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

Emily E. Crane, Matthew S. Bailey, Joseph C. Green, Jennifer L. Herchek, Joseph W. Hrivnak, Brian F. Massey, Ryan D. Seery, James N. Tobias, and Harold R. White

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,

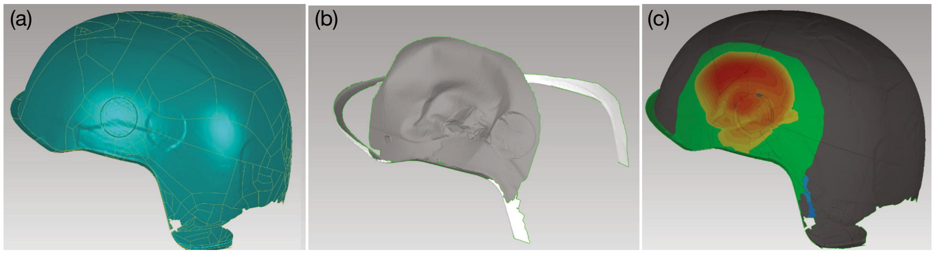


Figure 2. 3-D comparison before and after impact. (a) Un-deformed helmet scan used as reference. (b) Scan data of a deformed helmet after impact. (c) Scan data of the same deformed helmet projected onto the un-deformed helmet surface as a heat map with the color scale showing the degree of deformation 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

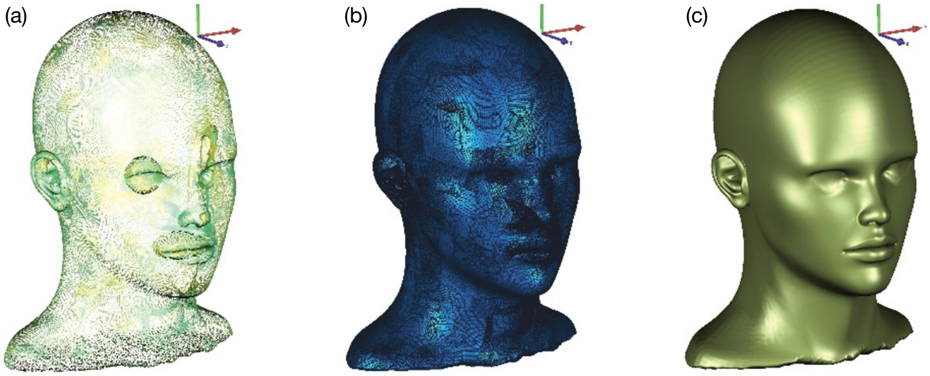


Figure 3. Reverse engineering process: scan to CAD. (a) Point cloud output from 3-D scan. (b) Tessellated surface connecting all the points. (c) Final mathematical surface generated by mapping to the tessellated surface.

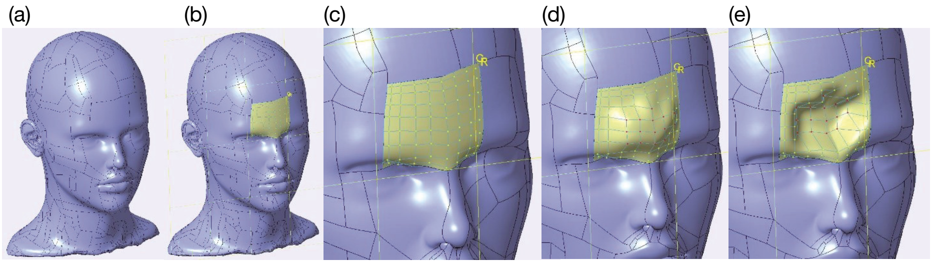


Figure 4. Example of advanced surface modeling. (a) A surface file is imported. (b) The surface area to be altered is selected (panel c shows a close-up of the surface area). (d and e) The knot points to manipulate are selected and pulled and pushed in all directions to achieve the desired outcome.

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.

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.

