

# Additive Manufacturing at the Johns Hopkins University Applied Physics Laboratory

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## ABSTRACT

Additive manufacturing (AM) is a rapidly developing class of manufacturing technologies that has received significant attention in recent years. The Johns Hopkins University Applied Physics Laboratory (APL) has invested significantly in AM and uses it extensively to support its mission areas and to meet the needs of its external sponsors, especially prototyping needs, as well as to create functional parts. The Laboratory's recent formation of an Additive Manufacturing Center of Excellence enables an increased research focus on these disruptive technologies, including addressing the technical limitations of AM and exploring novel applications for its use. This article provides historical perspective on prototype manufacturing; describes the AM process as well as AM benefits, considerations, and uses; provides examples of how AM is used at APL; and highlights the vision for science-based manufacturing through the Additive Manufacturing Center of Excellence.

## HISTORICAL PERSPECTIVE ON PROTOTYPE MANUFACTURING

An essential step in innovating and advancing technical systems is bringing them to life in the form of physical hardware that allows the engineer or designer to demonstrate a capability; evaluate its fit, form, and function; and evaluate the device's or system's effectiveness to meet its intended purpose. Fabricating a working model or prototyping a design is a critical step in realizing these goals.

### Challenges in Prototyping Hardware

Prototyping a new concept or design presents unique challenges. Principally, the lack of design maturity brings risk, which may manifest itself in manufacturability issues, assembly issues, or functional issues. As

a pathfinder, a prototype article is intended to expose such risks so that through an iterative feedback process, the design matures and risk is engineered out of the system. Each cycle introduces potential changes to the hardware, making the next build unique from the last. Without fabrication, experimentation, and testing via a prototype, there is often little assurance that an initial design meets its originally specified requirements or that the system of interest can even be manufactured.

Market pressures, computer-based design and analysis improvements, and a culture of rapid advancements have compressed the time available for these iterative development cycles, creating the need for faster, less expensive, and more flexible prototyping. Designers and

engineers expect to be able to model a potentially diverse set of solutions and down-select to a preferred approach in short order. However, prototype fabrication, by its very nature, is often time consuming and unpredictable.

Another challenge of prototyping is the inherently small (sometimes single) quantities and resultant process limitations. For example, manufacturing processes suitable for hundreds of units, such as injection molding, are traditionally prohibitively expensive for use on small-quantity prototype hardware because of nonrecurring tooling costs. In addition, the evolving nature of hardware designs ensures that “hard” tooling is quickly obsolete and impractical. Thus, the challenge in prototyping is to fabricate a prototype that closely approximates the finished part by finding and using methods that do not require a large up-front investment in cost and time.

### **Impact of Machining Technology on Prototyping**

Decades ago, computer numerically controlled (CNC) machining significantly advanced the practice of building prototype hardware. In addition to introducing improvements in speed and precision when removing material, CNC machining, in concert with computer-aided drafting (CAD), bridged design and fabrication to allow manufacturing that is driven directly by the design file. Not only did this advancement substantially accelerate the data-transfer process, but it also ensured that the hardware form and dimensions were consistent with the design model. As CNC technology progressed, increasingly complex features were made possible by multiaxis and multitask (e.g., dual mill and turn) capabilities and advanced programming techniques.

However, limitations with CNC machining remain. Features of parts and the design concepts that drive them are constrained by manufacturability limitations. CNC machines, in some cases, cannot physically reach all areas of a part because of the physical geometry of the tool. Hollows, voids, open mesh, or gradient structures, for example, cannot be machined in a single piece, if at all. Instead, they must be fabricated in separate pieces and joined together by another means. Complex features require significantly more time to machine, increasing cost and potentially reducing yield. The choice of raw material stock is commonly driven by the intended finished shape of the part. Therefore, rapidly producing a wide variety of hardware requires that a significant amount of raw stock be in inventory. Machining parts with a high degree of customization or individualization remains time consuming and less efficient than production-quantity runs.

### **Additive Manufacturing's Impact on Manufacturing**

Driven by rapid improvements in machine control, materials, and software, additive manufacturing (AM) has vaulted to the forefront of innovations that address

the shortcomings of the CNC machining process. Its ongoing and future impact on manufacturing, especially prototyping, has yet to be fully realized, but the technology is already proving revolutionary. Early systems, first introduced in the 1980s, built parts out of plastics suitable only for nonfunctional models. However, the technology rapidly evolved to a capability for building engineering-grade parts using a wide array of metallic and nonmetallic materials.

