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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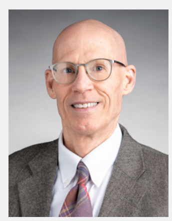

James R. Schatz, Research and Exploratory Development Department, Johns Hopkins University Applied Physics Laboratory, Laurel, MD

James R. Schatz is head of APL's Research and Exploratory Development Department. He holds a PhD in mathematics and a master's degree in computer science from Syracuse University. He joined APL in 2009. Prior to joining APL, he spent 15 years as a code breaker at NSA and went on to serve an additional 15 years as chief of the Mathematics Research Group, deputy director of research, and director of the Research Directorate at NSA. His career accomplishments have been recognized by several prestigious awards, including the National Intelligence Distinguished Service Medal and the Distinguished Executive Presidential Rank Award. His email address is james.schatz@jhuapl.edu.