An Abbreviated History of Design and Realization Capabilities at APL

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ABSTRACT

The Johns Hopkins University Applied Physics Laboratory (APL) has been developing, fabricating, and testing complex electronic, electromechanical, and mechanical systems from its very beginning. Although the underlying organizations, facilities, and technologies have evolved over this time, in some cases dramatically, the ability to advance ideas from concepts to realized hardware remains one of APL's core distinguishing capabilities, supporting a wide variety of diverse programs and projects across the organization. Throughout APL's history, a key enabler of these concept-to-realization capabilities has been the Laboratory's enterprise design, engineering, and fabrication operations. This article briefly traces the history of these functions and their impact on numerous noteworthy achievements of APL. Today, these areas are unified as the Concept Design and Realization Branch within the Research and Exploratory Development Department. The branch continues to serve APL, its sponsors, and the nation with hardware design, mechanical and electrical fabrication, systems integration, and breakthrough manufacturing science that will benefit the programs and missions of the future.

BEGINNINGS

From its very beginning, APL has solved some of the nation's toughest challenges by developing, fabricating, and testing complex electronic, electromechanical, and mechanical hardware. Development of the VT (variable time) fuze,[1] shown in Figure 1, was an all-encompassing effort that involved creating new and novel electronic and mechanical parts and integrating them into an effective ordnance system that has been recognized as one of the most important technological advancements of World War II, along with radar and the atomic bomb.[2,3] As work on the fuze evolved and progressed, the Laboratory's leaders recognized that many of the developers and testers relied on mechanical parts, and thus, they established a centralized machining operation.

After World War II ended and the US government and Johns Hopkins University agreed to maintain APL as a national resource in 1947,[4] the Laboratory began to explore the world of guided missiles as the next-generation defensive weapons for the fleet. To accurately track missiles, improved radars were needed, and APL made developments in this arena, as well as in atmospheric science, using sounding rockets and

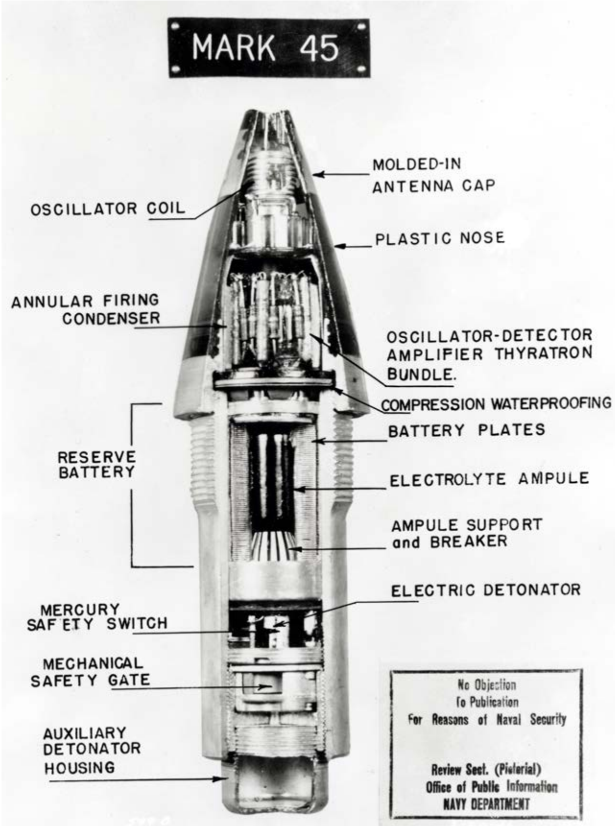

Figure 1. An annotated cutaway photo of the Mark 45 fuze showing its internal structure and key components.