Capping this evolution to date is General Electric's commitment to produce cobalt chrome fuel nozzles for its newest engine, called LEAP, using metal AM. This endeavor, for which General Electric has built a dedicated factory, marks the first production-scale use of AM for highly qualified, life-critical, high-stress components. This application leverages the many advantages of AM, including the ability to produce complex shapes not easily machined, the ability to build single parts that were previously built as assemblies, and the use of unique approaches to optimize parts based on their intended performance. General Electric's vast investment in equipment, facilities, and engineering experience necessary to accomplish such a feat has raised AM to the forefront of technical advances and validated its potential for an entire industry.

AM has enabled unique benefits in the world of prototyping as well. The ever-expanding range of materials available for use in AM machines provides engineers with rapid access to materials with a wide range of performance characteristics, including structural finished parts, without the need to hold large amounts of raw stock. Because it is not constrained by the limitations of conventional manufacturing, AM makes it practical, if not routine, to build designs with unusual form and complexity that are optimized for their applications. In addition, AM provides a means to rapidly produce tooling such as molds and mandrels for short-run use in a fraction of the time required to produce durable tooling.

### **AM at the Johns Hopkins University Applied Physics Laboratory**

As an organization focused uniquely on engineering and development of prototype systems, the Johns Hopkins University Applied Physics Laboratory (APL) has embraced AM as an essential element of its capabilities. AM is a perfect technology for APL to use because APL builds prototypes that are complex and highly customized, undergo frequent design changes, and are built in small lot sizes. Beyond simply fabricating hardware, APL has sought to apply machine tool metrology to understand and evaluate the performance of these machines, identify novel applications for their capabilities, and combine them with other processes for rapid development of prototypes.

Despite its previously mentioned successes, AM's potential to truly revolutionize and replace traditional manufacturing beyond prototyping is still limited by a number of factors. For example, the physical phenomenon occurring during the fabrication process is not fully understood, and means to rapidly qualify the materials, processes, and equipment remain unsolved. Understanding the potential to fabricate parts from unique materials such as biological tissue or combinations of materials that enable both mechanical and electrical functionality is still very much in its infancy. To fully leverage the potential for AM, the design and engineering communities must rethink their design processes and tools. APL's Additive Manufacturing Center of Excellence focuses on these and other challenges that could have far-reaching effects on APL's sponsor communities and beyond.

The remainder of this article explores the current state of the art of AM, including its benefits, and compares the available process technologies. Emphasis is on APL's range of capabilities and the unique applications in which they are used.

## BASICS OF AM

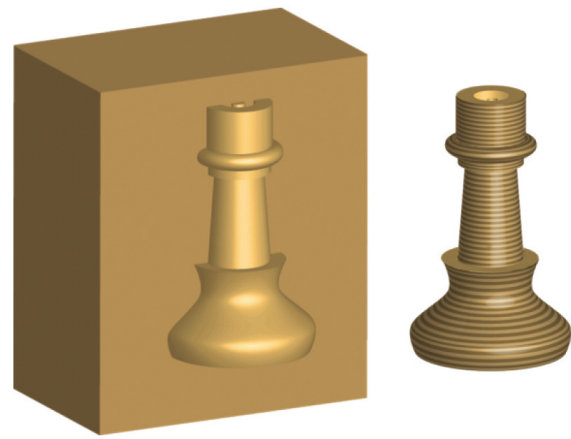
### AM Definition

The ASTM-I Committee F42 defines additive manufacturing as follows:

A process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive methodologies. Synonyms for Additive Manufacturing include additive fabrication, additive processes, additive techniques, additive layer manufacturing, layer manufacturing, and freeform fabrication.<sup>1</sup>

This definition includes two key aspects that distinguish AM processes from other processes: (i) AM processes are model driven, and (ii) the parts are built up layer by layer. (AM is frequently erroneously referred to as a welding process. Although it is certainly true that both welding and certain metal AM process have similar material melting and cooling phenomena, the model-driven, layer-by-layer nature of AM distinguishes it from traditional welding.) Figure 1 is a conceptual comparison of an identical part made by both traditional removal and additive processes. Whereas traditional processes require a block of material and a tool of some kind to remove the unwanted material, additive processes form a part layer by layer and consume primarily only the amount of material needed for the part, without generating waste such as the chips produced in subtractive processes.

