have helped APL achieve real results: fieldable products, patents and intellectual property disclosures, and sponsor demonstrations that keep the Lab at the forefront of innovation.

ACKNOWLEDGMENTS: We thank the EMAPS, APL Future Cockpit Experience, and PAPR design teams for allowing us to feature their usage of prototyping hardware in their design processes.

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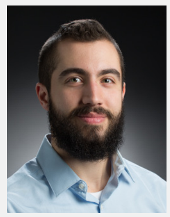

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From Drafting Boards to Virtual Reality: The Evolution of Mechanical Engineering and Design

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ABSTRACT

Mechanical engineering design is a traditional discipline that has advanced with the advent of new technology and techniques. Engineers can now combine traditional concepts with novel technologies and techniques to deliver creative solutions. These techniques include geometric dimensioning and tolerancing (GD&T), reverse engineering, advanced surfacing, haptics, augmented and virtual reality, and new methods of communicating designs. Mechanical design engineers at the Johns Hopkins University Applied Physics Laboratory (APL) leverage these advances every day to make critical contributions to diverse domains, such as space exploration and military dominance.

BACKGROUND

Historically, the mechanical design discipline involved talented drafters or detailers communicating solutions into mechanical detail drawings used for fabrication. These drawings were created manually on drafting boards, using tools such as T-squares, compasses, protractors, rulers, scales, drafting triangles, mechanical pencils, and eraser shields. In 1957, Dr. Patrick Hanratty introduced the foundation for what would eventually become computer-aided design (CAD), earning him the moniker the "father of CAD."[1] Despite this advance, for nearly 30 years, engineers still used rudimentary tools to make engineering drawings manually—CAD tools during this time merely digitized these drawings.[1] These early versions of CAD tools evolved from generating 2-D designs to eventually producing complex, parametric 3-D data sets. The advanced drawings contained embedded information, rendering the hand drawings nearly obsolete.

APL has actively engaged in the advancement of technology throughout its history, evidenced by discussions in the 1986, 1991, and 2000 *Johns Hopkins APL Technical Digest* articles,[2–5] and has been committed to achieving more efficient workflows in engineering design and fabrication. As new techniques have been introduced and commercial CAD software has changed, the lines have blurred around the roles of drafters/detailers, designers, and engineers as they continue to solve complex mechanical engineering design challenges.

GEOMETRIC DIMENSIONING AND TOLERANCING

Geometric dimensioning and tolerancing (GD&T) has been around since 1938, when the concept of true position was first developed to mitigate fabrication problems and reduce the number of scrapped parts. True position is the foundation for today's GD&T and has grown to include other concepts, such as flatness, roundness, and more. Today, GD&T is a design standard for managing the manufacture of high-precision parts and assemblies. It uses a series of rules that govern how different types of geometric features are allowed to vary from their ideal or nominal shape, size, position, and orientation within an allowable tolerance. GD&T provides a universal standard to account for manufacturing variability and ensures that parts will interface correctly, even when produced by different sources. Establishing a set of allowable tolerances at the beginning of a design and adhering to them throughout the process is critical to delivering a successful product. While it is impossible to completely eliminate manufacturing variability from a design, GD&T provides an in-depth understanding and precise control from the start, which maximizes production efficiency.

GD&T can be used in any application that requires manufacturing and assembling parts and can be scaled to parts of any size or complexity. Most importantly, GD&T helps predict the compounding effect of manufacturing variations, known as tolerance stack-up (Appendix 1). Understanding tolerance stack-up before producing at scale—and even before low-volume prototyping—is crucial for minimizing product development costs.

A traditional tolerance stack-up analysis would look at the statistical likelihood of variability of only the size and position of part features based on the anticipated production methods. Analysis with GD&T accounts for the form and orientation of these features as well. Consider as an example a simple assembly consisting of several cylinders that interface with each other end to end on flat surfaces, all of which must then be placed inside a sleeve of a particular diameter and length. To ensure proper fit, the designer would obviously need to control the tolerance of the cylinder diameters and their individual lengths. They would also need to consider the overall assembled length if each cylinder were to be manufactured to its worst-case allowable dimension. The designer could even go so far as to consider the statistical likelihood that each cylinder is manufactured to a particular size. Still, this analysis does not account for the fact that the faces of each cylinder might not be flat, parallel to each other, or perpendicular to the axis of the cylinder. As a result, even though the lengths and diameters are all deemed sufficient, the assembly of the cylinders could have a skewed or bowed shape, which, depending on the extent, could violate the envelope of the sleeve that the cylinders must fit within. GD&T provides a means to control every aspect of the geometry of the cylinders by accounting for the statistical variation in size, orientation, form, and location, giving a higher-fidelity look at the possible complications of the assembly.

Although this is a simplistic example, one can imagine real-world applications where a similar situation would be of critical importance—for instance, the assembly of multiple stages of a rocket where the overall straightness of the assembly directly impacts its aerodynamics, or segments of a missile that must fit within the envelope of the launcher space. Incorporating GD&T and associated tolerance stack-up analysis early in the design workflow sets the foundation for manufacturing sound mechanical components that will function as intended. When applied correctly, GD&T allows for efficient designs to be successfully fabricated in a cost-effective manner.

GD&T is applied to all types of mechanical design tasks within APL's Research and Exploratory Development Department (REDD), including large-scale flight assemblies, small-scale electronic assemblies, full system integration, and everything in between.

PROGRAMMING AND CABLING

GD&T is one of many best design practices that are important to follow when developing an electronics enclosure. Another critical practice is incorporating electrical cabling harnesses between components in the virtual space.

CAD modeling for electromechanical systems is often separated into two categories: electronic and mechanical CAD (ECAD and MCAD, respectively). ECAD allows electrical engineers to document the connectivity of electrical components and layouts of printed circuit boards in great detail, while MCAD allows the mechanical team to design and arrange the physical components that house or mount the electrical ones. Mechanical engineers must consider many factors when deciding how to arrange electronic components in an enclosure. For example, they must consider where cables will be routed between components and how they will be secured to facilitate good airflow and ensure that proper clearance and minimum bend radius requirements can be met to protect cables from damage. It is also valuable to be able to report approximate cable lengths and estimated masses to the fabrication team. To that end, it is often helpful to include cable models in the MCAD assembly.

Many CAD software packages provide cabling extensions for this purpose, but defining cables manually is extremely tedious for any significant number of cables. To overcome this obstacle, APL engineers developed a graphical user interface (GUI) in Python, known as WRLpool, that leverages logical referencing in PTC Creo Parametric, an industry-standard software package.

WRLpool allows mechanical designers to quickly turn wiring diagrams into 3-D MCAD representations. Leveraging Creo's logical referencing feature makes large-scale iterative design possible and simultaneously allows the engineer to include a level of detail that clearly communicates the design intent to the customer. Figure 1 shows an example of an electronics enclosure with a complex branching harness composed of more than 400 individual conductors. During the design process, as components inside the enclosure changed location and the electrical team revised routing within the harness itself, WRLpool allowed the MCAD designer

Figure 1. MCAD assembly featuring complex cabling harness. This design was created using the APL-developed WRLpool GUI and helped the MCAD designer account for over 400 conductors in the electronics enclosure.

to keep up with each design iteration and maintain an accurate harness representation. Without WRLpool, it would not have been possible to represent the cables at this level of detail within the schedule constraints of the project.

Typically, the electrical engineering team will produce a wiring diagram for the assembly. That diagram serves as the input to WRLpool, which prompts the user to define wire parameters and make associations between ports and components in the MCAD assembly. It compiles this information into a neutral wire format (NWF) document that can then be imported into Creo. In Creo, the user builds a cable network to prescribe a "skeleton" along which cables will be routed, then imports the NWF and commands Creo to automatically route all the cables. This network is parametric and can be used to adjust the general shape of the cables. Creo also has the ability to output a file containing the lengths of each cable in the assembly, which WRLpool can then use to estimate the mass of the cables. When a revised wiring diagram is provided, changes to the cabling in the MCAD assembly can be easily implemented by overwriting the data in WRLpool, exporting a new NWF, and reimporting into Creo.

Planning and developing the cabling and harness strategy during the hardware design process is important for development of efficient optimized designs and can complement the design and engineering.

HARDWARE REVERSE ENGINEERING

Reverse engineering is the practice of attempting to recreate an object that already exists. With the current tools, reverse engineering is often used to bring physical objects into the digital space for purposes such as:

- Replicating a product or component exactly
- Reproducing a product or component with additional functionality
- Redesigning a product or component for improved performance
- Repackaging a product or component
- Repairing or replacing damaged components
- Regenerating surfaces or geometry for use in a virtual environment, CAD, or finite element modeling (FEM)

The resulting virtual representation of a reverse-engineered part or component can be included in that part's digital twin environment. "A digital twin is a virtual representation of an object or system that spans its lifecycle, is updated from real-time data, and uses simulation, machine learning and reasoning to help decision-making."[6]

Before technological advances such as CAD, reverse engineering primarily focused on physically rebuilding an object using rudimentary measuring tools like calipers and scales, making molds to copy a part, or recreating a part's geometry using photographs. Reverse engineering tools have evolved to encompass multiple advanced techniques to capture 3-D data of varying resolution. New areas of expertise are required to gather and process the data. Modern reverse engineering tools and techniques include coordinate measuring machines, laser scanning, photogrammetry, and x-ray computed tomography (CT). These capabilities generate data points that can produce CAD geometry for a variety of outputs.

Commercial programs allow for visualizing and manipulating advanced geometries beyond the capabilities of traditional CAD packages. They can be used to convert 3-D point cloud data collected from optical scanning equipment into a closed surface or solid geometry. This capability allows the designer to incorporate unique objects into CAD assemblies and then analyze deformations and compare objects in three dimensions to detect small variations. In addition to analyzing optical point cloud data, these programs can also analyze CT scan data. This allows for 3-D modeling of geometry that may be embedded in a substrate or otherwise inaccessible to optical scanning devices. Because of their versatility, these products span many applications, including biomedical, military, rapid prototyping, advanced topology optimization, and more.

As an example, consider an off-the-shelf item that is made of cast aluminum and contains cavities and other complex features. Depending on its complexity, modeling this object from scratch would be extremely time consuming and costly. Instead, the object can be optically scanned, resulting in a highly accurate 3-D point cloud that is representative of the overall geometry. This data can be imported into a commercial software program, where it is converted into a closed surface and,

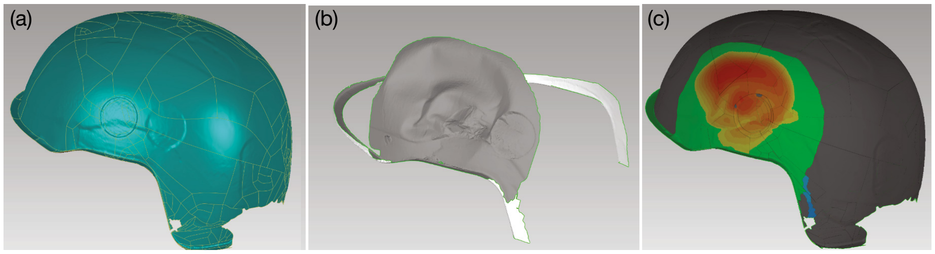

Figure 2. 3-D comparison before and after impact. (a) Un-deformed helmet scan used as reference. (b) Scan data of a deformed helmet after impact. (c) Scan data of the same deformed helmet projected onto the un-deformed helmet surface as a heat map with the color scale showing the degree of deformation over the area (red is the largest deviation, and green is no deformation).

consequently, a solid CAD object that can then be assigned mass properties and imported into an assembly to visualize fit and function. Instead of requiring hours of measuring and sketching the geometry, this process is relatively fast and accurate.

Another capability of such programs is the ability to overlay and compare multiple 3-D scans. This is particularly useful for comparing a CAD object to an as-manufactured part to visualize the deviation from nominal dimensions. This capability can also be used to compare an object to itself in a pre- and post-deformation state. An example is shown in Figure 2. The object shown is a helmet that was subjected to an impact by a projectile. The deformed area is shown as a color map, where the different gradations indicate a certain amount of displacement from the same helmet before the deformation occurred. This type of analysis can be used to characterize material behavior under impact loading to anticipate deformation.

In other instances, manually creating a traditional CAD object would be impossible, as in the case of biological and organic objects. The geometry in Figure 3 shows the stages to transform a scanned image to a CAD model that can then be imported into various software packages for further development. The headforms shown in Figure 3 are typically used for developing head gear, sensor packages, and various other products for testing. These products incorporate improved biofidelic features and expanded instrumentation. The models lend themselves to using advanced surfacing techniques to further manipulate the geometry.

Reverse engineering tools that manipulate and process scanned data can transition these complex geometric forms into files that enable them to be additively manufactured.

ADVANCED SURFACING

An organic object can be manually modeled with advanced surfacing techniques. Surfacing allows for more flexibility than solid modeling. Reverse engineering is often the initial step toward applying advanced surfacing to create and generate CAD models for various needs.

In a perfect 3-D modeling world, all CAD representation is in a solid form. This allows the parts to be sent out for manufacturing via various methods. It is important to note, however, that when CAD files are exported electronically (in file formats such as STEP, IGES, and STL) to be used in different manufacturing software, the files are translated into surfaces, curves, points, and numerical data.

Surface modeling was the precursor to solid modeling. Behind every solid model are surfaces that have come together to form the perfect water-tight model. Without surfaces, there would be no solid models.

Surfaces are the facets that make up the shapes of everything imaginable. Some facets are simple, like the sides of a cube. Others are more complex, like a human face or the texture of a jagged rock. When modeling simple 3-D parts, typical solid modeling techniques can be used. When modeling something more complex, advanced surfacing can play an important role.