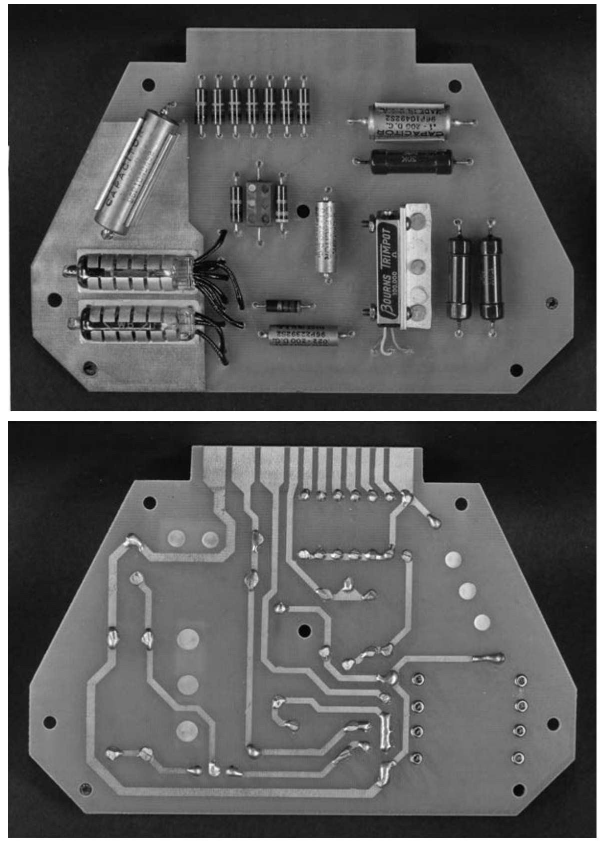

Figure 2. Early PCB fabricated at APL for the voltage regulator used in a telemetry system. Photo dated 1955.

captured German V2 weapons. To support these operations and scientific endeavors, the central machining operation grew (and added a design element to support engineers from nonmechanical specialties). In addition, pockets of electronic design and fabrication capabilities sprang up in various organizations around the Laboratory, with most aimed at designing and developing printed circuit boards (PCBs) to replace point-to-point wiring. The PCB, coupled with miniature advanced vacuum tubes and the soon-to-follow transistor, allowed APL to produce advanced circuitry in support of its fleet protection activities and enabled growing endeavors in atmospheric science and other research and technology areas. An example of an early PCB fabricated at APL is shown in Figure 2.

CHANGING WORK, CHANGING ORGANIZATION

In 1957, the launch of Sputnik and the Laboratory's invention of satellite navigation[5] spurred a need for advanced electronic facilities (design and fabrication) to support the growing satellite business, as well as other areas that also relied on the central mechanical operation that had been serving the Laboratory since its beginning. The Space Department established major electronic design capabilities as well as fabrication facilities for welded wire, stitch weld, and wire wrap interconnection methods. An example of a welded wire cordwood module is shown in Figure 3. The Space Department also began using PCBs to increase circuit density and forced the development of hybrids (many individual transistors and other circuit elements on a substrate in a common package) to further densify the electronics. An early hybrid from APL's initial satellite navigation days is shown in Figure 4.

In parallel to the hybrid work going on in the Space Department, scientists in APL's Research Center created a Transistor Group (circa 1960) to explore the ramifications of these new devices and to try to develop reliable thin-film support circuitry. (Thin films are a class of pure metals, alloys, oxides, or other dielectrics deposited by physical vapor deposition techniques, such as vacuum evaporation or sputtering. At that time, the thickness of such layers ranged from submicrometer to a few micrometers. These layers were almost exclusively patterned by photolithography. The adjective *thin* differentiates this technique from other materials layering techniques including plating, laminating, and screen printing, which at the time produced thicker layers in the tens to hundreds of micrometers range.) Within a few years, the hybrid electronics efforts in the Space Department and the Transistor Group from the Research Center were