The terms *3-D printing* and *additive manufacturing* are often used synonymously, especially in the popular press, even though they are not truly synonyms. 3-D printing most accurately refers to more modest consumer-grade AM systems that produce parts more cheaply and with less quality and functionality. 3-D printing systems are



**Figure 1.** Identical parts made from traditional removal processes (left) and AM processes (right).

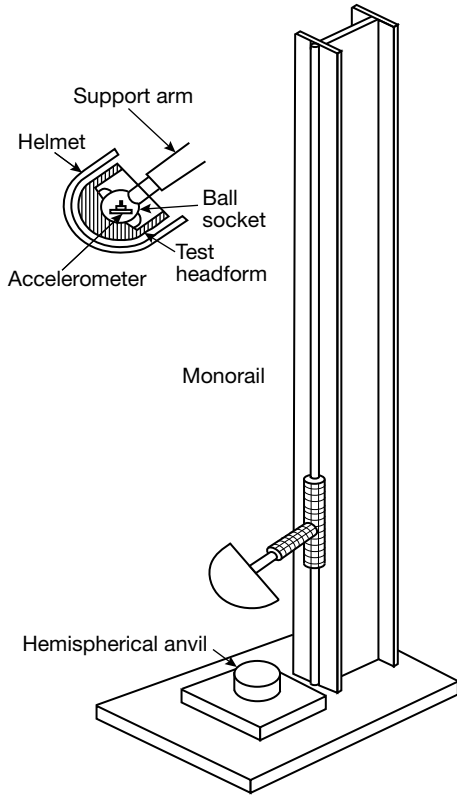
a subset of all AM and are more similar to true printers in that they deposit material through a print head of some form.<sup>1</sup>

### Descriptions of AM Processes

The AM industry, through the ASTM-I, defined the seven basic processes that make up AM. These are listed in Box 1, along with some representative trade-name processes and their official ASTM-I definitions. Each of these processes is distinct and has its own respective advantages and disadvantages. However, all of these processes embody the two key aspects of the ASTM-I definition of AM (i.e., a design-driven, layer-by-layer process) and share the advantages discussed in the next section.

#### BOX 1. AM PROCESSES

1. **Binder jetting:** An AM process in which liquid bonding agent is selectively deposited to join powder materials
2. **Directed energy deposition:** An AM process in which focused thermal energy is used to fuse materials by melting as they are being deposited
3. **Material extrusion (fused deposition modeling):** An AM process in which material is selectively dispensed through a nozzle or orifice
4. **Material jetting:** An AM process in which droplets of build material are selectively deposited
5. **Powder bed fusion (direct metal laser sintering, laser sintering, selective laser sintering):** An AM process in which thermal energy selectively fuses regions of a powder bed
6. **Sheet lamination:** An AM process in which sheets of material are bonded to form an object
7. **Vat photopolymerization (stereolithography):** An AM process in which liquid photopolymer in a vat is selectively cured by light-activated polymerization



**Figure 2.** Example of a monorail-guided free-fall drop tower impact test system.

APL uses industrial-grade material extrusion, material jetting, and powder bed fusion AM systems to make models for fit checks, display models, prototypes, and functional parts. APL also uses less-capable 3-D printers to assess developing AM technologies that may be of interest to its sponsors as well as in special projects. APL leverages its technical expertise in several different disciplines (mechanical design, materials, physics, etc.) to fully and successfully use AM processes.

**Advantages of AM Processes with APL Examples**

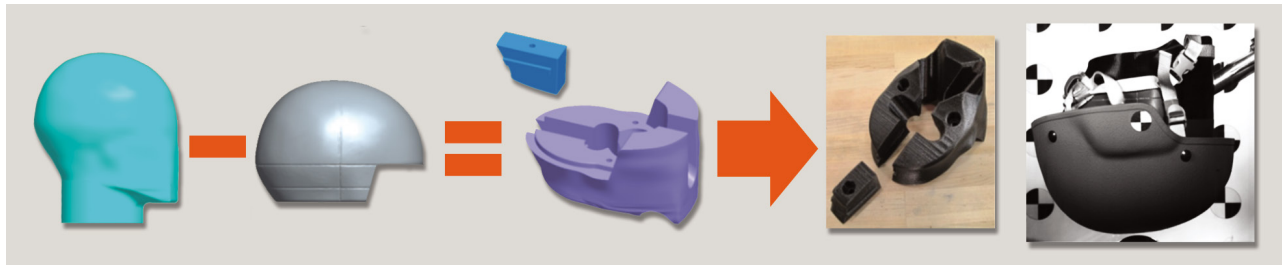
AM processes have several advantages that distinguish them from traditional subtractive processes. First, AM is highly customizable. It is relatively straightforward to customize design of a particular base part. This

flexibility is extremely useful for biomedical implants, for example, because a part's size and geometry can be tailored to an individual's anatomical features. AM can also realize complex structures, complex geometries, and internal features that are difficult or impossible to fabricate using traditional subtractive processes. "Complexity is free"<sup>22</sup> is a phrase the popular press often uses when discussing AM, and although it is not exactly true, it is true that complexity is inexpensive. The unit AM processes are not generally affected by increased complexity, but certain postprocessing steps, such as removing support structures required to ensure that certain complex features build properly, can incur additional time and cost.