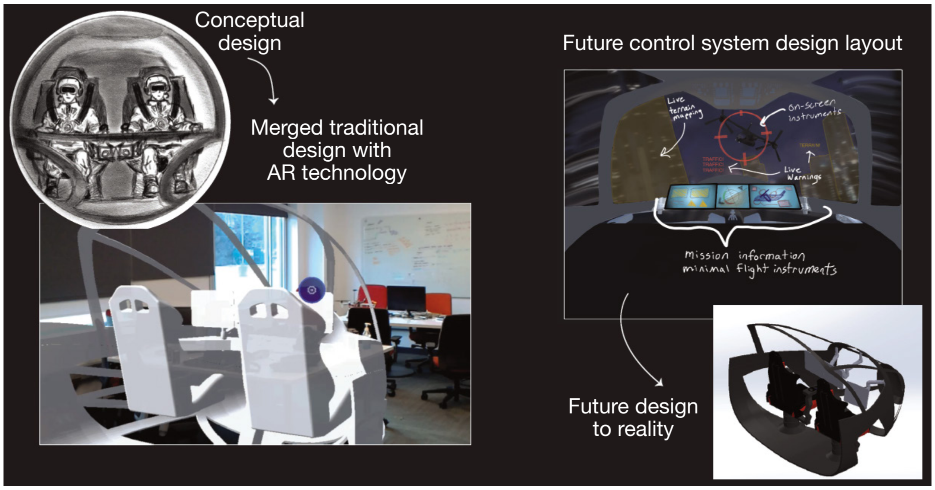


Figure 5. Workflow of transforming conceptual design sketches into a CAD model and then into a virtual cockpit enabled by AR. This approach allowed for rapid iteration of changes and let end users give critical feedback on positioning and visibility before a physical prototype was built.

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

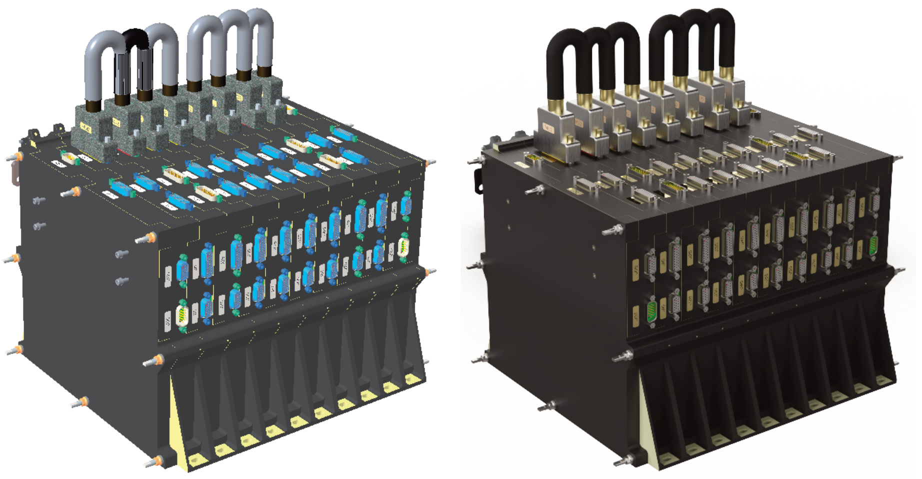


Figure 6. Comparison of the CAD render (left) and the photorealistic render (right) of the design for the redundant electronics module for Parker Solar Probe. These examples show the difference between a CAD model and a photorealistic image.

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.