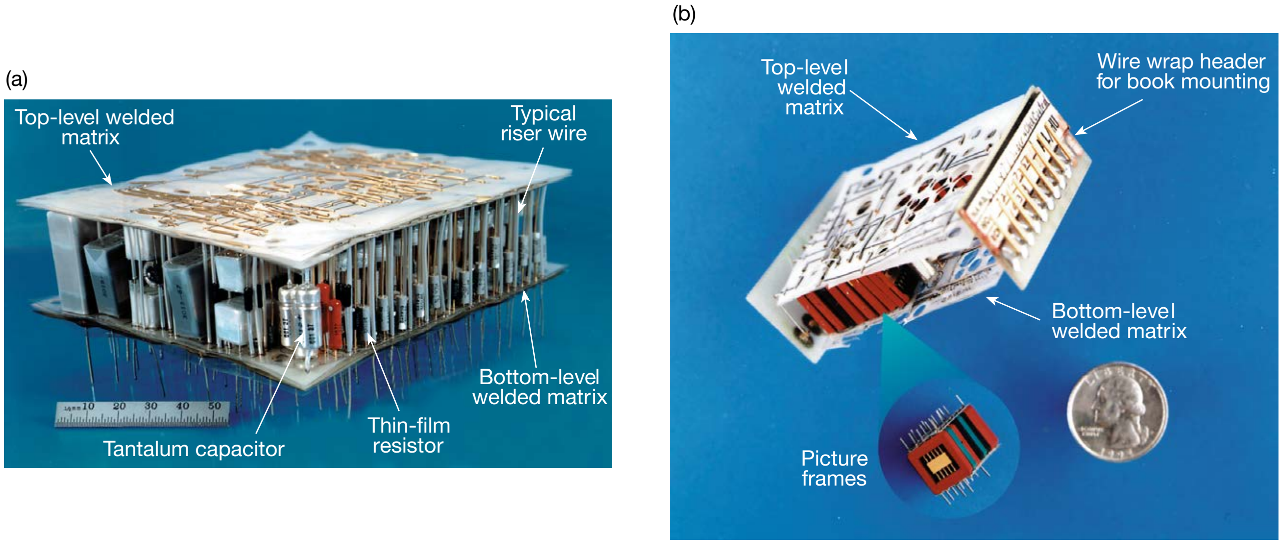

Figure 3. Cordwood modules. (a) Module designed for Transit in the early 1960s. (b) Module illustrating mounting in a picture frame. (From Wagner.[6])

merged into the Microelectronics Group (the parent of the operation that now exists within the Electrical Design and Fabrication Group in the Concept Design and Realization Branch of the Research and Exploratory Development Department, or REDD), whose mission was to produce hybrid circuitry for the entirety of APL and not just for the Space Department.

The central mechanical design and fabrication operations and the Space Department's module (PCB board) design and fabrication capabilities were combined with the Microelectronics Group to form the technical arm of the Engineering Facilities Division in 1970. This organization basically consisted of an Electrical Design and Fabrication Branch, a Mechanical Design and Fabrication Branch, and the Microelectronics Group. Staff members in this new organization were spread out across several Butler buildings. (Butler buildings, often referred to as the equivalent to the Navy's Quonset hut, are pre-engineered, rigid metal-framed and -clad buildings used by the armed services during World War II for many different purposes, including hangars, sleeping quarters, offices, and munitions storage. These buildings were manufactured by the Butler Manufacturing Company of Kansas City, Missouri, which still exists today and is a leader in metal-framed buildings. APL apparently acquired these buildings from government World War II surplus as it built its Howard County, Maryland, campus.) The Microelectronics Group was in one area (Building 16), the Electrical Design and Fabrication operations were in another area (the old Building 13), and the Mechanical Design and Fabrication operations were in another cluster of buildings (the old Building 14). A photograph of the "shops" location is shown in Figure 5.

As the decade of the 1970s passed into the early 1980s, new technology was introduced, including computer-aided design, computer numerically controlled machining, and scanning electron microscopy for materials analysis and inspection. Some of this then-new technology is captured in a 1986 issue of the *Johns Hopkins APL Technical Digest*.[7] Not only does that issue feature the technology of the day, but it also illustrates many of the products APL delivered to customers (and ultimately sponsors) using said technology.