Figure 4 illustrates the process from file import to surface panel manipulation for a variety of geometries that can be used to meet

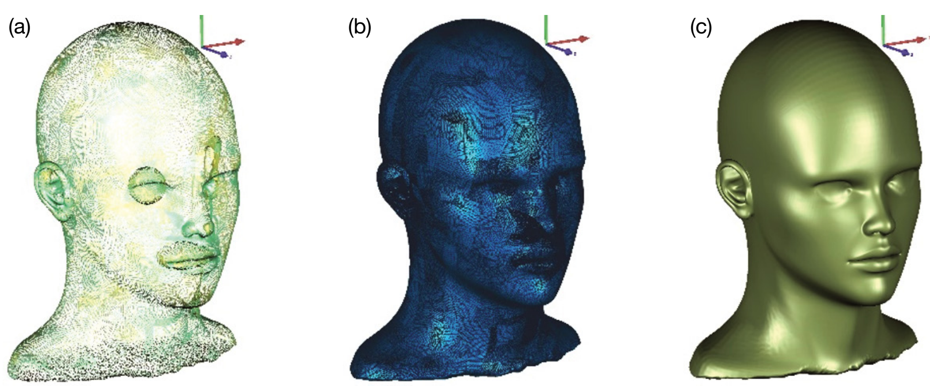

Figure 3. Reverse engineering process: scan to CAD. (a) Point cloud output from 3-D scan. (b) Tessellated surface connecting all the points. (c) Final mathematical surface generated by mapping to the tessellated surface.

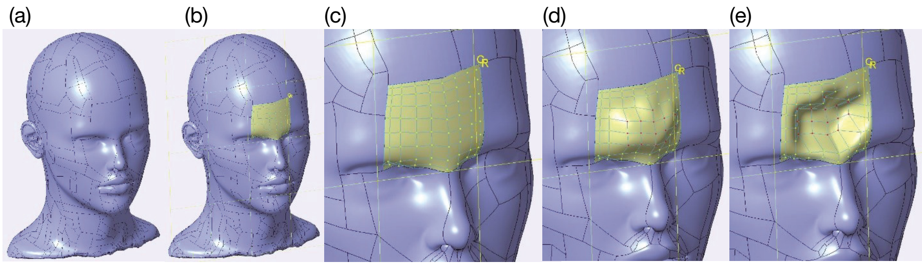

Figure 4. Example of advanced surface modeling. (a) A surface file is imported. (b) The surface area to be altered is selected (panel c shows a close-up of the surface area). (d and e) The knot points to manipulate are selected and pulled and pushed in all directions to achieve the desired outcome.

requirements for CAD representation, simulation, or build files.

When working with surfaces rather than solids, the ability to manipulate the surfaces allows for more complex curvatures to be represented. Once the final shape has been created, the surfaces can be solidified and the solid model of the design is complete. The design can then be imported in various environments for further use.

HAPTICS

Haptics refers to technologies that a user experiences through the sense of touch. The most common type of haptic feedback is the sensory vibration felt when using a smartphone keyboard. This is an example of tactile feedback. Haptic feedback can also be force feedback—for example, force feedback is added to robotic training surgery scenarios, allowing surgeons to feel different forces meant to mimic cutting through skin, ligaments, bones, etc. Haptic feedback has become increasingly important to mechanical design as our devices have changed from analog/physical devices to digital/virtual devices. Users are accustomed to applying touch for feedback, and haptics allows them to get that feedback even if the device is digital/virtual.

Haptics and CAD

Adding haptic feedback to a design has advantages beyond just this user familiarity. Haptic feedback in a virtual environment helps increase how realistic the virtual experience is. For example, Boeing developed the Voxmap PointShell Software Library[7] to enable detection of collisions in complex assemblies. This software, combined with other haptic interface tools, allows the user to feel forces of contact when assembling the parts, as if they were manipulating a physical object. This allows a designer to solve complex problems faster and validate assembly and plan for maintenance. The field of haptics continues to evolve from point interactions with tools such as haptic interfaces to haptic gloves that allow the user to feel their design in virtual reality. APL is exploring applications for these technologies as their fidelity improves and their cost decreases. Incorporating haptic feedback into the design process is just another complementary tool in the designer's tool set.

Applying Haptics in Sponsored Work

Staff members working on APL's Future Cockpit Experience project[8] theorized that haptics could benefit pilots as well, and they are working to incorporate haptics into future aircraft to help prevent fatal accidents. Between 1990 and 2000, 39% of all fatal US Air Force accidents were caused by spatial disorientation from low-visibility conditions.[9] Low-visibility scenarios make it difficult for pilots to maintain awareness of the horizon line, which is key to avoiding low-angle drift. Pilots currently have to rely solely on reading instruments and displays to glean this information. The team hypothesized that a haptic vest could provide situational feedback to the pilot.

To develop the vest, the APL team investigated various haptic technologies of different fidelities, ranging from a simple vibrating band to a complex tactile feedback suit. Any solution had to be both feasible for APL to develop and integrate with the larger cockpit system and acceptable to the end user. Ultimately, a complete suit was chosen for development of the modes of haptic feedback. The team is exploring methods to communicate aircraft altitude and attitude, wingman position, and various warnings, cautions, and threats via vibrational feedback delivered through the vest, which in turn will help increase a pilot's situational awareness. The team has prototyped these haptic feedback strategies and is working with pilots to determine the most useful and intuitive way to incorporate haptics for future iterations.

APL developed a proof-of-concept to create a virtual environment with meshed terrain that allowed the user to feel changes in elevation to assist in mission planning. The team added a chalkboard feature so that users could annotate their land-to-path plan.

Haptic feedback is a powerful element that can help trick human senses into thinking virtual environments are real. Haptic devices can also intuitively deliver critical information to users—in some cases, saving money and lives.

Before being used in a real cockpit, however, the haptic device developed by the Future Cockpit Experience team will be tested in a cockpit simulator that uses another emerging technology: augmented reality (AR).

AUGMENTED REALITY/VIRTUAL REALITY

APL is prototyping a cockpit simulator using AR to quickly test new changes and get feedback from the user. Traditional prototyping methods involve mocking up physical parts, a process that can be extremely time consuming. The cockpit hardware design team strives to merge traditional and conceptual design elements into a single user-centered design that combines innovative ideas with realistic engineering intuition. These considerations led the APL team to prototype the design in an AR space so that end users could interact with the design and the design team could iterate more quickly than with traditional prototyping methods. Figure 5 shows the workflow of conceptual design sketches, which are turned into CAD models and then again transformed into a training cockpit that uses AR. To design this futuristic cockpit, the team cannot simply incrementally iterate today's cockpit, so constant user feedback is critical.

First the STEP file is uploaded to a commercial web- and headset-based application. Once the file is uploaded, it can be decimated, reducing the polygon count, and individual parts can be shown and hidden. A session is created and the part is loaded into AR using an alignment target. In this case, the team chose to overlay the cockpit design on chairs set up in the physical space so that pilots could physically sit in the design. The location of the cockpit could be adjusted in the session by using the controls on the web app.

This method allowed the design team to make user-informed updates to the locations of controls and displays in the CAD model and then reupload the model within days for another feedback session. For example, users noted that the original location of the flight controls was uncomfortable, and the displays needed to be moved to improve visibility. The design team turned around changes faster in CAD than they were able to print a poster for the demonstration event! During the demonstration event, the pilots identified some areas of the cockpit that needed more visibility to allow them to see the wings of the aircraft—something the team had not considered. Without this rapid and iterative prototyping method enabled by AR, key details could have been overlooked in the design phase and left to be discovered only after the system was fabricated.

Haptics, along with AR/VR, can support rapid prototyping needs (as described by Sharp et al., in this issue), enabling designers to quickly solve problems by iterating from ideas and concepts to real solutions so that they can prove feasibility and success efficiently.

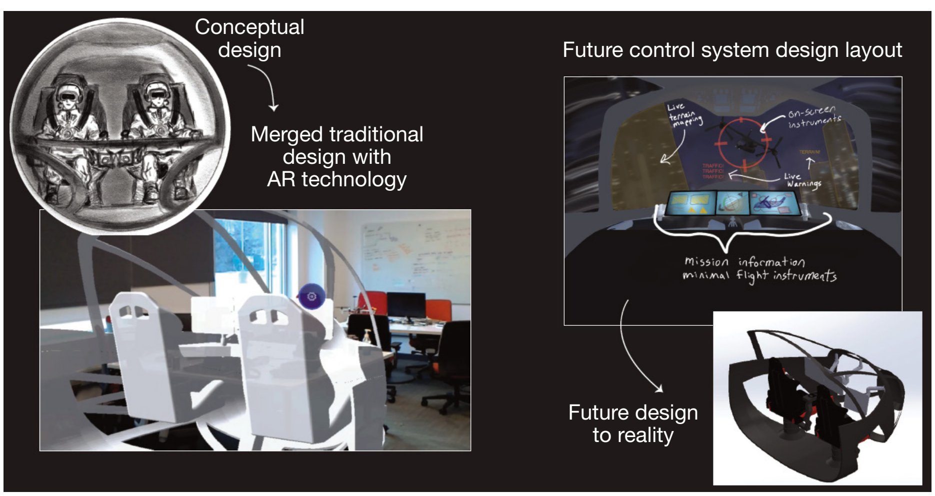

Figure 5. Workflow of transforming conceptual design sketches into a CAD model and then into a virtual cockpit enabled by AR. This approach allowed for rapid iteration of changes and let end users give critical feedback on positioning and visibility before a physical prototype was built.

PHOTOREALISTIC IMAGES AND ANIMATIONS

A key aspect of delivering any product is properly communicating the design. Often, end users are unfamiliar with how to read engineering drawings, and miscommunications can lead to assembly errors in the final product. Using photorealistic images and animations to communicate the intended design to end users can help prevent miscommunication. These renderings will look more like the final product than a drawing or CAD model. Figure 6 illustrates the difference between a CAD model and a photorealistic image. It shows two renderings of the redundant electronics module on Parker Solar Probe, NASA's mission to revolutionize our understanding of the Sun.[10] APL designed, built, and operates the spacecraft.

Several rendering programs are available to generate these images. Stand-alone rendering and animation programs can import many formats of 3-D data and integrate with CAD programs, allowing engineers to link a CAD model with the photorealistic environment. This ability makes it easy to modify different parts in the photorealistic rendering, whether a static image or animation.

The first step when making any rendering is setting the material surface properties. In addition to adjusting the generic "surface roughness," users can define complex textures and colors by using sample images of the surface. They can develop and select a variety of materials for their rendering and apply these to the entire component or

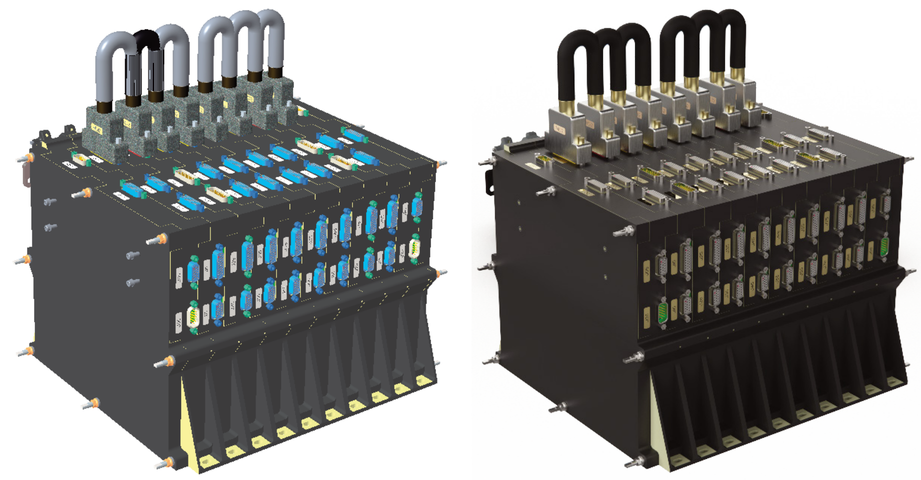

Figure 6. Comparison of the CAD render (left) and the photorealistic render (right) of the design for the redundant electronics module for Parker Solar Probe. These examples show the difference between a CAD model and a photorealistic image.

system being rendered. These programs also allow users to create a background that replicates the environment in which the component will be used.

After defining the materials and the environment, users can generate a still rendering. If the final rendering will include animation, users will define the movement of the system, as well as the camera. Figure 7 shows screenshots of the camera setup and final video.

Creating good renderings takes time, but taking this time ensures that both engineers and end users understand the product's purpose and design. An assembly animation, such as the one shown in the supplemental video, can greatly improve communication and presentation across all phases of a project from concept to design to realization.

WEB-BASED VISUALIZATION

Web-based visualization is another tool available to mechanical design engineers to overcome the challenge of effective design presentation. This is helpful when an end user is unfamiliar with reading engineering drawings and lacks the software or hardware needed to view models or renderings. Mechanical design engineers must create user-friendly interfaces with minimal system requirements imposed on the end user. Using CAD models from most platforms in combination with technical illustration and video creation and editing tools, engineers can make a menu-driven interface that only requires a web browser to operate.

Technical illustration tools that can create 2-D or 3-D illustrations can be used as a graphic technical guide. They can import CAD models directly, and users can animate sequences—showing, for example, how a part is assembled (Figure 8) or where a particular component is located within a larger system. These animations can be exported as .wmv files, which most computer systems can play.

Next, engineers need to package the designs in an easy-to-use format. They can create a user-friendly interface by using commercial video editing tools. They can place their videos along a timeline, narrate voice-overs, and create a menu-based system at the beginning of the timeline. The entire menu-based system can be exported, and end users can load it in a web browser. This approach allows engineers to communicate design plans visually and verbally and to present the entire package to end users without requiring expensive software or specialized computing equipment. Figure 9 displays a screenshot of creating such a timeline and shows what an end user would see in a web browser.