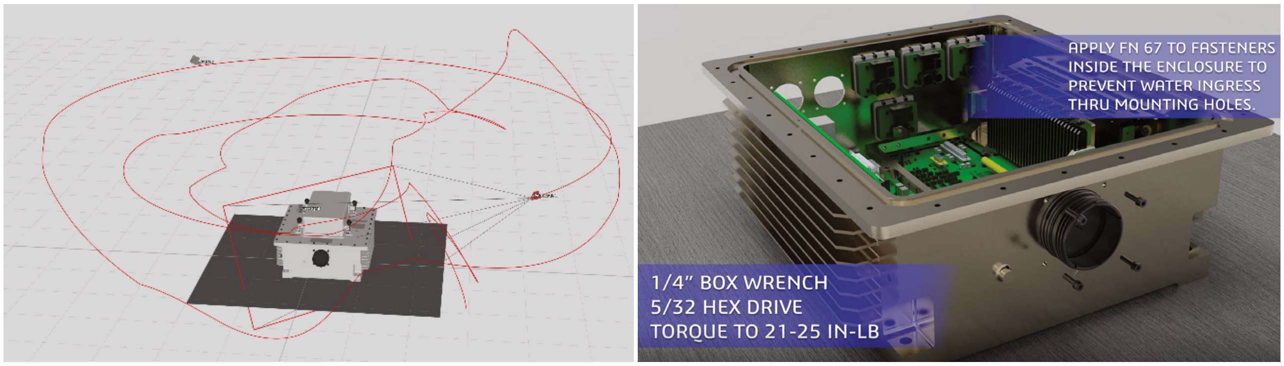


Figure 7. Screenshots of the camera setup and final video. The animation camera track is shown as a path line in red (left); the still image from the animation after post-processing is also shown (right).

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.

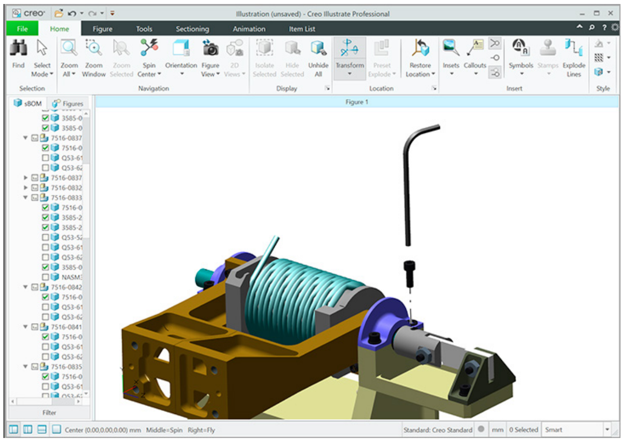


Figure 8. Screenshot of animating an assembly. In the final animation, end users would see the hex wrench tighten the bolt in place on the assembled part.

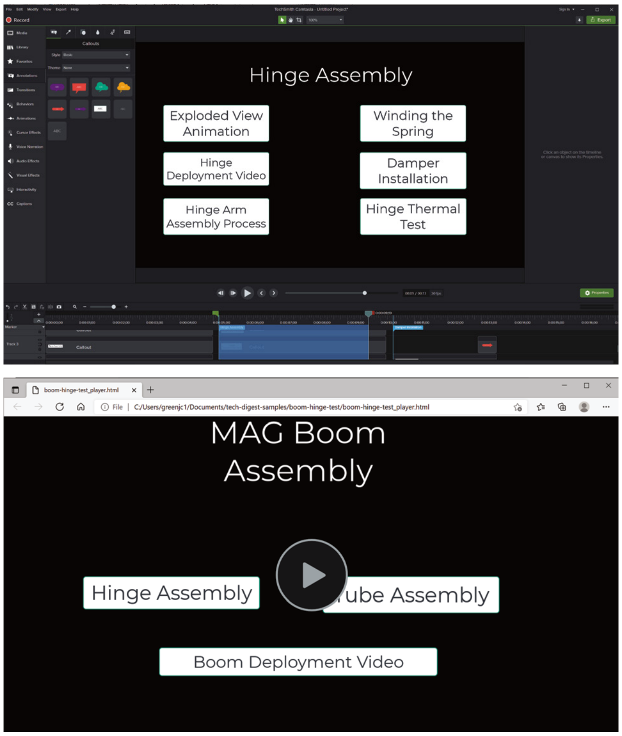


Figure 9. Web-based visualization example. A screenshot of creating a timeline in a video editing tool (top) and an end user's view in a web browser (bottom).

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.

REFERENCES

[1] A. Beck, ”60 years of CAD infographic: The history of CAD since 1957,” PARTsolutions, https://partsolutions.com/60-years-of-cad-infographic-the-history-of-cad-since-1957/ (accessed Nov. 10, 2021).