In 1982, the Engineering Facilities Division was absorbed into the Technical Services Department along with the central computing

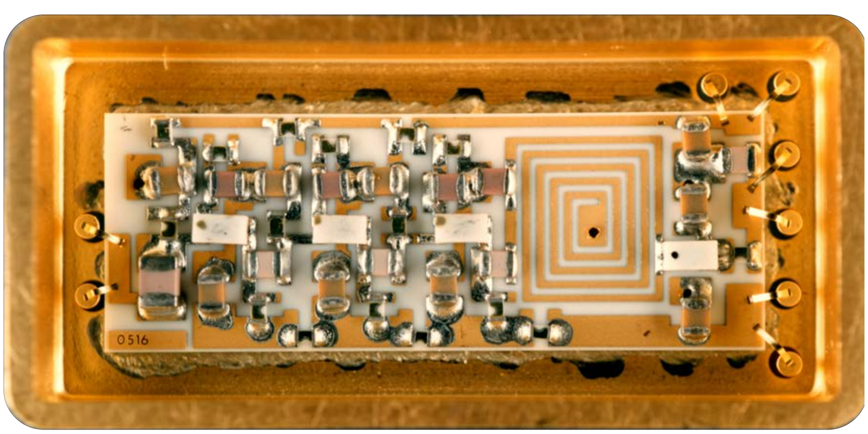

Figure 4. Transit program three-stage command receiver hybrid (circa 1975–1978).

facility (the McClure Center), the Art Department, the Gibson Library, the facilities maintenance operations, the Calibration Laboratory, and a few other central organizations providing enterprise services. Upon the formation of the Technical Services Department, the central hardware design and fabrication operation had two branches: the Engineering Branch (consisting of the Microelectronics Group and the Computer-aided Design Group) and the Design and Fabrication Branch (consisting of the Electrical Design Group, responsible for circuit board design; the Electrical Fabrication Group, responsible for circuit board fabrication; and the Mechanical Design and Mechanical Fabrication Groups, responsible for plating, welding activities, and eventually composite capabilities). Later a materials and quality assurance capability was added to the Design and Fabrication Branch, and the McClure Center electronic design element was incorporated into the microelectronics effort.

NEW FACILITIES, GROWING CAPABILITIES

In 1989, the two branches were combined into a single branch called the Engineering Design and Fabrication Branch, and this organization was realigned to include six major groups (Design Automation, Design and Packaging, Electronic Fabrication, Mechanical Fabrication, Microelectronics, and Quality Engineering and Materials). That same year, the organization's facilities were significantly upgraded when the Design Automation, Design and Packaging, Electronic Fabrication, Microelectronics, and Quality Engineering and Materials Groups occupied the Steven Muller Center for Advanced Technology (new Building 13; Figure 6). The old

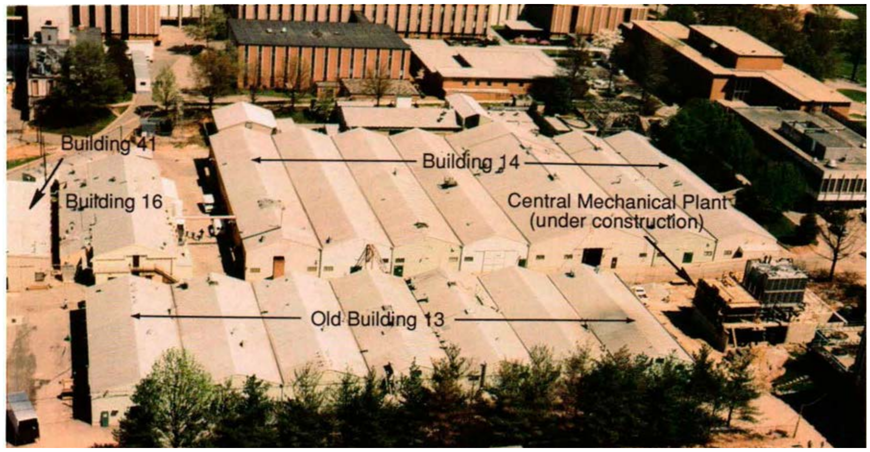

Figure 5. Aerial photograph of the physical facilities occupied by the technical arm of the Engineering Facilities Division circa the mid-1980s. (From Wagner, Falk, and Murphy.[8])

Figure 6. Steven Muller Center for Advanced Technology.