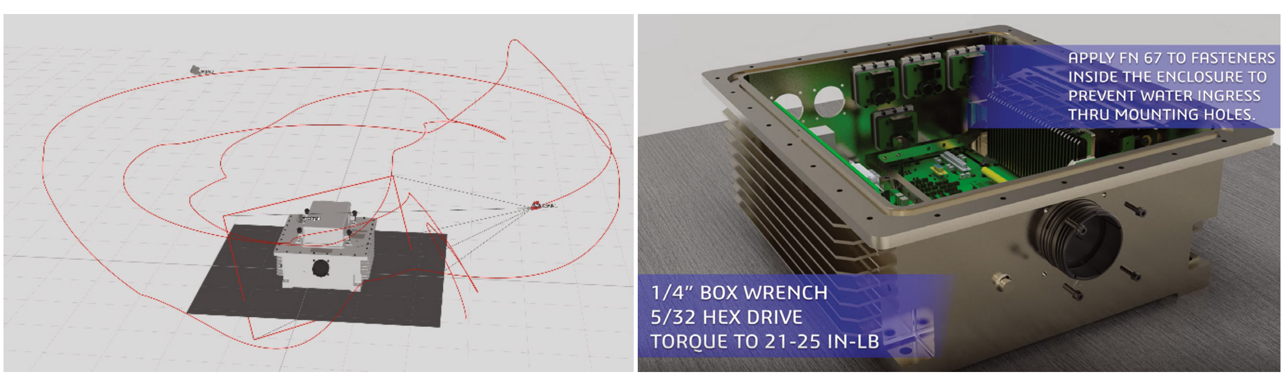

Figure 7. Screenshots of the camera setup and final video. The animation camera track is shown as a path line in red (left); the still image from the animation after post-processing is also shown (right).

APL put this method into practice during a vehicle test launch. Before the launch, over 500 sensors were installed on the interior and exterior of the vehicle as well as on the launch tube and support hardware. Before the web-based visualization method was incorporated, the end user had to interpret complex diagrams to locate each sensor in the assembly so that they could understand the results they received from that particular sensor. Using the web-based visualization method, the end user was able to go through the menu-driven interface to filter by the general location of the sensor (e.g., the launch tube, the test vehicle, or the vertical support group) and sensor type, as well as other characteristics, such as temperature, pressure, dynamic pressure, displacement, and linear or angular acceleration. The interface then displayed the sensor part numbers specific to the selected options. A simple click on the sensor part number launched a video clearly showing the orientation of the vehicle and panning and zooming to the specific location of the selected sensor. Using just a web browser, the end user was able to process the results of the launch test in less time and with less chance for error. An example of a web-based visualization for a representative hinge assembly can be experienced in the supplemental application.

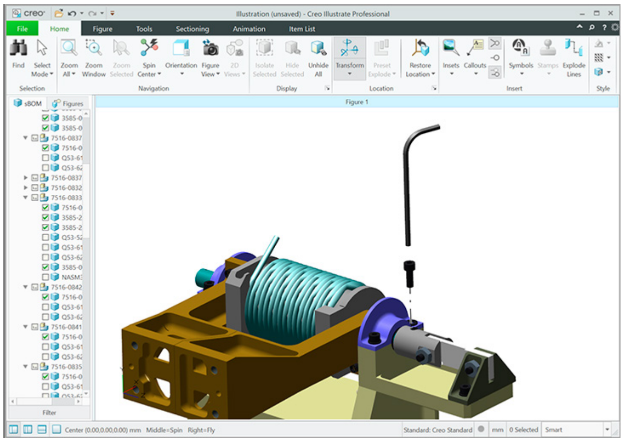

Figure 8. Screenshot of animating an assembly. In the final animation, end users would see the hex wrench tighten the bolt in place on the assembled part.

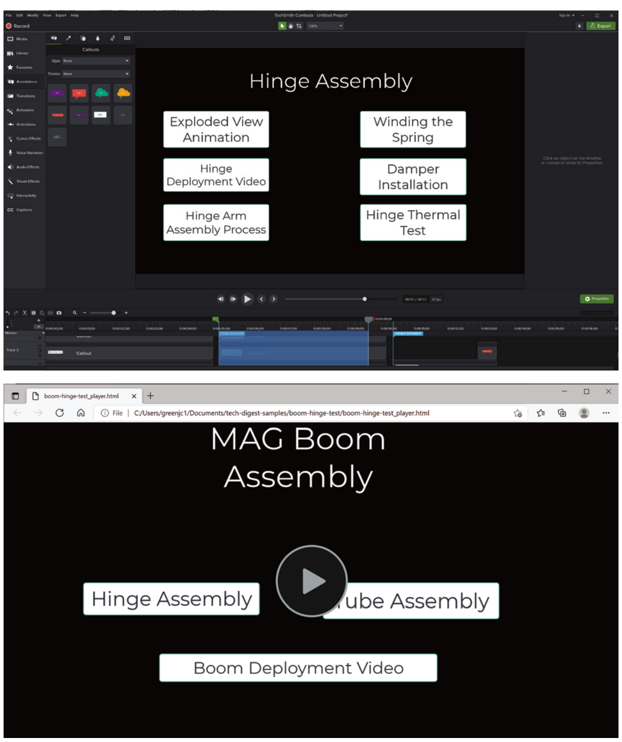

Figure 9. Web-based visualization example. A screenshot of creating a timeline in a video editing tool (top) and an end user's view in a web browser (bottom).

CONCLUSION

Various technological developments have advanced the field of mechanical engineering design, allowing APL engineers to realize innovative ideas to solve critical challenges. The advanced technique of GD&T allows an engineer to better visualize the efficacy of their solutions. The APL-developed WRLpool GUI supports complex cable design in 3-D space, improving electromechanical integrated designs. Hardware reverse engineering techniques capture complex and irregular geometry and translate them to the digital environment. Advanced surfacing techniques allow engineers to realize the design of complex organic structures. Leveraging haptics in design and demonstration contributes additional sensory information to a user's experience. Communicating designs and design intent with AR/VR, photorealistic images and animations, and web-based visualization all increase an end user's understanding. With these techniques, the mechanical engineering design discipline has evolved, giving engineers the opportunity to deliver increasingly advanced designs and to communicate these designs in new ways.

WHAT'S NEXT?

Where will the technology take us next? Will designers and engineers be completely immersed in a virtual environment in the actual application space to develop new solutions? Will CAD systems use artificial intelligence to seed a solution to a complex problem? Will neural interfaces connect the engineer's thoughts and apply them to a complex solution? While we do not know exactly what may lie ahead, new technologies as they emerge will be embraced, explored, and applied to the solutions to complex problems that mechanical engineers and designers face.

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APPENDIX 1. TOLERANCE ANALYSIS

Design engineers gain powerful tolerance analysis capabilities within their design environment by using specialized modules and extensions in their CAD tools. They can easily analyze, visualize, and understand the geometric tolerance stack-up and dimensional variation that impacts the fit and function of a design.

When integrated directly into the CAD design environment, tolerance analysis tools allow the designer to:

- Evaluate the impact of tolerances on the manufacturability of designs
- Ensure designs meet manufacturing requirements
- Utilize Six Sigma design methodologies to ensure design quality
- Streamline the design process, improve productivity, and reduce time-to-market

Figure 10 shows an example of an assembly containing Belleville washers where the tolerances of several parts contribute to the overall tolerance stack-up. Analyzing this via hand calculation would be tedious. It also would not produce as detailed a visualization of the statistical variation, which is what makes assessing the design easy and efficient.

In addition to showing the statistical variation, the tool shows each component's contribution to the overall stack-up. The contributions of each component's tolerance to the overall tolerance stack-up is shown as a percentage of the total in the histogram plot in Figure 11. The loop diagram is an alternative representation of the component contributions, shown as the length differential from the selected baseline of the analysis.

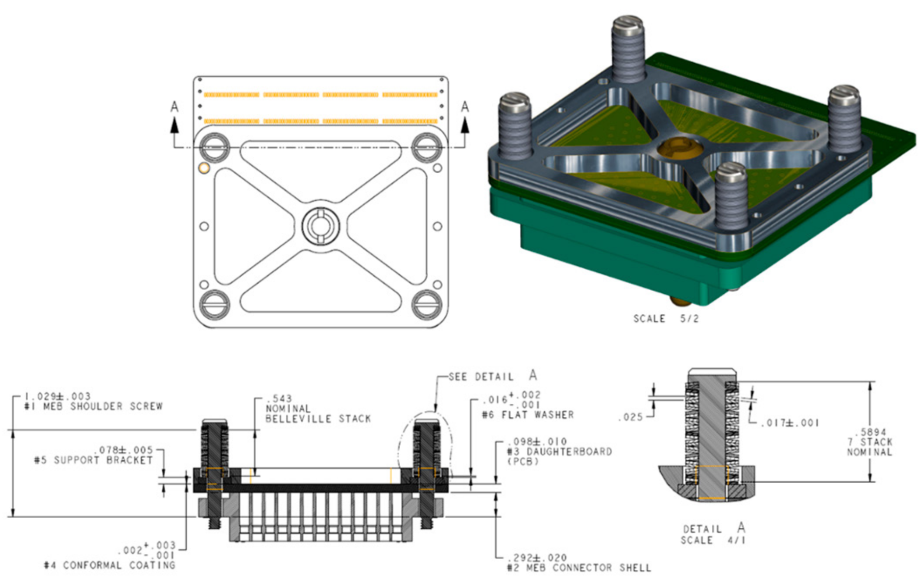
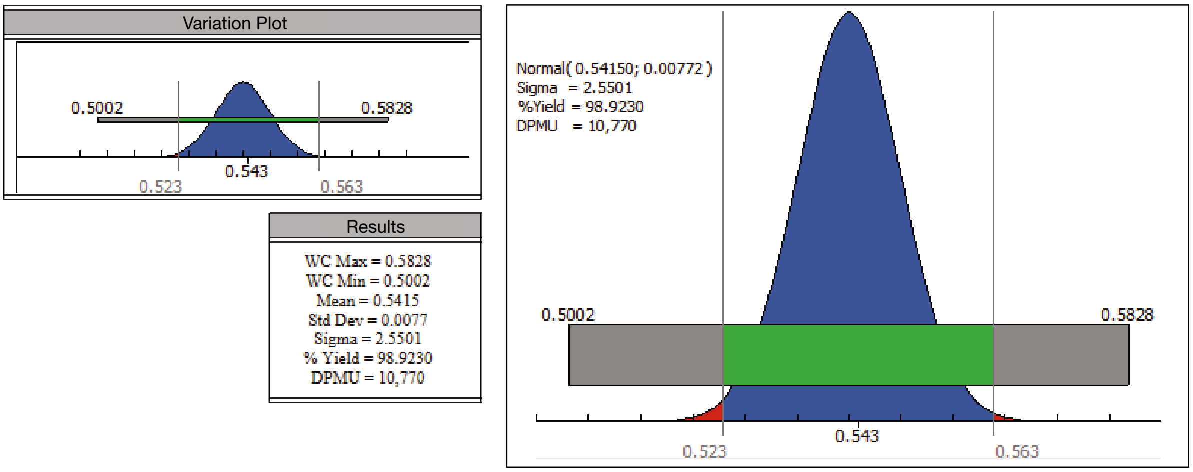


Figure 10. Example of assembly tolerances that influence a tolerance stack-up analysis. The visualization aids in determining the length of the four shoulder screws to ensure that the proper amount of preload is applied by the Belleville washers.

Analysis results



Dimension details

Name	Tolerance	Sensitivity	WC Range %Contribution
TOLERANCE-LAYOUT-MEB:d26	0.292 ±0.020	-1	48.43%
0420-01-PWB:d0	0.098 ±0.010	-1	23.73%
0400-TEST:d0	0.078 ±0.005	-1	12.11%
6204-01:d0	1.029 ±0.003	1	7.26%
TOLERANCE-LAYOUT-MEB:d27	0.002 +0.003/-0.001	-1	4.84%
WASHER-TEST-LAYOUT:d0	0.016 +0.002/-0.001	-1	3.63%

Name	Tolerance	Sensitivity	Cp	Distribution	Variance %Contribution
TOLERANCE-LAYOUT-MEB:d26	0.292 ±0.020	-1	1.00	Normal(0.292; 0.0066667)	74.59%
0420-01-PWB:d0	0.098 ±0.010	-1	1.00	Normal(0.098; 0.0032667)	17.91%
0400-TEST:d0	0.078 ±0.005	-1	1.00	Normal(0.078; 0.0016667)	4.66%
6204-01:d0	1.029 ±0.003	1	1.00	Normal(1.029; 0.001)	1.68%
TOLERANCE-LAYOUT-MEB:d27	0.002 +0.003/-0.001	-1	1.00	Normal(0.003; 0.00066667)	0.75%
WASHER-TEST-LAYOUT:d0	0.016 +0.002/-0.001	-1	1.00	Normal(0.0165; 0.0005)	0.42%

Dimension loop diagram

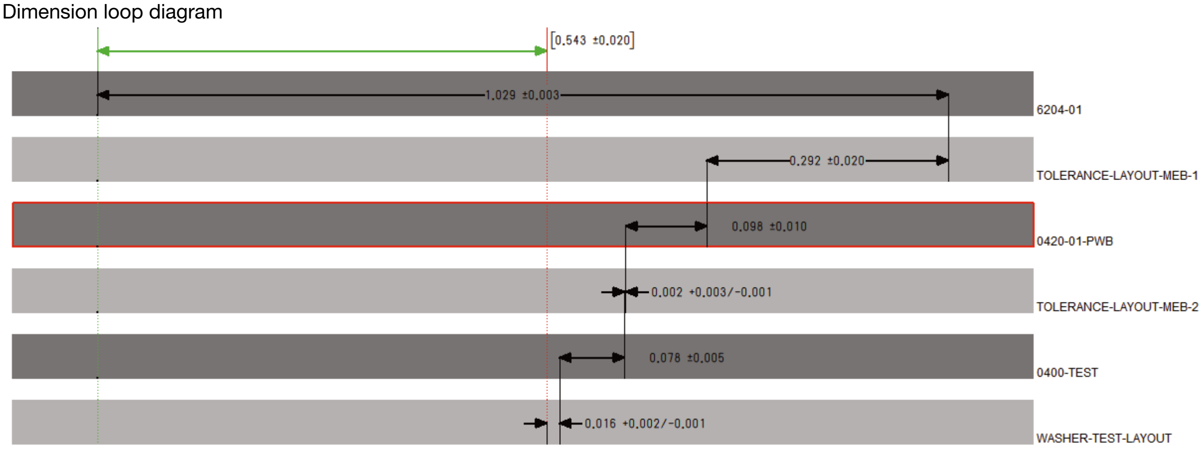


Figure 11. Visualization of each component's contribution to the overall stack-up. The contribution of each component's tolerance to the overall tolerance stack-up is shown as a percentage of the total in the histogram plot. The loop diagram is an alternative representation of the component contributions, shown as length differential from the selected baseline of the analysis.