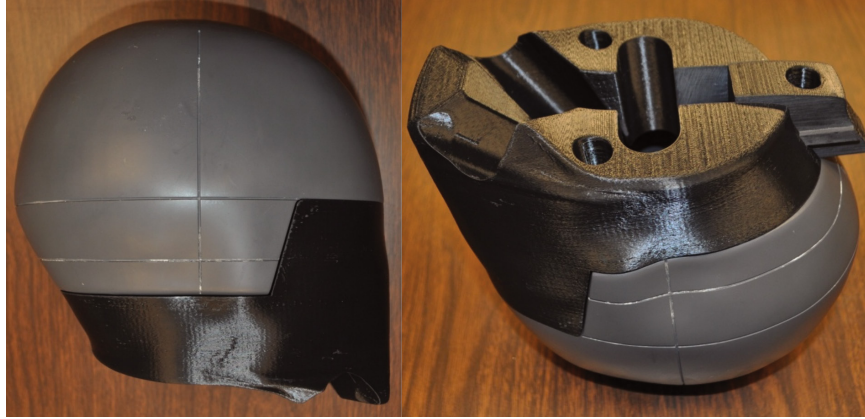
**APL AM COMPLEXITY EXAMPLE**

A chin surrogate was developed for a drop tower headform assembly to fit an existing half-headform as part of a blunt impact test (as shown in Fig. 2). AM was used to meet this need and to support the development of improved protocols to assess the performance of the combat helmet. The drop tower headform assembly consists of a half-headform, a ball clamp, a chin surrogate, and mounting hardware. The geometry for the chin surrogate system was generated by using a full-headform and subtracting the existing geometry for the half-headform, as shown in Fig. 3. The build parameters were adjusted to optimize the lattice structure to meet a required mass for the system. These build parameters were reported on the components drawings for the chin surrogate and the chin fitting and were optimized to be manufactured using APL's material deposition system. The components were generally manufactured with three contours with a double dense sparse fill. The parameter optimized to meet the target mass was the air gap dimension for the sparse fill. This type of material density customization would have been impossible to achieve with a standard material and manufacturing process. The drop tower headform assembly could be fabricated in multiple sizes. The design step and air gap optimization step were repeated for each of the sizes needed for the program. Figure 4 shows the final drop tower headform.

Unlike many conventional subtractive processes, AM systems typically do not require tooling (although support structures are often needed) or path planning (which is done automatically by the AM machine). This makes it easy and inexpensive to accommodate design changes. As a result, the overall AM production time is short. Although it generally takes a long time (rang-



**Figure 3.** Design process to generate CAD geometry for a chin surrogate and fitting.



**Figure 4.** Final design for drop tower headform.

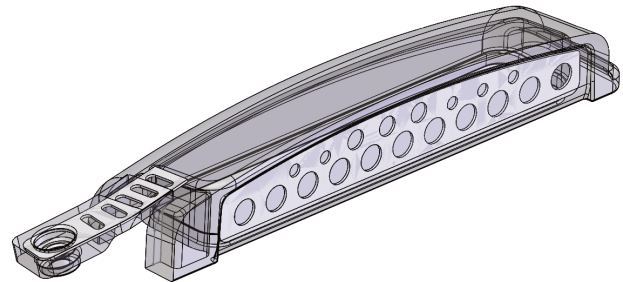
ing from fractions of a day to several days, depending on the part size) to complete AM unit processes, the entire production cycle is short relative to that of traditional processes when design changes, tooling, and fixtures are taken into account. With AM, it is also possible to produce multiple parts, even different parts, in the same build, constrained only by the build volume. Small lot sizes, even lot sizes of one, are possible both economically and physically. All-in-one assemblies can also combine multiple parts into one single part design. This is one of the features of the landmark General Electric LEAP fuel nozzle mentioned earlier. Fabricators traditionally made the fuel nozzle by painstakingly welding 20 individual components into one piece and accepting the high error rate that comes with such a process. With AM, this same part can be manufactured as one single component.

#### APL AM ALL-IN-ONE-ASSEMBLY EXAMPLE

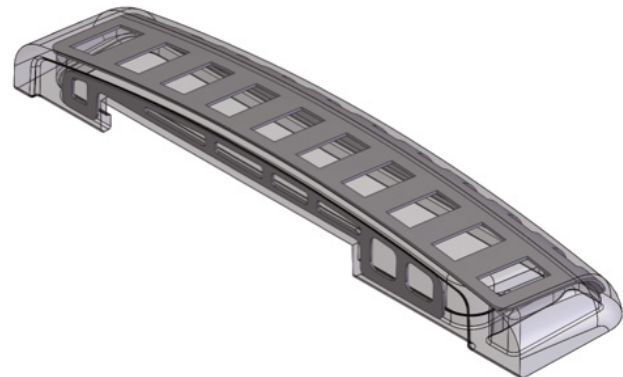
In support of a recent program requiring electronics to be integrated into a portable package, components were designed by using materials with various hardness values that APL's material jetting AM machine can build simultaneously. Four main components made use of the system's capabilities to integrate a stiffening material into the design while ruggedizing the design with a soft rubber "candy" exterior. The data collection and storage device incorporated a living hinge by using Vero plastic to provide the rigidity needed, while the rubber "candy" coating provided flexibility (as shown in Fig. 5). Access to the data storage connector is via a cover that was also designed as a multibody part with a Vero plastic interior structure for strength and a rubber exterior to provide a ruggedized finish (Fig. 6).