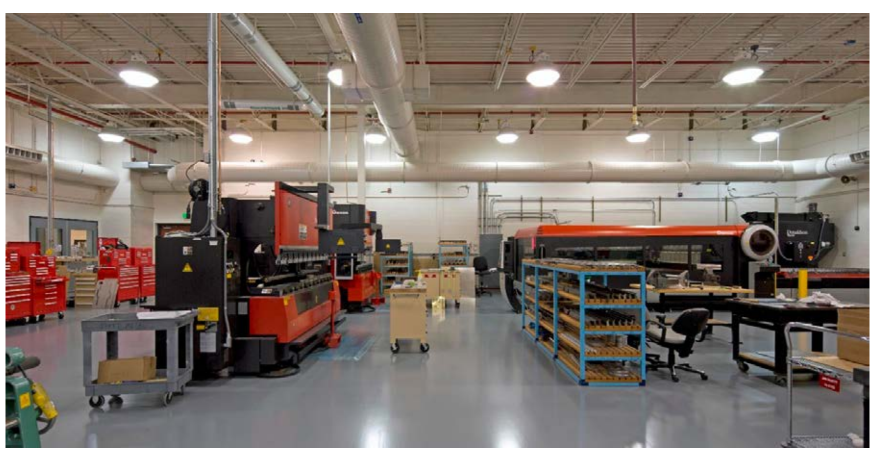

Figure 7. Sheet metal fabrication area. This area is housed in the new mechanical fabrication facility in Building 15.

Building 13 had been razed some 2 years prior to make way for construction of the new facility. The Mechanical Fabrication Group would need to wait until 2007 to move into new facilities (Building 15; Figure 7). The Steven Muller Center greatly advanced design, packaging, and electronic fabrication capabilities at APL. Full details on the then-new center can be found in a 1991 issue of the *Digest*.[9] To support the ever-evolving nature of technologies and the work performed at the Laboratory, APL is now pursuing a new vision for a facility that will house the electrical fabrication labs, as described later in this article.

In 1996, the organizational structure described above was dissolved and the groups began reporting directly to the department through the assistant department head for engineering. The number of groups was also reduced from seven to four: Microelectronics, Electrical Design and Fabrication, Mechanical Design and Fabrication, and Computer Engineering. This structure was ultimately reduced again to two large groups: Electrical Services and Mechanical Services. This organization and its myriad capabilities, products, and services at the turn of the century in 2000 are presented in another *Digest* issue.[10] The Electrical and Mechanical Services Groups described in that 2000 issue formed the basis of the engineering, design, and fabrication capabilities inherited by REDD in 2011. Under REDD leadership, these activities have grown significantly, as described in more detail below.

THE MODERN ORGANIZATION

REDD formed in 2011 when the Laboratory's Research and Technology Development Center joined with the Engineering Design and Fabrication Branch and the biomechanics team in what is now the Force Projection Sector (formerly the National Security Technology Department). This merger brought together capabilities ranging from fundamental research to prototype realization and the actual fielding of hardware. The establishment of REDD also included the creation of a parallel mission area focused on developing and executing sponsor-funded work. This presented a new and unique opportunity for the engineering design and fabrication groups. Before this point, they had been considered enterprise-support functions and therefore had limited ability to engage with and perform tasking for APL's external sponsors.

Incorporating the Engineering Design and Fabrication Branch into this new mission area was advantageous for several reasons. Fabrication technologies in areas like additive manufacturing and microelectronics were, and still are, rapidly advancing and, in some cases, increasingly merging to enable new approaches and solutions to long-standing challenges that had been constrained by traditional fabrication methods. In addition, the introduction of artificial intelligence tools, along with the continued rapid growth in computational capabilities, made it feasible to model and evaluate the complex shapes these processes enabled and the unique materials they were based on. These developments have stimulated the advanced manufacturing sector, including many APL sponsors focused on military hardware, to try to understand the fundamental mechanics of these processes and accurately predict and qualify outcomes. REDD's alignment of research and fabrication capabilities (Figure 8) created a unified organization with a breadth of capabilities to address these needs and also opened new possibilities for impact in many of APL's sponsored and active programs.