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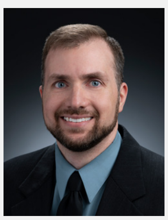

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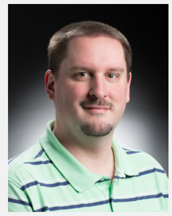

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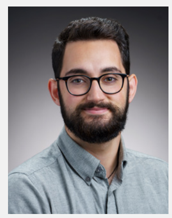

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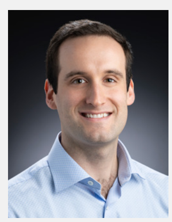

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Advanced Development and Fabrication at APL: Machines, Components, and Processes

Joseph A. Walters, Kameron F. Stevenson, Claude H. Farrington Jr., Nicholas A. Knowlton, and Kyle J. Garrett

ABSTRACT

The Johns Hopkins University Applied Physics Laboratory (APL) solves complex research, engineering, and analytical problems that present critical challenges to our nation. Its work requires collaboration across a broad realm of scientific domains and technologies, including manufacturing. APL has established modern fabrication techniques and processes for real-world applications, enabling fabrication of components for a diverse set of systems operating from the depths of the oceans to the farthest parts of the solar system. APL delivers high-quality, cutting-edge hardware by pairing state-of-the-art equipment with knowledgeable manufacturing personnel who directly interact with engineers, designers, and research scientists to achieve creative solutions. This synergy allows for rapid iteration and swift system integration. To highlight the impact of this approach, this article describes a few of APL's critical manufacturing contributions: (1) the rapid redesign of components for the Didymos Reconnaissance and Asteroid Camera for Optical navigation (DRACO), the lone instrument in the Double Asteroid Redirection Test (DART) payload; (2) the close collaboration of engineers, scientists, and fabricators on the Boundary Layer Transition (BOLT) hypersonic flight experiment; (3) the advantages of multiaxis turning for the Interstellar Mapping and Acceleration Probe (IMAP) feed horn; and (4) the use of additive manufacturing to produce novel solutions for fabricating the shielding components for instruments on the Europa Clipper and Martian Moons eXploration missions.

INTRODUCTION

Fabrication has been one of APL's core capabilities since its inception. The Lab continues to maintain the resources, facilities, and expertise to fabricate mechanical parts for complex systems that ultimately travel to the deepest depths of the ocean, the highest points in our atmosphere, and the outer reaches of space. These systems' unique missions, operating environments, and performance requirements drive quests for ever-increasing tailored functionality, lighter weights, highly organic and often non-Cartesian designs, and advanced materials. This article offers a few examples highlighting how APL manufacturing experts collaborate with engineers, designers, and research scientists and leverage advanced machining equipment and capabilities to achieve some of these goals. Related advancements in design, analysis, and programming facilitate a collaborative relationship among engineers, designers, and fabricators, accelerating the maturation of ideas into designs and ultimately functional hardware. Designs that used to be limited by manufacturing constraints such as three-axis control are now the beneficiary of more advanced fabrication capabilities, such as live tooling with five-axis control. Similarly, additive manufacturing is disrupting the industry by expanding the breadth of what can be fabricated. The impact of additive manufacturing will be increasingly profound as this technology leads a paradigm shift in the production of critical hardware.

This article describes APL's critical manufacturing contributions to four recent programs: (1) the Double Asteroid Redirection Test (DART); (2) the Boundary Layer Transition (BOLT) hypersonic flight experiment; (3) the Interstellar Mapping and Acceleration Probe (IMAP); and (4) the Europa Clipper and Martian Moons eXploration (MMX).

RAPID REDESIGN AND FABRICATION FOR NASA'S DART MISSION

NASA's DART[1] was the world's first planetary defense test mission. APL built and operated the DART spacecraft and managed the DART mission for NASA's Planetary Defense Coordination Office as a project of the agency's Planetary Missions Program Office. As the spacecraft was being prepared for its November 2021 launch, issues with the mirror assembly on its single instrument, the Didymos Reconnaissance and Asteroid Camera for Optical navigation (DRACO), were discovered during vibration testing. The camera's mirror sustained damage because the hanger it was bonded to was not flexible enough to withstand the vibrations that would occur during launch. Engineers from APL collaborated with NASA Goddard Space Flight Center engineers and determined that an undercut on the mounting surfaces would provide the required flexibility, but they were unsure what was possible within the short time frame before the launch. Many discussions among engineers and fabricators culminated in a solution: a custom undercut tool. The fabrication team designed a four-flute form keyseat cutter (Figure 1), and a custom tooling company manufactured it according to the design specifications. Using this tool, the fabricator was able to modify the hanger so that it could correctly mount the mirror.

The process of fabricating the flexible hanger involved many steps. The material for the part, a nickel-iron alloy, offers thermal expansion and good strength but is difficult to machine. Therefore, all machining was completed on a five-axis milling machine

Figure 1. The custom four-flute form keyseat cutter used to modify the mirror hanger on DART's DRACO instrument. To prevent damage to DRACO's mirror during launch, APL's fabrication team collaborated with the engineering team to design a custom tool that was used to modify the mirror's hanger to maximize its flexibility.

whose flexible machining platform allows for five-sided machining. The first step was to rough-machine the part within 2.0 mm (0.08 of an inch) of the finished dimensions so that it could be heat treated. This additional surface material allowed for some movement during the stress-relieving process. APL material scientists identified the proper processes for heat treating the part: the part was annealed at 830°C (1,526°F) for 1 h in a furnace, then allowed to cool to room temperature in the furnace at a rate of less than 90°C per hour. This process minimized thermal expansion and maximized stability. After the roughed part was heat treated, it was held in a fixture with a set of hard jaws, shown in Figure 2. Most of the part was machined while being held by these jaws. Then the part was flipped over and finished while being held by a set of soft jaws. After final machining, the part was inspected to ensure accuracy and precision of all dimensions. Finally, it were heat treated again, this time aged at 93°C for 48 h.

The final hardware was delivered 16 calendar days after the final design was agreed upon, after more than 50 test specimens were produced to enable verification of the design before final assembly. Because of this rapid deployment, the DRACO team was able to reassemble the mirror and hanger and pass vibration testing,

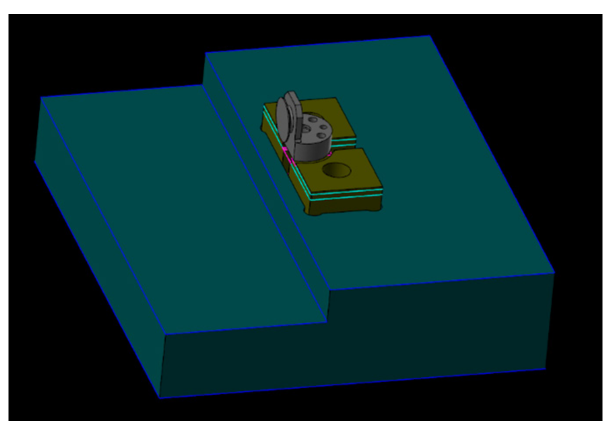

Figure 2. A model of the fixture that held the part for keyseat machining. The hard jaws (small squares) held the part (shown between the jaws) in place.

Figure 3. Before (left) and after (right) of the DRACO mirror hanger. The rapid deployment of the redesigned part allowed the spacecraft to pass vibration testing and maintain its scheduled launch date.

allowing the DART team to meet its new launch period for the mission. Figure 3 shows the original part and the final part after the design changes.

FABRICATION FOR THE BOLT FLIGHT EXPERIMENT

The BOLT flight experiment, a collaboration among academia, government, and industry, aims to further understanding of boundary layer transition—a critical phenomenon affecting hypersonic vehicle design.[2] In addition to the partnerships outside of APL, this program required a long and in-depth collaboration among APL research scientists, engineers, and machinists. The fabrication team's first task for this program was to build a 1/3-scale model out of aluminum and polyether ether ketone (PEEK), a plastic-type material, for use in wind-tunnel testing. The machinists and engineers discussed tolerances, instrumentation paths, mounting, and scheduling. This model had to have close tolerances to accurately represent a full-scale nose tip. Internal paths for instruments and the mounting of the model to the wind-tunnel mounting structure were critical considerations. And because wind-tunnel time must be scheduled in advance, on-time delivery was also paramount.

The machining was completed on a five-axis milling machine with a highly versatile range of motions and liner guides for greater accuracy. Fabrication of the small-scale model, with its complex shapes and material type, presented many challenges. PEEK tends to relieve itself while being machined, causing it to warp and move, making it difficult to assemble the components and post-machine them to hold the necessary tolerances (Figure 4) while maintaining their shape. The model was delivered on time, and the wind-tunnel tests were completed. The model was later displayed during the Smithsonian National Museum of American History's 2018 Military Invention Day.[3]

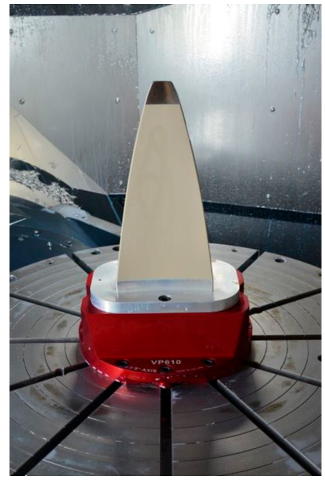

Figure 4. The 1/3-scale model of BOLT. Fabricated out of aluminum and PEEK, a plastic-type material, the model had to achieve close tolerances and on-time delivery.

After the success of the 1/3-scale model, the focus turned to modeling a full-size flight vehicle. The effort began with a kickoff meeting involving sponsors, scientists, engineers, designers, and machinists. Sponsors specifically requested that machinists attend the meeting to provide input on the manufacturability of certain features in order to avoid potential pitfalls in the fabrication process. The machinists advised adding tooling features that would ease workholding concerns and expedite manufacturing. The final full-scale model comprised a molybdenum TZM (TZM is an alloy of molybdenum, titanium, and zirconium) nose tip, a 316L stainless steel midsection, an aft end consisting of four interconnected pieces of 6061 aluminum, and, finally, four additively manufactured fairings on the back. Each material presented its own challenges during machining.

TZM is a refractory alloy whose characteristics make it difficult to machine. The material tends to tear while cutting, rather than shear, which leads to poor surface finishes, and it is abrasive to the point of wearing flats on tungsten carbide end mills while it is being cut. By using high-end coated end mills with the rigidity and precision of the five-axis milling machine, coupled with new cutting strategies offered by advanced programming software, machinists were able to efficiently process the TZM. New dynamic cutting paths enabled the TZM to be machined at a rate of more than 80 in. per minute and at a cut depth of 0.75 in.—results that were unheard of just a few years ago. Uncoated carbide tooling was used to achieve the fine surface finish required on the nose tip (Figure 5). The micro-radius on the flute generated by the coating contributed to the shearing factor, which in turn affects the surface finish. In this case, the coatings that usually extend tool life during heavy roughing were a detriment during finishing.

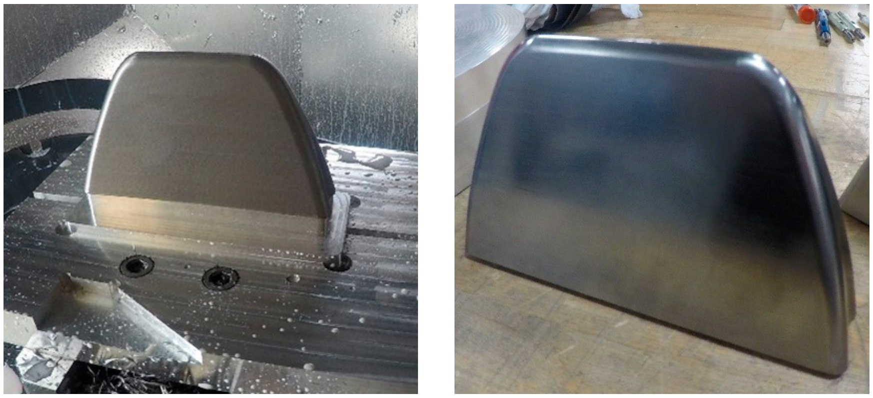

Figure 5. The TZM nose tip for BOLT. Left, the part just after the roughing operation in the machine. Right, the part after being finished and taken out of the machine.

The aft end of the assembly posed some of the greatest challenges, not because of its material but because of its shape. The four parts that made up the aft end required precise fitment (Figure 6) to avoid any unwanted steps between the parts that could affect flight or data collection. Although all pieces needed fixturing, these pieces especially required complicated custom fixturing so they could be held during machining. Modular workholding enables the machinist to pull vises or fixtures out of the machine and relocate them precisely, within 0.001 in. or closer to their previous location, to continue machining. Modular workholding systems increase flexibility and quality and speed up collaboration since the machinist can take the parts, the vise, and the fixture out of the machine with the parts still attached. The entire setup can then be given to inspection teams to check or can be taken to meetings with engineers to discuss features, mistakes, or changes, and it can then be put back into the machine for further machining. This ability was critical for the BOLT assembly, which required several skim cuts and test fits to achieve the necessary fitment. Without the precision and repeatability of the modular workholding system, fabricating these parts would have been extremely complicated and difficult.