The remote sensor housing (Fig. 7) was also an all-in-one material jetting build with a rubberized exterior, translucent LED windows, and an operable switch. The door assembly (Fig. 8) for the sensor housing was built separately as an all-in-one build, with a rubber battery cushion space integrated into the design. The Vero material was used as the stiff interior, and the rubber exterior was used to rubberize and ruggedize the door component. Without the jetting processes' capability to use multiple materials, these parts would have been impossible to make in one production step.

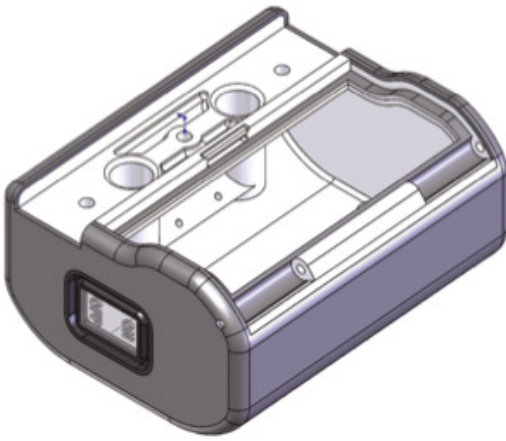
Biocompatible materials, such as cobalt chrome and titanium, are commonly built using AM. In addition, porosity, which is good for tissue integration (osseointegration), can be engineered into parts such as biomedical implants (Fig. 9). Some AM systems can build gradient materials, and AM processes work well on materials that are traditionally very hard to machine because of excessive tool wear, such as titanium and Inconel. Some polymer AM materials can be used to mimic the behavior of human bone.



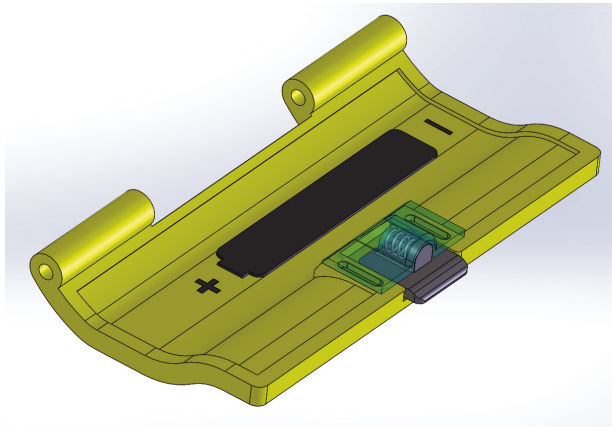
**Figure 5.** Data storage boot, a hard rubber-like material with embedded Vero plastic.



**Figure 6.** Connector cover, a hard rubber-like material with embedded Vero plastic.



**Figure 7.** Remote sensor housing (material jetting) all-in-one build with rubberized exterior, translucent LED windows, integrated door gasket, and operable switch boot/cover.



**Figure 8.** Door assembly with integrated battery cushion spacer. Latch tab and latch cover are separate items bonded at assembly.



**Figure 9.** A metal biomedical implant made via AM that has a porous surface that is conducive for osseointegration. With AM, it is fast and easy to customize a part of this type to account for an individual's particular physiological size and geometry.

**APL AM BONE-LIKE MATERIALS EXAMPLES**

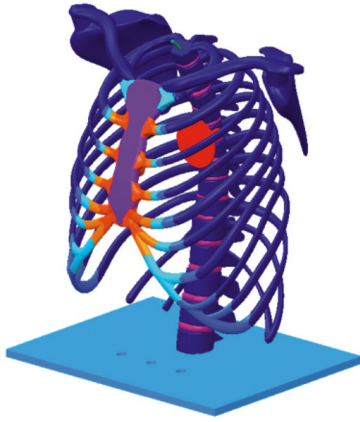
AM processes and materials are being investigated for use in human surrogates for blast and ballistic evaluation. Specifically, they are currently being evaluated for the manufacture of the skeletal rib cage structure for torso surrogates in the Biomechanics and Injury Mitigation Systems program area. AM is expected to produce bone material parts faster and with more repeatable properties than did the previous process, which consisted of casting individual rib rings by hand and bonding them with fiberglass sleeves. Whereas the traditional process was very labor intensive and took about 6 weeks for a single build, AM, using material extrusion, can manufacture the skeleton in about an 88-h automated build with about an hour of manual cleanup time. As mentioned above, a benefit of AM is that the geometry can be easily updated and a new design built without making new molds, saving time and cost.