Positioning engineering design and fabrication activities within REDD also fostered a transition in the functions' relationships with sectors around the Laboratory. Engineering design and fabrication staff members leveraged these new relationships to become valued partners on programs. Increasingly, these staff members, especially designers, have been collocated with technical teams all over the Laboratory's campus, positioning valuable REDD talent and expertise within immediate

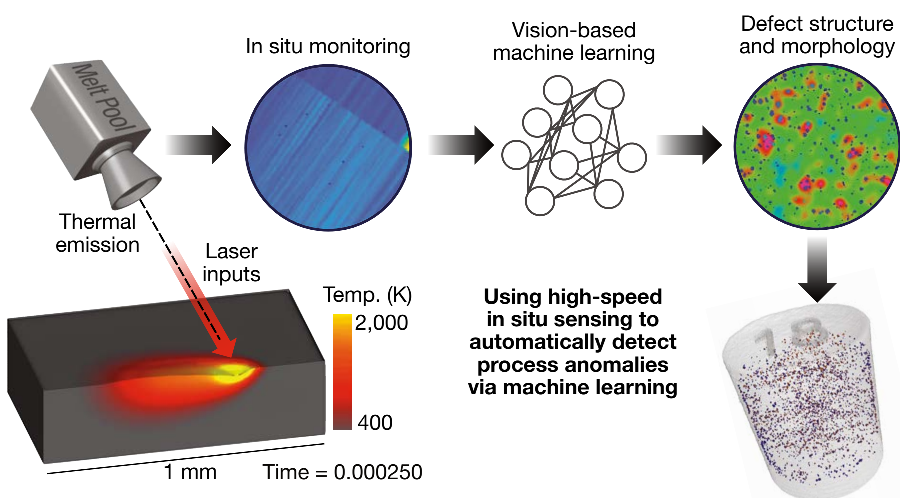

Figure 8. Aligning advanced manufacturing, novel sensing, and machine learning with materials science research has enabled independent research and development efforts such as this one. An APL team is working to develop real-time detection of defects using high-speed in situ sensing that is coordinated with machine learning to high-resolution x-ray computed tomography to reveal signals associated with stochastic defect formation.

proximity to the core technical teams they support. This collocation benefits everyone involved by furthering the technical teams' connection to engineering design and fabrication experts and facilitating those experts' greater impact on the technical programs. Some REDD staff members have become highly influential in the technical leadership of work on these programs and have been recognized as project leaders. This model has proven highly beneficial to many projects, especially those whose success depends on prototype hardware, and engineering design and fabrication staff members are increasingly being asked to play key leadership roles on project teams.

In addition to project management, product engineering has proven highly valuable to some segments of the Laboratory. REDD meets an array of design and fabrication needs with varying levels of complexity, and it can be challenging for technical staff members in the sectors to identify the appropriate REDD teams to engage if they are unfamiliar with the span of services. Driven by the need to rapidly build and integrate complex hardware, REDD and the Asymmetric Operations Sector (AOS) collaborated to identify a REDD product engineer who, as a core member of the program's technical team, oversees the configuration, scheduling, fabrication, and integration of hardware for an entire family of quick-reaction projects. As a single source of communication between both REDD and AOS engineers and designers as well as REDD fabrication teams, the product engineer is able to quickly respond to program changes and ensure that the overall department is responsive to changing needs. Trusting in the product engineer to make decisions about priorities and ensure that resources are available to support the work allows AOS staff members to focus their talent on the program's deeply technical, highly specialized tasks and challenges with confidence that hardware for systems will progress as planned.