On the other end of the tooling spectrum from the TZM, aft-end parts were cut using high-performance cutters for aluminum. The same dynamic toolpaths used for the nose tip enabled cuts at a rate of more than 400 in. per minute in aluminum. The ability to machine so quickly allowed the team to quickly turn around this highly complicated hardware. The assembly contained a few hundred instrumentation holes of various types (Figure 7). Many of these holes required deep drilling in diameters as small as 0.0625 in. With the holes all normal to the outside contour, they can only be achieved through the use of multiaxis machining.

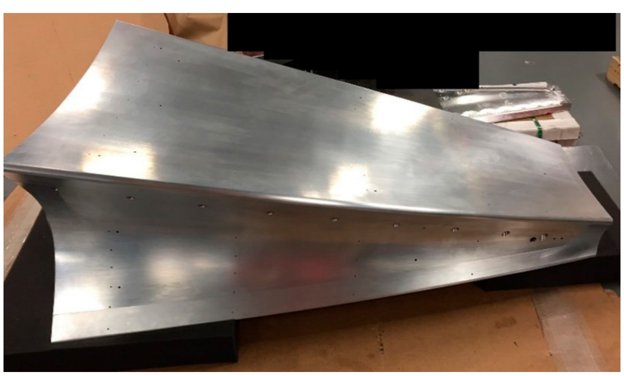

Figure 6. Precise fitment between panels for the BOLT assembly. The four parts that made up the aft end required precise fitment to avoid any unwanted steps between the parts that could affect flight or data collection.

Figure 7. BOLT aft-end assembly. Top, partially assembled BOLT aft-end assembly. Bottom, complex internal structure and instrumentation holes.

Figure 8. BOLT fairings. The fairings were additively manufactured and then post-machined.

Bolted to the back of the aft section were four fairings that were produced using metal additive powder bed technology. The fairings would have been difficult to produce using subtractive machining. Therefore, they were made of a powder-based material and post-machined to finish the critical connection surfaces (Figure 8). The machinist collaborated with the additive manufacturing team to determine where material should be left for post-machining after the additive fabrication process. In a process that is not typical of APL builds, the machinist spent many hours painstakingly gluing in and hand-filing hundreds of sensors to perfectly match the contour of the machined assembly, as well as routing and marking wires for later integration.

This collaboration continues today: BOLT 1B is being fabricated at the time of this writing, and the program's engineers and scientists continue to work closely with machinists on the next iteration of hardware.

Figure 9. IMAP medium-gain antenna feed horn. To create the grooves on the inside walls, this part was fabricated using a custom groove tool on an advanced multiaxis turning machine.

IMAP FEED HORN FABRICATION

The advantages of multiaxis machining can truly be maximized when engineers are able to use these capabilities to their advantage during the design phase. This was evident in the design of the low-gain and medium-gain antennae for IMAP, a NASA mission to investigate the heliosphere, the space filled with plasma from the Sun that envelops all the planets of the solar system.

The biggest design challenge with IMAP's medium-gain antenna was the internal geometry of the feed horn (Figure 9). Because the grooves on the inside walls are taller than most tools will reach, this part had to be machined on an advanced multiaxis turning machine. Turning and milling at the same time obviates the need to handle components multiple times, reducing the probability of a mistake. The machinist worked with a tooling vendor to determine the maximum tool diameter that would fit inside of the inner bores and be able

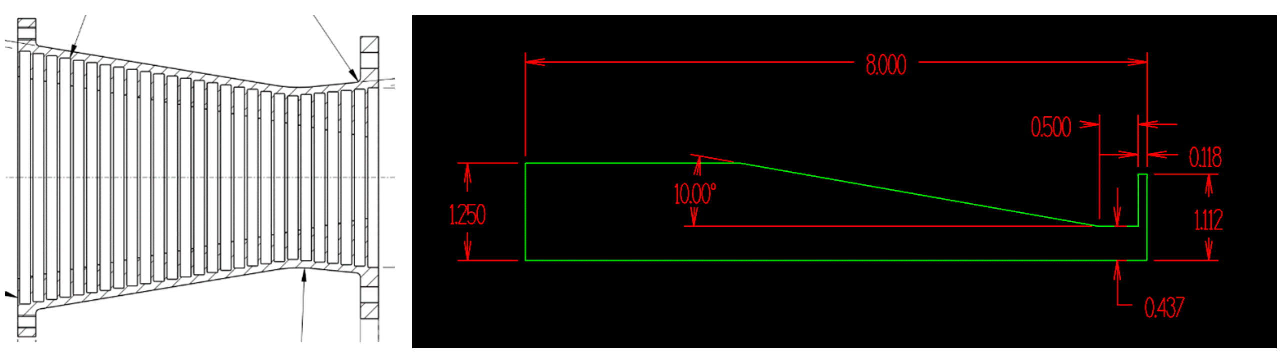

Figure 10. Computer-aided design (CAD) models for the IMAP custom grooving tool.

to groove the requested profile. The grooves were about 0.140 in. wide with 0.035 in. walls in between. The tallest grooves were 0.700 in. from the internal bore. The challenge was fitting a tool through a 1.130-in. hole, leaving a ~7/16-in.-diameter tool shank to go 5 in. deep into the part. The machinist drew up a custom groove tool, shown in Figure 10, which used the internal angle of the bores to obtain a good finish on the deep, thin-walled grooves. Collaboration between designers and machinists, along with new machining technology and the ability to work with tooling partners, made fabrication of the feed horn possible. This type of direct engagement, along with out-of-the-box thinking to reduce complexity and schedule, is another ingredient that makes APL's fabrication operation successful.

ADDITIVELY MANUFACTURED TOOLING FOR EUROPA CLIPPER AND MARTIAN MOONS EXPLORATION INSTRUMENTS

One of the most innovative breakthroughs in prototype manufacturing has been rapid development and integration of unconventional tooling. Traditionally, novel tooling has been fabricated by subtractively machining from metal billets. This process requires significant time and resources and is subject to the constraints of machining methods. The integration of additive manufacturing enables a new rapid and highly adaptable solution to achieving complex fabrication requirements that once were difficult and cost prohibitive. APL took full advantage of this advancement to fabricate custom tooling for instruments on NASA's Europa Clipper, a mission to explore Jupiter's icy moon, Europa, and the Japan Aerospace Exploration Agency's MMX.

Both spacecraft require highly specialized instruments with novel electronics shielding components. Because of the small form factor of the electromagnetic interference shielding (Figure 11), fabrication presented a significant manufacturing challenge. Designers and fabricators discussed the possibility of using rapid prototyping and engineered additively manufactured materials to fabricate forming tools to accommodate the small form factor and tolerance. The scope of work fell into the micro–sheet metal category, which is common in electronics design and components. Mechanical fabricators, mechanical engineers, and electrical fabricators collaborated to determine that the complex shielding shape for Europa Clipper's Europa Imaging System (EIS) and MMX's Mars-moon Exploration with GAmma rays and NEutrons (MEGANE) could be manufactured quickly in low volume by using polymer additive tooling. Technical experts in the mechanical fabrication area designed and fabricated polymer form tools in fewer than 48 h to produce multiple versions of the 100-μm-thick beryllium copper components. Leveraging expert knowledge in additive manufacturing processes, materials, and finite element analysis, the team generated a design that was structurally compliant and dimensionally accurate.

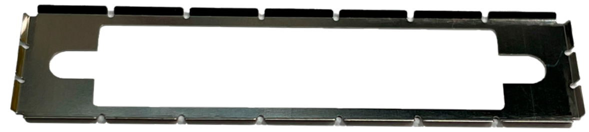

Figure 11. EIS and MEGANE electromagnetic interference shielding gasket.

The tooling was fabricated so that it could accept interchangeable inserts to accommodate different versions of the connectors for pin count, flange length, and bend radii. One of the unique challenges was the 0.006-in. bend radius; no existing standard tooling offered this radius. One of APL's sheet metal technicians proposed using a standard utility knife blade whose edge was rounded to a 0.005-in. radius—a solution that was safe for the fabricator and would not damage the part. Working closely with the inspection team, the fabricator used metrology tools to measure the radius of the blade after burnishing until it met dimensional requirements. This blade geometry was debossed into the tool holder design to capture it securely (Figure 12). Steel dowel pins replaced the back gauge for length control because the gauge on the press brake machinery could not accommodate such thin and small parts (Figure 12).

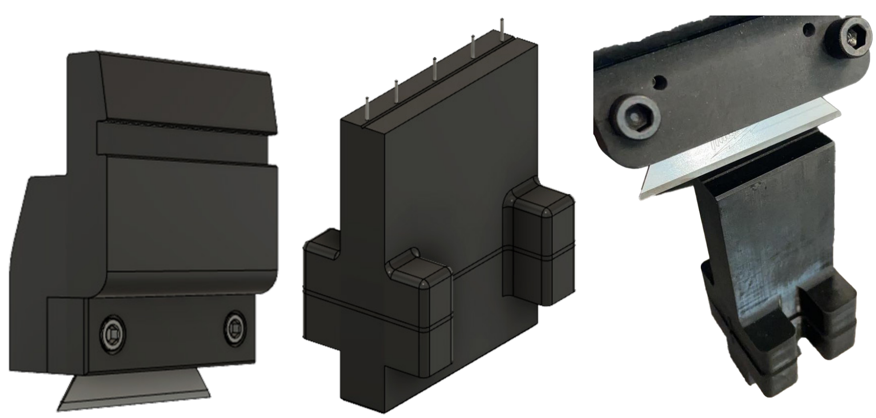

Figure 12. Custom tooling for the EIS and MEGANE. Left, model of the beryllium copper punch tool with the utility blade. Middle, model of the beryllium copper bending die with dowel gauges. Right, the completed tool.

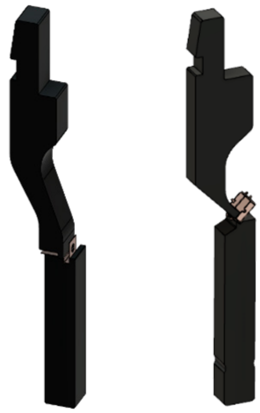

Figure 13. EIS and MEGANE printed wiring board components. Left, the EIS polymer forming tool verification model. Right, the EIS surface-mount printed wiring board shield with integrated solder pins (enabling clearance and bending verification).

Several other printed wiring board components were fabricated using additive tooling when feature dimensions and sizes did not allow for the use of conventional tools. CAD models of the tools allowed the bend clearance to be verified (Figure 13). Additionally, these fabrication efforts were ultimately part of a feasibility study that engineers could use in future manufacturing and design.

Multiple discoveries resulted from this manufacturing solution. Collaboration across multiple disciplines allowed for new capabilities to be integrated into the manufacturing process successfully and rapidly. Use of new technologies and novel approaches to manufacturing removed constraints to electronics and instrument design. In addition, these efforts unlocked applications for functional end-use additively manufactured components. The increasing use of additive manufacturing is due in part to the feasibility results from the fabrication of the electronics shielding components.

SUMMARY

APL's ability to leverage modern manufacturing processes—along with its collaborative approach in which knowledgeable manufacturing personnel directly interact with engineers, designers, and research scientists—has contributed to the success of many critical programs. This article highlights just a sample of the creativity and collaboration required to fabricate components for complex systems. The expanded role fabricators now often play in the design and development of these systems has required them to continue to expand their technical knowledge. In addition to mechanical aptitude, APL fabricators have the ability to use and understand design and manufacturing software. This knowledge and ability enables them to collaborate with designers and engineers at all stages of the design and fabrication process, as well as to program APL's cutting-edge equipment to solve complex challenges.

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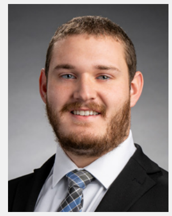

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Composite Materials: Enabling APL to Meet Complex Requirements for Critical Systems

Ryan M. Quinn

ABSTRACT

With their proven performance, unique properties, and manufacturability, composite materials lend themselves to many applications. The Johns Hopkins University Applied Physics Laboratory (APL) uses composite materials for advanced prototypes and flight-worthy assemblies in support of a variety of systems and missions, from spacecraft components and instruments, to ground- and air-based communication hardware, to uncrewed aerial vehicles of all shapes and sizes. APL designers and engineers typically use thermoset polymer resins reinforced with a variety of fiber types and architectures to create high-performing composite structures. Leveraging its expertise in several composite molding techniques, APL is able to manufacture parts that meet complex requirements and perform as intended to ensure mission success. This article describes APL's composite fabrication capabilities and contributions.

INTRODUCTION

Composite materials—created when materials with different physical, chemical, and mechanical properties are combined to maximize the desired qualities of each material for a specific application—have been used for thousands of years (Figure 1). For example, a mud brick, one of the world's oldest construction materials, combines mud or a mud-like material with a filler such as straw, resulting in a material that is resilient to squeezing, tearing, and bending and is therefore strong enough to be used in walls, buildings, and other structures. Concrete and fiberglass are examples of modern composites. As the state of the art continues to advance with the formulation of new materials, processes, and manufacturing technologies, not only do composite materials remain important in many traditional applications, but they also have the potential to revolutionize capabilities in contemporary and future applications.

For example, composite materials for spacecraft, aircraft, underwater vehicles, infrastructure, and ground-based structures continue to be in demand. Boeing is building an aircraft that is 80% composite by volume and 50% by weight.[1] NASA is flying a helicopter on Mars with composite rotor blades.[2] Composite bridges are replacing aging steel and concrete,[3] and robots are fabricating composite structures for critical applications.[4] Material suppliers continue to formulate new polymer chemistries that will drive new applications and opportunities for advanced manufacturing.