In the first iteration using AM to fabricate a skeleton surrogate, the capabilities of the material jetting system were explored. Material testing concluded that the thermoset acrylic plastic material mimicked actual skeletal components reasonably well, while variations and different mixtures of the rubber-like resin material were sufficient for the intervertebral discs, sternum, and transition materials. The entire skeleton was built as a fully integrated multimaterial (with multiple durometer characteristics) skeleton built as one component. The discs were made out of the fully compliant rubber material; most of the ribs were made out of white Vero material with a transition region to the sternum material. The transitions between the sternum and the ribs had to be accounted for in the actual design. A cup-in-cone technique was used to ease the transition smoothly from the more rigid Vero bone-like material to the more compliant sternum material, as illustrated in Fig. 10. Each region had to be defined in the CAD file so a material could be assigned during the build. The actual build definitions for the all-in-one skeleton build are shown in Fig. 11, and the final build is shown in Fig. 12. The material's properties were characterized to confirm that the material had suitable mechanical properties and behavior to meet the skeleton's needs to mimic bending strength. Although these AM tools have been piloted on the thoracic skeletal system, there are opportunities to expand the approach to other body regions such as the skull and extremities, as well to improve surrogate designs.



**Figure 10.** Multimaterial build transition technique.

Finally, AM can realize topological optimization routines that can result in nonintuitive part designs that maximize part strength and minimize part mass. The major benefits of AM have not yet been achieved because current design software caters to traditional manufactur-



**Figure 11.** Material definitions for an all-in-one skeleton build. Purple, sternum; dark orange, transition material A; light orange, transition material B; cyan, transition material C; light blue, transition material D; dark blue, bone; magenta, discs (rubber).



**Figure 12.** Final all-in-one skeleton build.

ing methods. Current design practices restrict geometric possibilities and require an iterative approach. Commercial tools automate the optimization process to produce innovative designs, combining design and analysis in a highly efficient process. Although there is still work to be done, and acceptance of the results needs to be vetted and refined, innovative designs primed for AM will soon be realized by using these topological optimization techniques.

### Design for AM

Design for AM is fundamentally different from design for traditional mechanical fabrication processes. The overall engineering design process still remains the same: define the requirements for the greater problem that needs to be solved; gather information regarding

external interfaces, weight limitations, thermal loads, etc.; brainstorm solution spaces and develop conceptual designs; iterate on the feasibility and manufacturability; analyze the results; evaluate the final product; and repeat the design steps as needed to ensure the final product meets the needs of the problem set. Using AM, designers must consider fabrication techniques and opportunities for design creativity much earlier in the process to account for the benefits and limitations AM offers. This requirement is distinctive from those of traditional design, where the manufacturing process is often not considered up front. The benefits of AM (e.g., complex and internal features, material gradients, all-in-one assemblies, etc.) give designers the opportunity to think about their designs in a more creative and holistic manner. Figure 13 shows the general design process. The boxes highlighted in red indicate that discussion with the fabricators and AM engineers is required to best use the varying technologies to meet the needs and requirements of the design. When a team is considering AM as part of the solution to manufacturing components, discussion with the fabricator and AM engineer needs to be part of the solution during the information-gathering step. These discussions regarding the possibilities, advantages, and limitations of AM technologies will help to provide creative design space to the designer. As