In 2017, REDD formalized the Concept Design and Realization Branch by uniting the aforementioned groups focused on electrical and mechanical engineering, design, and fabrication. This branch is organizationally very similar to the Engineering Design and Fabrication Branch that was housed within the Technical Services Department. However, today's new materials, processes, and tools have moved advanced fabrication into the enviable position of enabling previously unimaginable solutions, and this new branch is further empowered to pursue the discipline of manufacturing science and engage in new areas of study.

APL staff members have always engaged in deeply technical, research-oriented work that pushes the boundaries of current possibilities. At the time the new branch formed, much of the Laboratory's work aligned with a growing number of manufacturing science disciplines. The Concept Design and Realization Branch increasingly hires staff members with advanced degrees to lead and to further enhance the impacts that advancements in manufacturing technologies can have on the prototype systems APL develops. Some examples of recent developments include advanced modeling of complex multiscale systems, deep understanding of the physics associated with metal additive manufacturing, and novel packaging schemes for microelectronics.

The branch is highly focused on the technical work of the Laboratory and its sponsors and embraces its role in furthering fabrication capabilities that can achieve greater performance, higher reliability, shorter production times, and often lower life-cycle cost. To that end, the branch annually asks staff members to propose ideas to investigate and develop novel methods and processes that could have broad impact. The competitive program seeks proposals that advocate improvements to existing technical capabilities or processes (accuracy, productivity, or both) or evaluation of new and emerging capabilities previously not offered. These highly sought-after funding opportunities have launched several of the advanced capabilities delivered by the branch today.

The contributions to the more than 80 years of mission success for programs around the Laboratory would not have been possible without the dedicated facilities that house the staff, the workspaces, and the equipment enabling delivery of world-class prototyping capabilities. The proximity of these facilities to engineers and scientists fosters unparalleled collaboration that is critical to prototyping and eventually maturing ideas suitable for fielding and production at scale. APL leadership has regularly invested in the construction, maintenance, and renewal of these special-purpose facilities, realizing that they enable a broad, distinct, and unique set of services that, when coupled with APL's technical prowess, produce unmatched value for its sponsors.

In 2007, APL opened its System Integration II building (known as Building 15). Today, 16 years later, this modern, flexible facility houses the mechanical fabrication operation, including machining, sheet metal fabrication, welding, composites, molding, and bonding, as well as polymer and metal additive manufacturing. It is a showcase area for Laboratory visitors and home to some of the most advanced fabrication capabilities the Concept Design and Realization Branch offers. In particular, after the branch first invested in metal additive manufacturing in 2016, this building was the obvious choice to house the Additive Manufacturing Center, a space dedicated to enabling breakthrough applications of the burgeoning technology. Several articles in this issue describe unique hardware solutions that were developed and qualified for deliverable systems by the Additive Manufacturing Center.

LOOKING TO THE FUTURE

As the APL campus continues to grow and change, the Concept Design and Realization Branch leadership

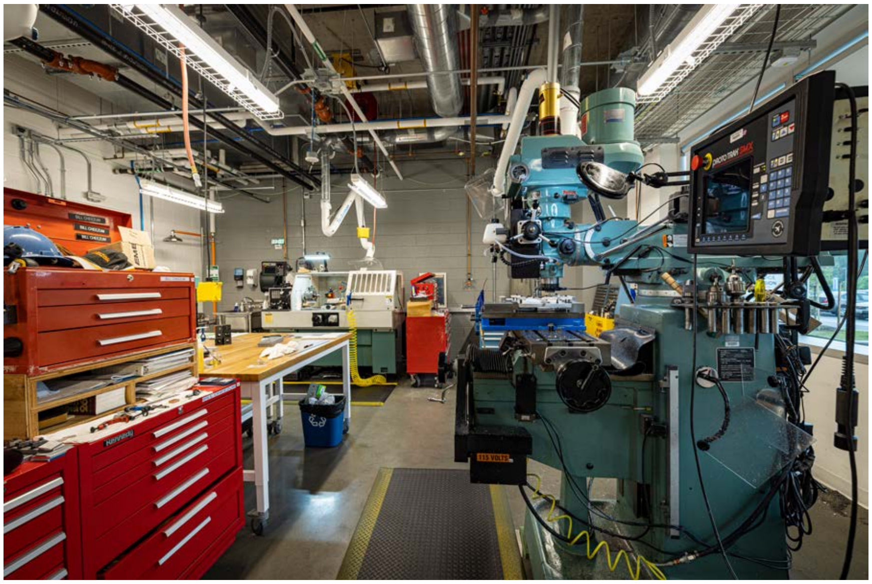

Figure 9. Engineering development lab in Building 201.