APL is no stranger to composite materials. In the 1980s, APL engineers were tasked to redesign a center

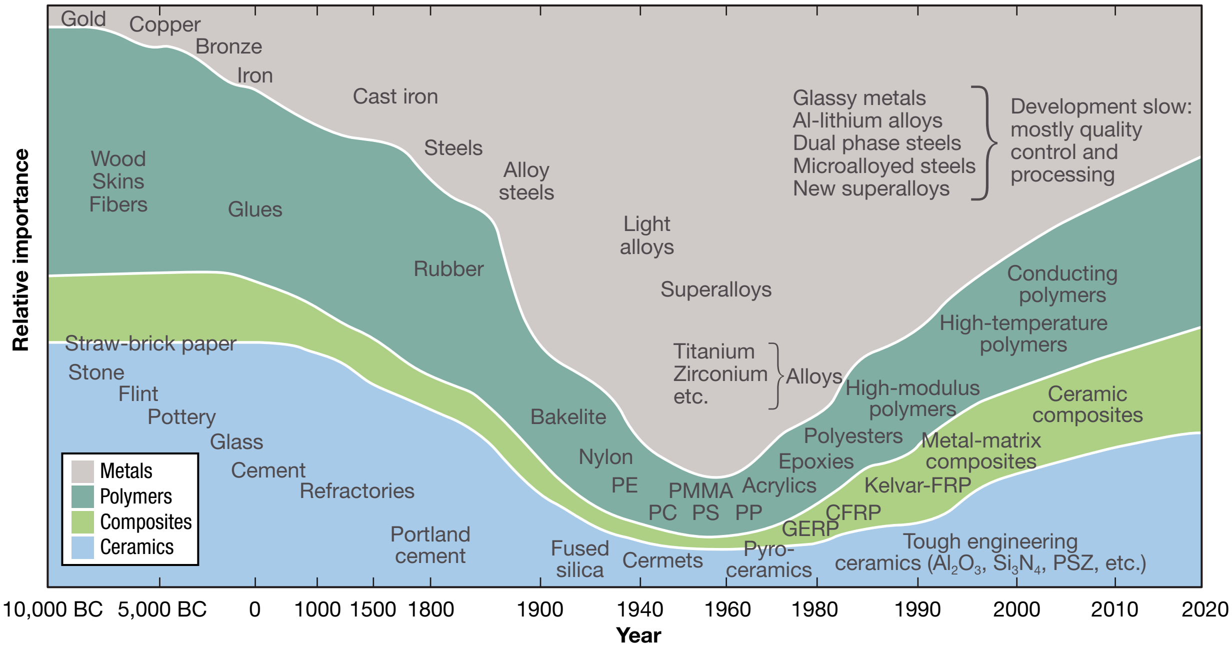

Figure 1. Evolution of engineered materials, including composites. (Modified from Ashby,[5] with permission from Elsevier.)

support structure for the POLAR BEAR satellite using graphite/epoxy composite.[6] In the 1990s and 2000s, APL engineers were involved with composite structures—for example, with the high-temperature solar panels for MESSENGER (MErcury Surface, Space ENvironment, GEochemistry, and Ranging)[7] and the Seeman Composites Resin Infusion Molding Process (SCRIMP), which has been applied to great advantage in the Advanced Natural Gas Vehicle Integrated Storage System Program and for the submarine sensor fairings used on SCAMP.[8] The Lab has been manufacturing composite structures for 35 years. This work started in prefabricated sheet-metal buildings on APL's campus where staff members used a 1 × 1 × 3-ft "Mini-Bonder" autoclave to cure the composite materials. Parts were size limited, ply patterns were manually designed, and molds were fabricated from aluminum using three-axis computer numerical control (CNC) machining. Fast-forward to today: APL experts work in a modern facility that includes a 625-ft^2 cleanroom and is home to a 4 × 8-ft autoclave and a 5 × 5 × 6-ft walk-in oven to cure larger parts. They use flattening software to generate ply patterns, an automated ply cutter to cut them, and additively manufactured molds to support low-cost rapid tooling. And they have a large five-axis CNC router to machine molds and composite parts to size.

In addition to designing, analyzing, and manufacturing composite structures in-house, APL often collaborates with external vendors to supply prototype and fully configured composite hardware for flight when parts are too big to cure using in-house equipment or have other unique requirements. In these cases, during all phases of fabrication, APL subject-matter experts maintain technical oversight of both critical and noncritical composite structures built outside of the Lab. They participate in formal reviews, write material and process specifications, travel to contractor sites to witness fabrication and acceptance operations, and provide input on any nonconformance or fabrication issues.

This article outlines APL's current composite fabrication capabilities, some of the challenges associated with composite structures exposed to extreme environments, and how the Laboratory is using composites in critical systems that explore our solar system, monitor deep space, and fly through the atmosphere to support our nation's defense. It also discusses the future of composites manufacturing at APL.

OVERVIEW OF COMPOSITES AT APL

Materials and Process

The current state of the art for composite fabrication at APL is a manual hand layup of fiber-reinforced thermoset polymer prepreg material. *Prepreg* refers to reinforcement (unidirectional, woven, or braided) that is impregnated with a semi-cured, or "B-stage," resin. Plies of prepreg are stacked on top of one another at specific fiber angles over a mold and then vacuum bagged and cured in an oven or autoclave at an elevated temperature to achieve a full degree of cure and cross-linking. After curing is completed, the parts are trimmed and drilled to their final shape for assembly. Prepreg is the material of choice at APL because it is engineered to a resin content that yields a cured laminate with a specific fiber volume fraction and ply thickness. Fiber volume is important for composite structures because the fiber is what contributes to the overall mechanical performance.

Two other composite fabrication processes used at APL are wet layup and vacuum-assisted resin transfer molding (VaRTM).[9] During wet layup, dry reinforcement is applied over a mold and impregnated with resin using a squeegee or a similar tool, and this progression is repeated for subsequent plies. This age-old process was used to build some of the earliest composite structures. It is still used today, particularly for commercial fiberglass parts and for repair of advanced composites. The drawbacks to the wet layup process are that it is messy and it is hard to achieve a laminate with a low void percentage, consistent resin content, and specific fiber volume fraction. With the VaRTM process, dry reinforcement is applied to a mold as a full stack (or preform) and vacuum bagged. Resin is drawn through the entire preform until it is fully impregnated, and then it is cured at room temperature or in an oven, depending on the resin system.

Popular fiber reinforcements in use at APL include carbon fiber, fiberglass, quartz, and Kevlar. Each of these fibers has distinct properties and is chosen based on the application of the hardware. Much like the reinforcement, the resin is also chosen based on the environment the hardware will be subjected to. The resins used most at APL are epoxies and cyanate esters. Epoxies make up roughly 70% of the resins APL uses to build composite hardware, with cyanate esters making up 20% and a combination of phenolic and vinyl esters making up the last 10%. Cyanate esters are very stable in space and are often used for spaceflight hardware, such as solar array substrates or tubes used for magnetometer booms and struts. Certain cyanate esters also have the ability to be post-cured at higher temperatures than most epoxies to achieve a very high glass transition temperature. Composite laminates, depending on the reinforcement and polymer resin, can be any of the following: strong, stiff, lightweight, damage tolerant, thermally and electrically conductive, insulated, or radio frequency (RF) transparent. Composite materials have a wide array of applications and continue to be realized for new applications.

Additive Molds to Enable Rapid Prototyping of Unique Designs

To successfully build composite hardware, the mold design, fabrication, and use are critical to avoid fabrication and fit-up issues in later assembly steps. Typical molds for composites are made from machined metal ranging from Invar (a nickel–iron alloy) to aluminum or even from composite materials themselves. Although APL teams sometimes use machined aluminum molds, more often they use additively built molds to rapidly create prototypes. The additive molds are built via fused filament fabrication (FFF), a process that combines thermoplastic model and support filament to build a part. APL's additive molds are built using polycarbonate or ULTEM 1010 because these materials have high-temperature capability for 250°F or 350°F cure cycles. While the coefficient of thermal expansion (CTE) is greater for these additive materials than for standard aluminum or other low-CTE materials, the molds can be scaled appropriately to generate the required part shape. Figure 2 shows an example mold that was additively manufactured for composite layup using ULTEM 1010.

In addition to using polycarbonate and ULTEM 1010 filament to fabricate composite molds, APL has used soluble additive support filament material to build molds for layup. The support material used for polycarbonate can be used as a mold for elevated-temperature cures and then dissolved in a bath of mostly hot water and alkaline solution to separate the part from the mold. Soluble molds enable composite parts to be fabricated with geometries that would otherwise prevent the tool from separating from the part. An example is the work that an APL team did for a project called CRACUNS (Corrosion Resistant Aerial Covert Unmanned Nautical System).[10] For CRACUNS, a soluble additive mold

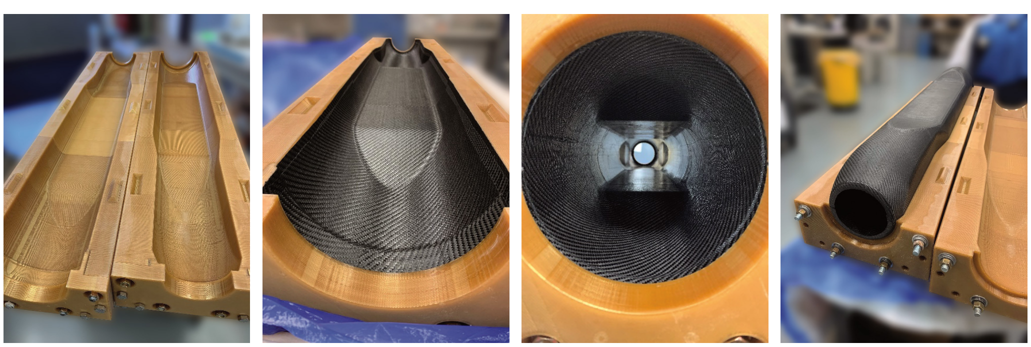

Figure 2. An fused deposition modeling additively manufactured layup mold for composite fabrication using ULTEM 1010. This two-part clamshell mold was used to manufacture a composite fuselage for a drone aircraft prototype. Each mold half had carbon prepreg material applied to it, and when the molds were stacked, the material was joined on the inside to make the continuous barrel.

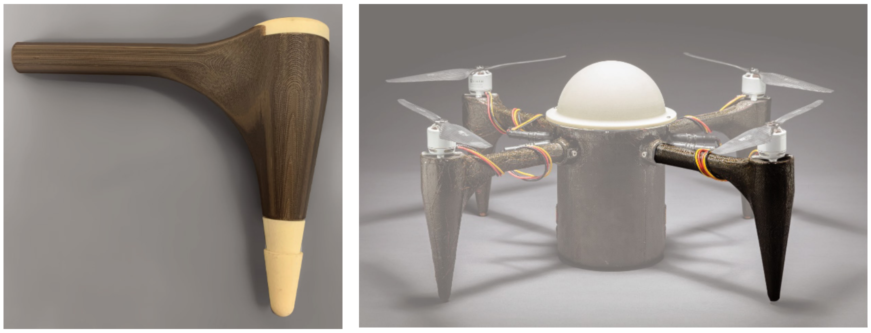

Figure 3. Mold and finished product for the CRACUNS aircraft. Left, Additively manufactured layup mold using soluble support material (brown) and glass-filled nylon inserts (cream color). Right, Assembled CRACUNS aircraft showing the composite leg assemblies.

with additively built glass-filled nylon feet and caps was used to build out the legs of the aircraft (Figure 3). Carbon fabric prepreg was wrapped around the mold and co-cured to the glass-filled nylon parts. After it was cured, the soluble mold was dissolved away, leaving a hollow co-cured composite assembly. Because of the geometry of the leg and co-cured assembly, a soluble tool was required to enable this design.

Composites Manufactured outside of APL

As mentioned earlier, when parts are too big to cure using in-house equipment or have other unique requirements, APL collaborates with external vendors. Two great examples of this kind of collaboration, discussed below, were for the Europa Clipper spacecraft that will explore one of Jupiter's moons. Instead of being constructed at APL, Europa Clipper's 3-m high-gain antenna and extremely large solar arrays are being built by external vendors because of their large size and complexity. In both cases, APL composites experts worked to test potential materials and select the materials that will best meet the application's requirements, and then they oversaw the fabrication work. There are also many examples of APL composites experts assisting with and overseeing fabrication work for major Department of Defense programs as part of the Lab's trusted agent role. This work has been performed for a variety of applications, including tactical rocket motor cases, shipboard radomes, and Navy aircraft.

EXAMPLES

Europa Clipper Composite Structures

The Europa Clipper mission[11] is being developed by NASA's Jet Propulsion Laboratory and APL. The spacecraft (Figure 4, left), scheduled to launch in late 2024, uses composite materials on the two main systems required for communication and power: the solar array panels and the high-gain antenna. The massive five-panel solar array assemblies on each side of the propulsion module, once deployed, will span roughly 100 ft (30 m). Each solar array panel is 8.2 × 13.5 ft (2.5 × 4.1 m) in size and consists of a composite sandwich laminate that provides the substrate for the solar cells. The sandwich laminates consist of thin high-modulus carbon fiber/epoxy face sheets bonded to an aluminum honeycomb core. The high-gain antenna attached to the main spacecraft bus contains a 9-ft (3-m) composite main reflector, backing structure, strut tubes, and sub-reflector (Figure 4, right). The main reflector, the sub-reflector, and the backing structure for the main reflector are sandwich laminates that use thin high-modulus carbon/cyanate ester face sheets bonded to carbon composite honeycomb core. The carbon composite honeycomb core is used for applications that require dimensionally stable structures during changing temperatures. The reflector is a fully carbon composite structure to avoid RF receiving and transmitting issues due to thermal distortion at temperature extremes. If aluminum honeycomb core were used for the reflector, the CTE mismatch between the aluminum core and composite skins at temperature

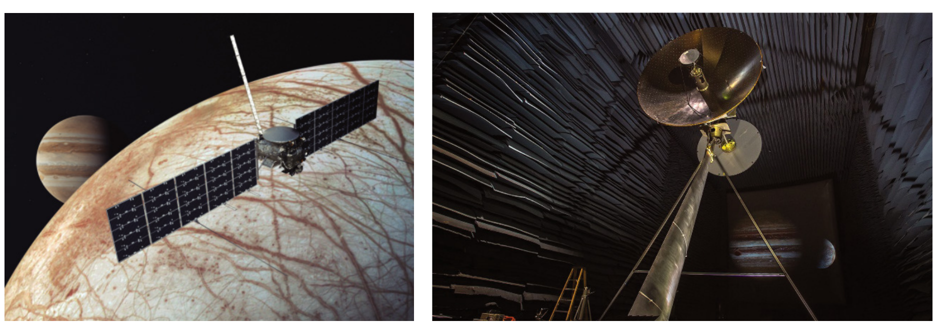

Figure 4. Composite structures on Europa Clipper. Left, Artist's rendering of the Europa Clipper spacecraft orbiting Europa. The high-gain antenna and massive solar arrays are shown, both of which are constructed with composite materials. (Photo credit: NASA/JPL-CalTech, https://europa.nasa.gov/resources/182/2021-europa-clipper-spacecraft-artists-concept/.) Right, The full-scale prototype of the Europa Clipper's high-gain antenna being tested at NASA Langley. The all-composite main reflector, strut tubes, and sub-reflector are visible. (Photo credit: NASA/Langley, https://www.jpl.nasa.gov/news/europa-clipper-high-gain-antenna-undergoes-testing.)

extremes could result in a change in the reflector shape that would adversely affect its function. While the flat solar array substrates can afford to use aluminum core, the high-gain antenna benefits from using composite core because of its shape stability requirements.