#### BOX 2. BASIC DESIGN CONSIDERATIONS FOR A LASER-BASED METAL POWDER BED FUSION SYSTEM

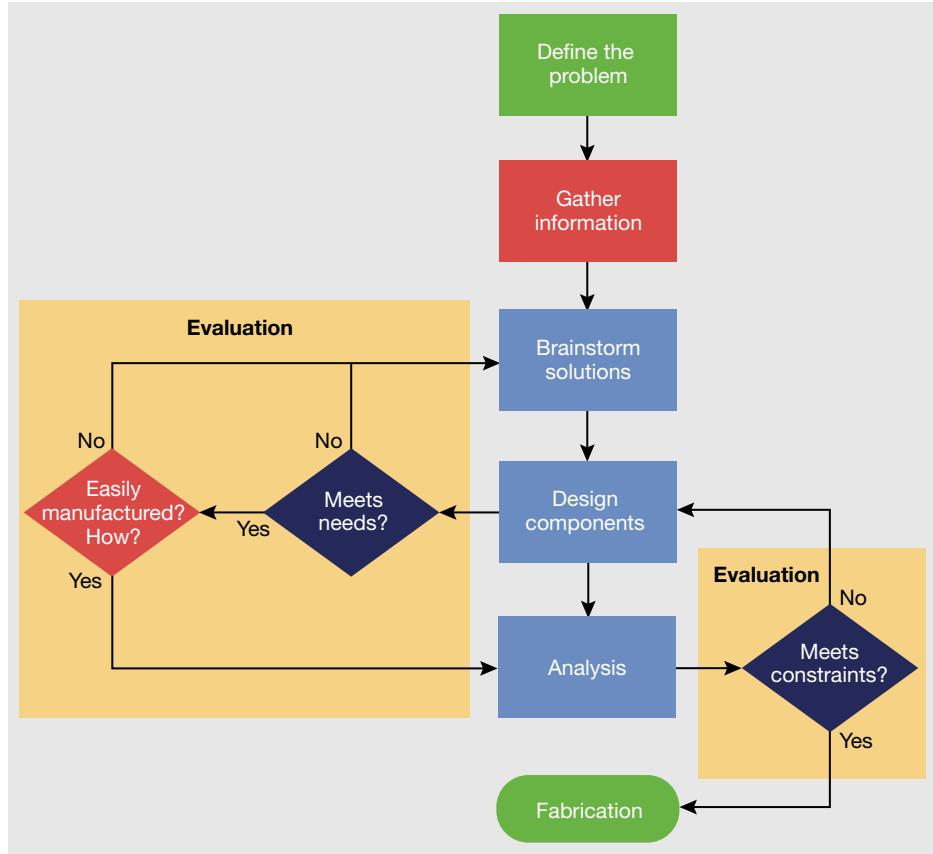
- Overhangs in the part geometry will need to be supported during the build.
  - Overhangs must be accessible so that the support structures can be removed after fabrication.
  - Overhangs with angles less than 35° from the vertical can be built without supports.
- Wall thickness
  - It is typically greater than 400 μm (0.016 in.), but this varies slightly for each system.
  - Build cost is a function of volume and build height, not part complexity.
- Second operations are often necessary.
  - Parts must be cut from the build platform.
  - Supports must be removed.
  - The raw surface finish is closer to that of a casting than of a machining.
  - Heat treatments to remove residual stress or to improve ductility are often needed.
- Build orientation considerations
  - Removal of support structures
  - Thermal/electrical conduction
  - Build direction
  - Build time

previously mentioned, each AM technology has advantages and uniqueness that can be optimized for a given design problem. In general, depending on the additive technology used, considerations for support structure for overhangs greater than 35° (which would later need to be removed) need to be addressed either in the specific feature design or in the build orientation. Each system and material combination has different wall-thickness limitations and varying minimum aspect ratios that will survive the build.

Unfortunately, standard design rules and guidelines have not been formally established for AM. The unique characteristics of AM, along with certain process-specific aspects of AM, could be used to help guide design and optimize geometrical and/or mechanical aspects. The greater design freedom AM affords is beneficial, but there are limitations to those freedoms. Finally, it behooves designers to work with AM engineers early in the production process to foster better synchronization between the design and manufacturing processes.

**APL AM DESIGN EXAMPLE**

A scale model of the EUROPA spacecraft was generated for use at a sponsor engagement. The physical scale model is not simply a rescale of the original. The designer must communicate with the fabricators to discuss options to accurately capture the different features. Often times, multiple additive and manual techniques are used to generate a scale model. Some features must be addressed if they are too small and need to be either artificially enlarged or removed altogether. Other features need to be simplified so that general detail, but not all the fine detail, can be seen. The scale model of the EUROPA spacecraft was fabricated using the glass-filled nylon in APL's powder bed fusion machine for the main body of the satellite, while acrylonitrile butadiene styrene (ABS) from APL's material extrusion system was used to additively build the remaining components (Fig. 14). The solar array panels were laser cut from sheet metal with an image applied to reveal the detail as shown in the final product on display in Fig. 15.

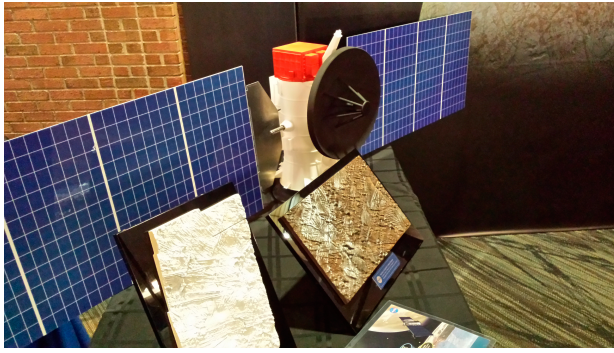


**Figure 13.** Design process with highlighted areas for additional AM consideration.



**Figure 14.** Main structure of EUROPA satellite scale model. The white main body was made with glass-filled nylon on a powder bed fusion AM system, and the black and red sections were made out of ABS thermoplastic on a material extrusion system.