is exploring ways to provide world-class facilities while maintaining the need to remain physically close to engineering and scientific development teams. While the main shops in Building 15 support the entire Laboratory, often, because of the nature of the work, the concurrent design process benefits from even closer collaboration and minimal process controls. To this end, Building 201, which opened on APL's South Campus in May 2021, includes an engineering development lab (Figure 9). This facility, staffed and managed by the Concept Design and Realization Branch, houses a full-time fabrication expert and equipment for rapid prototyping and hardware modification, enabling rapid response to the engineering and research community residing on the South Campus. Because it is a remote extension of the central Advanced Mechanical Fabrication facility in Building 15, work is able to flow seamlessly between the two, offering both rapid response and broad capabilities.

A plan to renew the Advanced Electrical Fabrication labs in Building 13 is underway. Housed on the lower two floors of the building, the Printed Wiring Board Fabrication, Electronics Assembly, and Microelectronics teams have experienced dramatic and seemingly unending changes in their work, including the need for much smaller components, more integration, and more complex processing methods, since first occupying the building in 1989. These teams build and assemble the majority of electronics for NASA missions such as

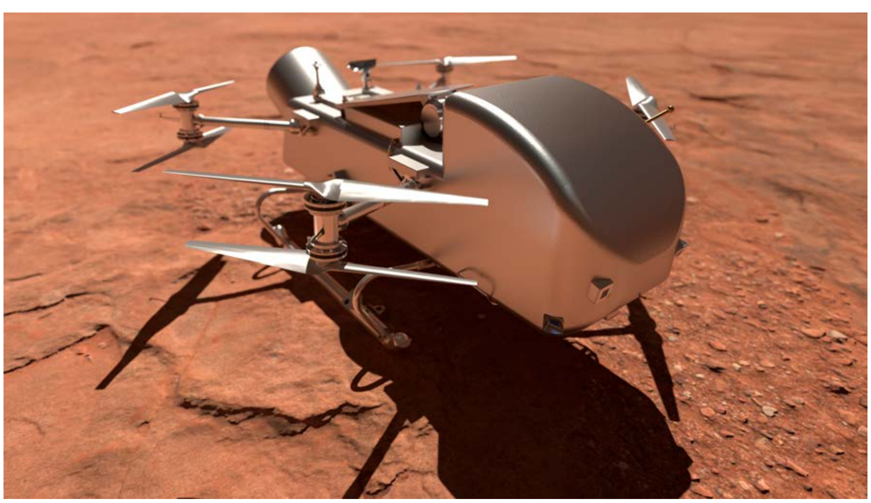

Figure 10. Dragonfly spacecraft rendering. Built by APL and expected to launch in 2028, this rotorcraft will explore and conduct science on the surface and within the atmosphere of Titan, Saturn's largest moon.

Parker Solar Probe and the Double Asteroid Redirection Test (DART) and are now looking forward to building high-reliability electronics for the Dragonfly (Figure 10) spacecraft expected to launch around 2027. Within the same facility, staff members are also building electronics for a range of applications spanning from benchtop use to fielded prototype systems. It is this wide array of requirements, tailorable processes, quickly evolving technologies, and the need to respond rapidly that will guide the design and layout of facilities to support this work—no easy task for a building that will be expected to last for decades.

Built on a long foundation of successfully supporting the unique mission of APL, the Concept Design and Realization Branch is mapping a path for its future that leverages the latest technologies, perfects their application, and applies them to solve some of the hardest challenges our nation faces.

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