A Substrate Design and Investigation for Cryogenic Temperatures

During the initial design phase for the Europa Clipper solar array substrates at APL, prototype substrate coupons failed testing during conditioning intended to simulate the Europa environment and qualify the substrate design. Clipper will experience periods of extremely cold, cryogenic temperatures in addition to periods of high radiation. The initial substrate design that was tested leveraged designs from previous APL-designed spacecraft; however, the effect of the cold temperature and radiation exposure on the composite substrate was unknown since those past substrate designs were never qualified to these extremes.

Initial testing of the substrates revealed large disbonds between the skin and honeycomb core (Figure 5). During thermal cycling between –238°C and –120°C, the change in temperature caused the composite skins to disbond from the aluminum honeycomb core. There was no question that thermal strain from CTE mismatch contributed to the issue, but it was not the only contributor. Two other confirmed causes were the residual stress in the nonsymmetric layup of the composite skins and the dense honeycomb core (8.1 pcf). Other identified possible causes were residual stress at the fiber–resin matrix interface, the surface preparation method, inconsistent application and insufficient volume of film adhesive, fiber sizing issues, and issues with consolidation pressure during bonding of the skins to the core.

The team generated a design of experiment to test a number of material, layup, and process variables. These variables included changes in the prepreg (same fiber, different resin), areal weight of the unidirectional fibers, film adhesive (areal weight, number of plies, and reticulation versus non-reticulated), and face sheet layup configuration. Multiple test panels were built using different configurations, conditioned, and tested in flatwise tension. Then large test panels were built using different layups, and after each environmental exposure, test coupons were removed from the panels and tested. Test coupons are small sections of the large panel that are machined into a specific size depending on the mechanical test. Conditioning cycles prior to testing included a room temperature baseline, cycling between –178°C and +120°C for seven cycles, –238°C to –120°C for seven cycles, irradiation at 63 Mrad, and another –238°C to –120°C thermal cycle for seven cycles. After each conditioning cycle, the large test panels were nondestructively inspected using both ultrasonic and laser shearography to detect any disbonds or delaminations that occurred from conditioning. Half the substrates conditioned at the cold cycle (–238°C to –120°C) completed testing with no signs of damage. Those test coupons were irradiated, thermally cycled between –238°C to –120°C, and tested. The sandwich laminate chosen presented the tightest data set of all the variations tested and exceeded the flatwise tensile strength requirement of 600 psi after each conditioning run. Table 1 outlines the specifications of the chosen versus the original panel configuration.

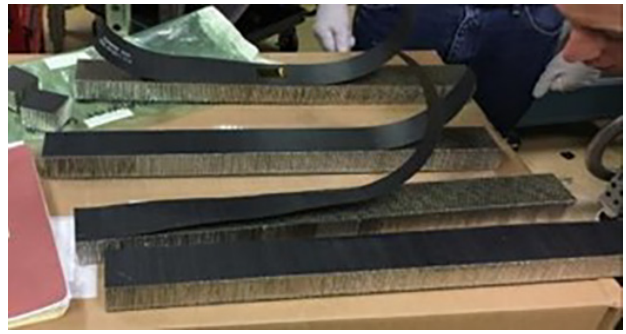

Figure 5. The initial sandwich laminate design for the Europa Clipper solar array substrates. The test coupons exhibited skin-to-core disbonds after thermal cycling down to –238°C.

Because delaminations and disbonds were avoided, the team acknowledged this design as a solution for the Europa Clipper composite solar array substrate. The density of the core, lower cure temperature of the prepreg, laminate layup, adhesive application, and surface preparation all played significant roles, resulting in a

Table 1. Differences between the initially designed solar array substrate for Europa Clipper and the design that passed all testing without failure

	Original Debonded Coupon Configuration	Non-Debonded Coupon Configuration
Core density	8.1 pcf, 1/8-in. cell, 0.002-in. foil	6.1 pcf, 1/8-in. cell, 0.0015-in. foil
Prepreg	M55J/cyanate ester, 0.002-in. cured ply thickness (CPT)	M55J/cyanate ester, 0.0017-in. CPT
Facesheet	Asymmetric, [0/+45/90/–45], 0.015-in, thickness, 350°F cure temperature	Symmetric, $[0/+60/-60]_s$, 0.010-in. thickness, 250°F cure temperature
Film adhesive	FM-300-2U 0.015 psf, 0.030 psf, reticulated, beyond shelf life	FM-300-2U 0.030 psf, nonreticulated, within shelf life
Surface preparation	Light abrasion	Heavy abrasion

composite substrate that would survive the harsh Europa environment and carry out its role as the backbone for the solar cells that power the spacecraft.

A Composite Radome for Deep-Space Radar

Damage tolerance and service temperature are two important characteristics of composites. In the case of a thin, composite ground-based radome for a high-power antenna, it is critical to understand how the material will behave when the system heats up or suffers potential damage—for example, from a hail strike. For a deep-space monitoring initiative, an APL team developed an array of ground-based transmit and receive antennas to support radar installations to monitor, identify, detect, and evaluate objects in orbits far from Earth. A very powerful antenna is required for these tasks, and the radome assembly is one critical part the team had to develop.

Material Identification, Modeling, and Down-selection

The team identified five materials, along with their respective fabrication processes, as potential candidates for building the radome: fiberglass/epoxy composite, quartz/cyanate ester composite, polycarbonate, high-density polyethylene (HDPE), and fluorinated ethylene propylene (FEP). These materials were selected because of their low dielectric constant and loss tangent, allowing for a nearly RF transparent radome. A material with a low dielectric constant has poor electrical conductivity (i.e., an insulator) and less tendency to store an electrical charge, which could disrupt the signal. A material with a low loss tangent is able to provide a clear signal transmission and return. The team then built a computer model based on a hemispherical shell design and input the electrical properties of each material to simulate the radome's performance. Dissipated power was calculated at eight stations along the radome surface (Figure 6, left). Those power values were fed into the thermal model (Figure 6, right) so that the team could understand how the radome would heat up during operation and identify any potential thermal concerns. Thermoset and thermoplastic polymers require thermal considerations because their amorphous or semi-crystalline molecular structure will break down or melt and start to degrade at certain temperatures. A radome must be able to keep its shape, maintain its transparency, and protect the transmit/receive elements inside, so understanding the material's thermal properties and behaviors is paramount. Once the thermal modeling was complete, the team established the peak temperature for each radome simulation using the five materials and calculated the thermal margins between peak temperature and service temperature.

Only three of the five materials and processes considered for manufacturing the radome had positive thermal margins: quartz/cyanate ester composite, polycarbonate, and injection-molded FEP. Of these, the team chose quartz/cyanate ester composite because of its high thermal margin and manufacturability.

Using a machined aluminum mold, three plies of 4581 quartz/cyanate ester prepreg were applied to the mold, bagged, autoclave cured, and oven post-cured. The particular cyanate ester resin used for the radome has the ability to be post-cured at a higher temperature than the initial 350°F cure to develop and increase the laminate's glass transition temperature. After post-cure, the radome could experience temperatures upward of 450°F and remain intact without softening or losing shape, ensuring it would withstand the peak temperatures that could occur during high-power operation.

Hail Strike Testing for a Thin Composite Radome

Three plies of the 4581 quartz/cyanate ester prepreg yielded a radome thickness of roughly 0.033 in., which is considered thin for a composite laminate in this type of application. Therefore, radome damage in the event of severe weather, like a tornado or hailstorm, was a concern. To understand the radome's damage tolerance in a hailstorm, the APL team conducted hail strike testing on a sacrificial radome assembly.

The team developed an approach to deliver simulated hailstones of varying diameters to the radome at different velocities in order to test for hail strike. The solution was to use an air cannon to propel molded ice spheres

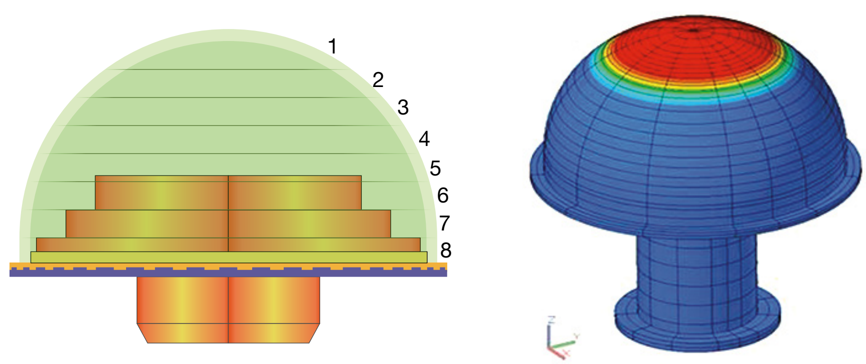

Figure 6. Analysis of composite materials for a deep-space radome. The team designing the radome chose five potential materials for simulation. Left, radome model showing stations for electrical and thermal analysis; dissipated power was calculated at eight stations around the radome for each material. Right, thermal model showing peak temperature location (red). The peak temperature of the radome during high-power operation was calculated to reach upward of 400°F.

Figure 7. Hail strike simulation to test radome resilience to damage. The team tested simulated hail strikes at various speeds using a silicone mold filled with ice to simulate hailstones (left). The ice was loaded into additively manufactured sabots (center), and an air cannon delivered the simulated hailstones to the radome (right).

supported by additively manufactured sabots (Figure 7) to simulate hail strikes at different speeds.

Using a 1-in.-diameter ice ball as the worst-case scenario for a hail strike event, the team simulated a hail strike and tested its impact on the thin composite radome. In addition to testing the worst case, very large hailstones, the team decided to test a few smaller hailstones to understand any potential failures that may result from strikes from hailstones of more common sizes. Terminal velocities were calculated for hailstones that were 0.375 in., 0.500 in., 0.625 in., 0.750 in., and 1 in. to define how fast a hailstone of each size could strike the radome. To determine whether there might be premature failures at slower speeds before the hailstones reached their terminal velocities, the team fired hailstones of each size at a few slower velocities first, then eventually fired them at their terminal velocities.

After each firing, the team visually inspected the radome and performed a tap test to detect any damage or delamination. A tap test is a form of ultrasonic nondestructive testing in which a small hammer is used to tap the surface of a laminate to detect defects based on pitch changes. Tapped areas that present a pitch that is different from the pitch of what is known to be a "good" section suggest a potential issue in the form of a delamination in the composite laminate. The radome did not suffer any internal or surface damage in any of the firing cases and survived a 1-in. hailstone delivered at >200% of its terminal velocity. The calculated terminal velocity of a 1-in. hailstone is 28.84 m/s, and tests achieved a delivery velocity of 63.30 m/s without damaging the radome. The team did not test to failure. After the testing concluded, the impact areas were sectioned from the radome and examined under a microscope to determine whether there were any undetected delaminations in each impact zone. No delaminations were detected, even in zones that had experienced multiple impacts.

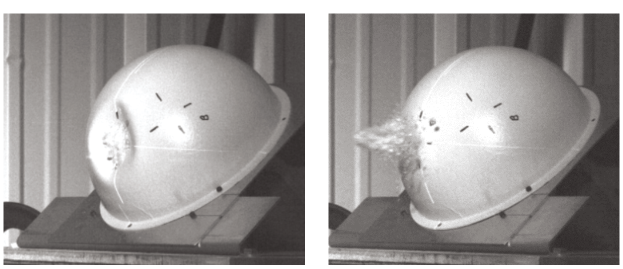

Figure 8. High-speed camera images capturing impact during testing. Left, the radome at impact using a sphere of ice with a 1-in. diameter delivered at 63.30 m/s. Right, the radome after impact, fully recovered.

The team used a high-speed camera to capture each hail strike so they could look at the radome's response at impact. Interestingly, the radome exhibited fully elastic behavior. At impact, the radome deformed around the impact area (Figure 8, left), and when the simulated hailstone shattered and fell away after impact, the radome returned to its original shape (Figure 8, right).

This testing confirmed the selection of the quartz/cyanate ester composite for the radome. Although quartz fibers are more expensive than fiberglass, they are stronger, stiffer, and less dense and offer about twice the elongation at break (stretch before failure), making them a good choice when durability is a priority.[1] The quartz fibers not only provide better electrical properties than fiberglass, but they also provide an advantage that was unknown before the teams' testing: they are resilient to damage in the event of a hailstorm. The quartz composite material was chosen for fabrication because of its manufacturability and electrical and thermal properties. Although the team suspected that a radome this thin would survive a common hailstorm, they were pleased to confirm through testing that it could endure even the worst-case impact without failure.