**Figure 15.** Final scale model of EUROPA satellite.

## THE FUTURE OF AM

APL's future use of AM includes the enhanced use of metal AM processes for functional parts as well as tools and materials for novel applications in electronics, biology, and medicine. Through its Additive Manufacturing Center of Excellence, APL is expanding its research portfolio to include topics that address current technical hurdles that are preventing more widespread adoption of AM. These include *in situ* sensing of additive processes (for feedback control and model validation), robust topological optimization of AM part designs, machine performance and material property studies, and development of inexpensive and rapid methods of qualification.

## CONCLUSIONS

The rapidly developing AM technologies are an excellent fit with APL work, because many of the systems that

APL produces are complex, undergo frequent design changes, and are built in small lot numbers. This article demonstrates how the advantages of AM were applied to parts and systems that would have been much more difficult to realize with conventional manufacturing processes. Through its Additive Manufacturing Center of Excellence, APL is aggressively pursuing research and development that will enable it not only to remain an advanced practitioner of AM but also to broaden the potential applications for these technologies in the critical and demanding systems it develops for its sponsors. In addition, APL is pursuing research and development of unique methods and applications for emerging AM technologies that will enable revolutionary solutions to challenges in electromechanical systems, biology, medicine, and many other fields.

**ACKNOWLEDGMENTS:** The authors acknowledge the helpful contributions of Rick Startt, Jason Stipes, Jeff Paulson, Scott Swetz, Katy Carneal, Jack Braine, and Drew Seker. The SMART-TE blunt impact chin form was developed as part of research supported by the U.S. Marine Corps Systems Command, PM Infantry Weapon Systems. The content included in this article does not necessarily represent the position or policy of the U.S. government.

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## APPENDIX. APL ADDITIVE MANUFACTURING CENTER OF EXCELLENCE

In February 2016, APL announced the formation of the APL Additive Manufacturing Center of Excellence. The center builds on APL's existing capabilities in advanced mechanical fabrication and will guide APL efforts to creatively apply this disruptive technology, which is rapidly revolutionizing how a wide variety of parts and systems are designed and built. The center's initial focus is on significant technical challenges that are currently preventing the DoD from widespread adoption of AM technologies and also on topics of interest to intelligence communities. Other future initiatives will include printed microelectronics and bioprinting. APL plans to serve as a leader in these important areas.

The center will engage in the following activities:

- AM design and fabrication services for prototypes and limited-volume runs in support of sponsor programs
- Research on new design and fabrication methods and new materials for AM

- Research on the characterization, testing, and evaluation of AM processes
- Exploring the innovative applications of embedded electronic circuits
- Pioneering the use of AM in the creation of biological parts and organs
- Serving as a trusted agent for AM test and evaluation
- Serving as a trusted adviser on application of AM in Department of Defense and intelligence community projects

The new center builds on APL's expertise and capabilities in metal and polymer AM, mechanical design, materials science, physics, intelligent systems, and bioengineering. Staff at the center will also collaborate with other organizations in the Hopkins enterprise, including the Johns Hopkins Whiting School of Engineering and the Johns Hopkins School of Medicine, to leverage their expertise and provide potential research opportunities for students.

## THE AUTHORS

**John A. Slotwinski** is the Additive Manufacturing Section Supervisor in APL's Research and Exploratory Development Department (REDD). In this capacity he serves as a principal engineering resource for leading and conducting AM development activities; researching and implementing advanced additive materials, technologies, and applications; and leading technical teams for advanced AM-related projects in support of Lab programs. He also serves as the Vice Chair of ASTM F42 Committee on Additive Manufacturing Technologies. **Emily E. Crane** is a mechanical engineer and section supervisor in REDD's Mechanical Engineering, Systems Analysis and Design Group. She has expertise in mechanical systems and design as they apply to the conceptualization and realization of AM parts and systems. **Todd Ramsburg** is the Supervisor of the Advanced Mechanical Fabrication Group in REDD. This group houses the Additive Manufacturing Center of Excellence and is responsible for providing a broad range of capabilities including composites fabrication, CNC machining, and sheet metal fabrication and assembly in support of the Lab's diverse sponsor programs. **Erin D. LaBarre** is a materials engineer in REDD with 10 years of experience in materials characterization. **Ryan J. Forrest** is REDD's AM Production Manager, responsible for the scheduling and production related tasks for all of APL's AM parts. For further information on the work reported here, contact John Slotwinski. His e-mail address is [john.slotwinski@jhuapl.edu](mailto:john.slotwinski@jhuapl.edu).