THE FUTURE OF COMPOSITES MANUFACTURING

APL has been actively investigating the additive manufacturing of true continuous fiber composite structures as a potential game-changer for next-generation composites manufacturing. Two identified technologies would allow the realization of the goal of truly building composite structures additively. The first is a multiaxis

CNC machine that leverages an FFF-type additive process where the polymer filament incorporates continuous fiber reinforcement that can be incorporated into a part in any direction. The reinforced filament could be applied not only in the *x* and *y* planes but also in the *z* direction to achieve strength and stiffness in three dimensions.

The second technology is a multiaxis CNC machine that uses the automated fiber placement (AFP) process for composite part fabrication. AFP typically involves a machine that applies slit tape thermoset composite material to a machined mold for layup. Once the layup is complete, the part is vacuum bagged, autoclave cured, and final machined. To get closer to a true additive-like process, the same machine would have one head that applies thermoplastic filament as well as continuous fiber thermoplastic slit tape that could then be swapped out with a head for machining. The available thermoplastic filament types would include both soluble and non-soluble filaments to support rapid mold fabrication and high-performance thermoplastic composite structures using polyetheretherketone, polyetherketoneketone, or polyetherimide. All these functions would be programmed and run in a single build process, resulting in a finished continuous fiber thermoplastic composite structure in true additive fashion.

These technologies would enable engineers and fabricators to build one-piece composite structures with integrated internal channels or duct sections or could incorporate core geometries optimized for strength, stiffness, and weight. In addition, they would enable rapid manufacturing of complex composite structures. Additive manufacturing of continuous fiber-reinforced composites is a game-changing technology that has the potential to revolutionize the way composites are designed and built. Unique designs achieved only by additive manufacturing, combined with the performance of fiber-reinforced polymer material, could enable solutions to problems that cannot be solved by using legacy manufacturing approaches.

CONCLUSION

APL continues to use composite materials for applications with components that have performance requirements that other materials cannot achieve, often in extreme environments. APL teams use composite materials to build hardware for complex systems that make an impact for our nation, in aerospace, underwater, ground, and space applications. Innovative composite materials and manufacturing technologies will lead the way for future novel solutions to new challenges, enabling APL to meet the needs of its sponsors and the nation.

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Perspectives on Engineering Design and Fabrication at APL

James R. Schatz

In October 2021, APL's Research and Exploratory Development Department (REDD) celebrated its 10th anniversary. We are now just a few years out from that anniversary—an opportune time to reflect on the history of engineering design and fabrication at APL over the past decade. This short retrospective article looks back on the essential role these areas have played in the success of the Laboratory and offers some thoughts for the future as well.

When REDD was created as a new APL department in 2011, the engineering design and fabrication elements of the Laboratory were united with the existing APL research center into a single organization.[1] This was the vital first step in acknowledging that the fabrication elements of APL were not simply service organizations but were an essential part of the APL innovation machine. In fact, the design and fabrication elements are precisely what distinguishes the Laboratory from most other national research and development enterprises. At APL we can address critical challenges facing our nation by carrying out pioneering research with mission intent, creating advanced concepts, designing engineering systems that meet operational requirements, and building advanced prototypes. Which is to say, we can transform imagination and ideas into *deliverables*. When REDD was formed as a department, its design and fabrication teams were immediately embraced as equal partners in this life cycle.

The Concept Design and Realization Branch in REDD comprises three groups: Electrical and Mechanical Engineering, Electronics Design and Fabrication, and Mechanical Fabrication. These groups collaborate with all four APL sectors and with the other two branches, Exploratory Science and Intelligent Systems, in REDD. In a very real sense, the Concept Design and Realization Branch is the heart of APL and exemplifies the REDD vision: *Accelerate transformative innovation and invent the future for APL*.

From the earliest days of REDD as a department, the fabrication elements have taken a strategic view of the changes in their profession and the potential impact of these changes on APL projects and missions. A great example of this strategic planning is the creation of the additive manufacturing (AM) capability for the Laboratory. Having utilized polymer AM machines since their emergence more than two decades prior, shortly after REDD was formed, the mechanical fabrication team invested aggressively in industrial-level polymer AM machines. These early systems had two fundamental purposes. First, they were useful for developing models and surrogate systems for biomechanics. More importantly, however, they allowed the team to learn and experiment with this new fabrication technology. In these early days, the metal AM machines were not yet at the level of quality for APL operational projects, so working on the composite materials was an excellent strategy. In time, the first laser sintering metal AM machines were purchased, opening up a new world of possibilities for fabrication at APL. Along with providing the capability to manufacture components that were impossible to build on conventional machines, the metal AM machines opened up a robust research collaboration between the AM experts and the REDD materials science team. A key topic of study in this joint work has been the comparison of parts made on AM machines and the same parts made with conventional machining tools.[2] In particular, the strength and corrosion resistance of AM parts have been important research areas. Optimizing the performance of components produced by AM technology and ensuring that these components are certified for operational applications is now an essential element of this cross-disciplinary research effort. Here are some examples.

Recent research in AM has investigated how tailoring composition powders in metal ceramic alloying can produce components with the strength of titanium, the stiffness of steel, and the thermal conductivity of aluminum. Metal matrix composites are new alloys with extreme properties that can only be manufactured in complex geometries using the unique laser synthesis processing of AM. The key here is the introduction of a ceramic phase to reinforce a metallic matrix to achieve enhanced strength and improved corrosion performance.

Materials scientists in REDD and mechanical fabrication experts are also pioneering the art of 4-D printing in which components change shape in response to changes in temperature. Thermally activated self-deploying spacecraft structures will enable new approaches to energy harvesting and power generation. Shape-memory alloy hinges will be used to deploy and retract structures in space. In fact, a key research area that REDD is now moving into is the study of methods for building new structures in space completely from basic materials. AM and 4-D printing will certainly be key technologies in this area.

The AM team in REDD is also partnering with APL's Asymmetric Operations Sector and the Defense Logistics Agency to introduce AM components into the US Marine Corps supply chain. The first foray into this area was an effort to design, analyze, fabricate, test, certify, and deploy additively manufactured impellers for M1A1 tanks as part of the Steel Knight exercise at Marine Corps Air Ground Combat Center in Twentynine Palms, California. The Marine Corps has identified AM as an important approach to rapidly repair and field new technology and to increase overall readiness and capability. As another example of this, AM has the potential to produce better armor by creating geometric features that impart rotational and lateral kinetic energy to the projectile, thereby reducing the kinetic energy per unit of impact area. However, all of these research areas are still in the early stages. Due to variability in fabrication, for example, AM technology can also introduce increased risks for equipment and personnel. Therefore, APL is playing a vital trusted agent role to define standardized procedures for identifying and mitigating these risks to ensure that AM components are introduced safely into the Marine Corps supply chain.

In October 2022, APL engineers, in partnership with the Naval Surface Force Atlantic and Naval Sea Systems Command (NAVSEA) Technology Office, installed the first hybrid metal 3-D printer onboard a Navy ship, the USS *Bataan* (LHD 5). About a year later, with support from the NAVSEA Technology Office and APL, sailors onboard the *Bataan* used the printer to fabricate a stainless steel sprayer plate that was installed to repair one of the ship's de-ballasting air compressors, and they did it in fewer than five days. The inside back cover of this issue highlights this success.

Partnerships with the Whiting School of Engineering at the Johns Hopkins University are also advancing the state of the art in AM. One current project involves using thermodynamic modeling to spatially tailor the microstructure of additively manufactured tungsten-based materials.

APL's Space Exploration Sector has been a long-standing customer and partner for the fabrication teams. Just to give a sense of the magnitude of fabrication work that goes into a space mission, REDD teams produced 75 unique electrical components for the Parker Solar Probe mission, and these designs resulted in over 4,000 printed wiring boards and assemblies. In 2021, REDD teams built mechanical components for 13 spacecraft and instruments. These projects included the Double Asteroid Redirection Test (DART), Europa Clipper, Psyche, Galactic/Extragalactic ULDB Spectroscopic Terahertz Observatory (GUSTO), Interstellar Mapping and Acceleration Probe (IMAP), the Particle Environment Package (PEP)-Hi onbaord the Jupiter Icy Moons Explorer (JUICE), and Dragonfly. Some of this work is discussed in this issue as well as in the 2023 companion issue on the branch's work.[3]

Currently, the electrical design and fabrication elements of REDD are supporting nearly a dozen concurrent development programs. High-reliability flight hardware is an absolute necessity for all of these missions, of course, and the quick-turn prototyping capabilities of our fabrication teams play an essential role in testing and qualifying parts.

To provide some sense of the outstanding quality provided by the electrical fabrication teams at APL, consider the following excerpt from the Wikipedia article[4] on the Van Allen Probes mission that APL carried out for NASA. Note that the last contact with the Probes was in October 2019.

> The primary mission was planned to last only 2 years because there was great concern as to whether the satellite's electronics would survive the hostile radiation environment in the radiation belts for a long period of time. When after 7 years the mission ended, it was not because of electronics failure but because of running out of fuel.

It is not uncommon for the APL fabrication teams to carry out quick-reaction efforts to keep a mission on launch schedule when an external fabrication team is unable to deliver reliable components. The most recent example of this involved the DART mission. The REDD mechanical fabrication team rallied to enable the mission to meet its new launch period by rapidly redesigning and fabricating a critical part for the spacecraft's lone instrument. The article by Walters et al., in this issue, offers more details.

AM is now playing a key role in space missions as well. For the European Space Agency JUICE mission launched in 2023, REDD AM experts designed and fabricated the Jovian Energetic Electrons (JoEE) collimator. Presley et al. discuss this work in the 2023 companion issue.[5] This sensor required 4,662 individually angled hexagonal holes separated by very thin walls, and the laser parameters for the AM processing were customized by the team in REDD. It would have been impossible to create this component with conventional manufacturing techniques. The collimator is the first component additively manufactured at APL to be used on an actual space mission.

Numerous major projects are completed each year for APL's Air and Missile Defense Sector (AMDS) and the Force Projection Sector (FPS) as well, but many are too sensitive to discuss in detail here. In one example, a project supporting an important operational test, REDD collaborated with FPS engineers to design, analyze, fabricate, and install two special velocity sensor systems for US Navy submarines. The systems were completed in less than a year and supported an operational mission. This is a great example of the collaboration we see every day between the fabrication teams and APL's sectors.

In recent years, the total number of components produced by the mechanical fabrication team for all of APL has exceeded 30,000 annually. Needless to say, an enormous amount of mechanical design work was necessary to enable these realizations, too. Over the past decade, the electrical fabrication team completed nearly 3,000 unique printed circuit board designs and fabricated more than 70,000 circuit boards. Micro-electro-mechanical systems (MEMS) have been an important part of this portfolio throughout the past decade as well. MEMS offer dramatic, orders-of-magnitude reductions in size, weight, and power for small electromechanical devices.

In addition, APL's mechanical fabrication team created a unique outreach program for local high school students. As part of APL's efforts to build the gondola for a balloon mission to study solar magnetic activity, sun spots, and coronal mass ejections, students at a local trade career training facility were engaged to build some of the flight parts that will fly on this mission.

The APL fabrication teams will continue to be central to the Laboratory's success into the future. When APL celebrates its centennial in 2042, it is certain that APL staff members will look back on the Lab's history and be extremely grateful for the dedicated teams that live by the motto "Fabricate the Future!"

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SUPPORTING THE NAVY'S ADDITIVE MANUFACTURING ADVANCEMENTS

In October 2022, APL engineers, in partnership with the Naval Surface Force Atlantic and Naval Sea Systems Command (NAVSEA) Technology Office, installed the first hybrid metal 3-D printer onboard a Navy ship, the USS Bataan (LHD 5). About a year later, with support from the NAVSEA Technology Office and APL, sailors onboard the Bataan used the printer to fabricate a stainless steel sprayer plate that was installed to repair one of the ship's de-ballasting air compressors, and they did it in fewer than five days. APL is also supporting the Navy in its quest to develop and field additive manufacturing systems to supplement traditional casting methods and accelerate submarine production. In July 2023, APL hosted a working group to discuss the current state of in situ monitoring in additive manufacturing, identify opportunities for advancement, and develop a path forward for future Navy implementation of such technology.

From top left clockwise:

APL staff members Hunter Turco, Jason Reese, Ben Miller, Sarah Bostwick, Alan Huang, and Deepu David stand in front of a 3-D printer system in the Laboratory's machining shop. APL installed an identical machine on board the amphibious assault ship USS *Bataan* (LHD 5) in October 2022. (Credit: APL/Craig Weiman)

Hunter Turco, a senior mechanical fabrication technician, adjusts parts on a 3-D printer in one of APL's fabrication facilities. (Credit: APL/Ed Whitman)

The USS *Bataan* sails in the Arabian Gulf on April 23, 2020. A 3-D-printed sprayer plate was used to repair the ship's ballasting system, which provides critical stability while the vessel is underway. (Credit: U.S. Navy/Mass Communication Specialist Seaman Apprentice Darren Newell)

Machinery Repairman 1st Class Cory Hover demonstrates the software used to design the sprayer plate used to cool, lubricate, and maintain oil pressure for one of the *Bataan*'s de-ballasting air compressors. The sprayer plate was completely designed and fabricated aboard the ship using the newly installed additive manufacturing hybrid CNC machine. (Credit: U.S. Navy/Mass Communication Specialist 2nd Class Bradley Rickard)

APL staff members Drew Seker, Bryan Kessel, and Hunter Turco were part of the team that helped Navy sailors fabricate the stainless steel sprayer plate at sea. Kessel is holding an identical replica of the sprayer plate that was fabricated at APL. A close-up of the sprayer plate is shown in the middle image. (Credit: APL/Ed Whitman)

The In Situ Monitoring Working Group gathered at APL for a two-day event in July 2023 that brought together industry and government partners to identify tools and methods to improve the Navy's reliance on additive manufacturing. (Credit: APL/Ed Chapman)

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