[2] R. L. West, F. P. Brelsford, and R. A. Eschbach, “The computer-aided design and engineering facility,” *Johns Hopkins APL Tech. Dig.*, vol. 7, no. 3, pp. 244–249, 1986, https://secwww.jhuapl.edu/techdigest/Content/techdigest/pdf/V07-N03/07-03-West.pdf.

[3] S. R. Schachtner and S. D. Ahlbrand, “Putting computer-aided design to work,” *Johns Hopkins APL Tech. Dig.*, vol. 7, no. 3, pp. 250–255, 1986, https://secwww.jhuapl.edu/techdigest/Content/techdigest/pdf/V07-N03/07-03-Schachtner.pdf.

[4] H. K. Charles Jr., “The engineering design, fabrication, testing, and qualification process within the Steven Muller Center for Advanced Technology,” *Johns Hopkins APL Tech. Dig.*, vol. 12, no. 1, pp. 4–13, 1991, https://secwww.jhuapl.edu/techdigest/Content/techdigest/pdf/V12-N01/12-01-Charles_Eng.pdf.

[5] D. W. Wilson, L. E. Bailey, and C. E. Bennett, “Expanding mechanical design and fabrication horizons,” *Johns Hopkins APL Tech. Dig.*, vol. 21, no. 4, pp. 606–515, 2000, https://secwww.jhuapl.edu/techdigest/Content/techdigest/pdf/V21-N04/21-04-Wilson.pdf

[6] “What is a digital twin?” IBM. https://www.ibm.com/topics/what-is-a-digital-twin (accessed Apr. 13, 2022).

[7] “Voxmap PointShell (VPS) Software Library.” 3D Systems. https://www.3dsystems.com/scanners-haptics/application-gallery/vps-software-library (accessed Nov. 10, 2021).

[8] P. Campbell and K. Melton, “Johns Hopkins APL team gives Marine aviators a glimpse of the future,” APL, Laurel, MD, Sep. 7, 2021, https://www.jhuapl.edu/NewsStory/210907-marine-aviators-glimpse-the-future.

[9] J. B. Erp and B. P. Self (eds.), “Tactile displays for orientation, navigation and communication in air, sea and land environments,” RTO Technical Report TR-HFM-122, NATO Research and Technology Organisation, Aug. 2008, https://apps.dtic.mil/sti/pdfs/ADA492500.pdf.

[10] “Parker Solar Probe.” APL. http://parkersolarprobe.jhuapl.edu/ (accessed Nov. 10, 2021).

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.

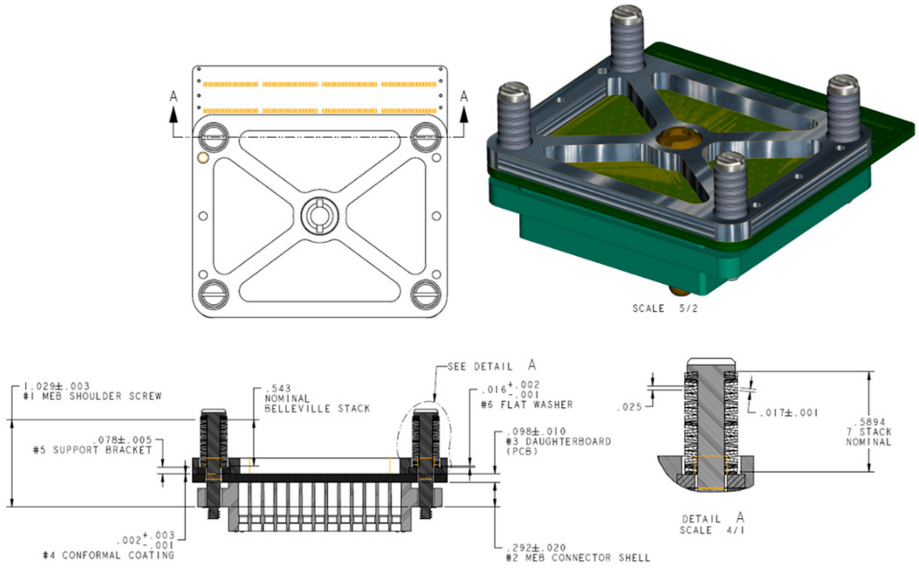
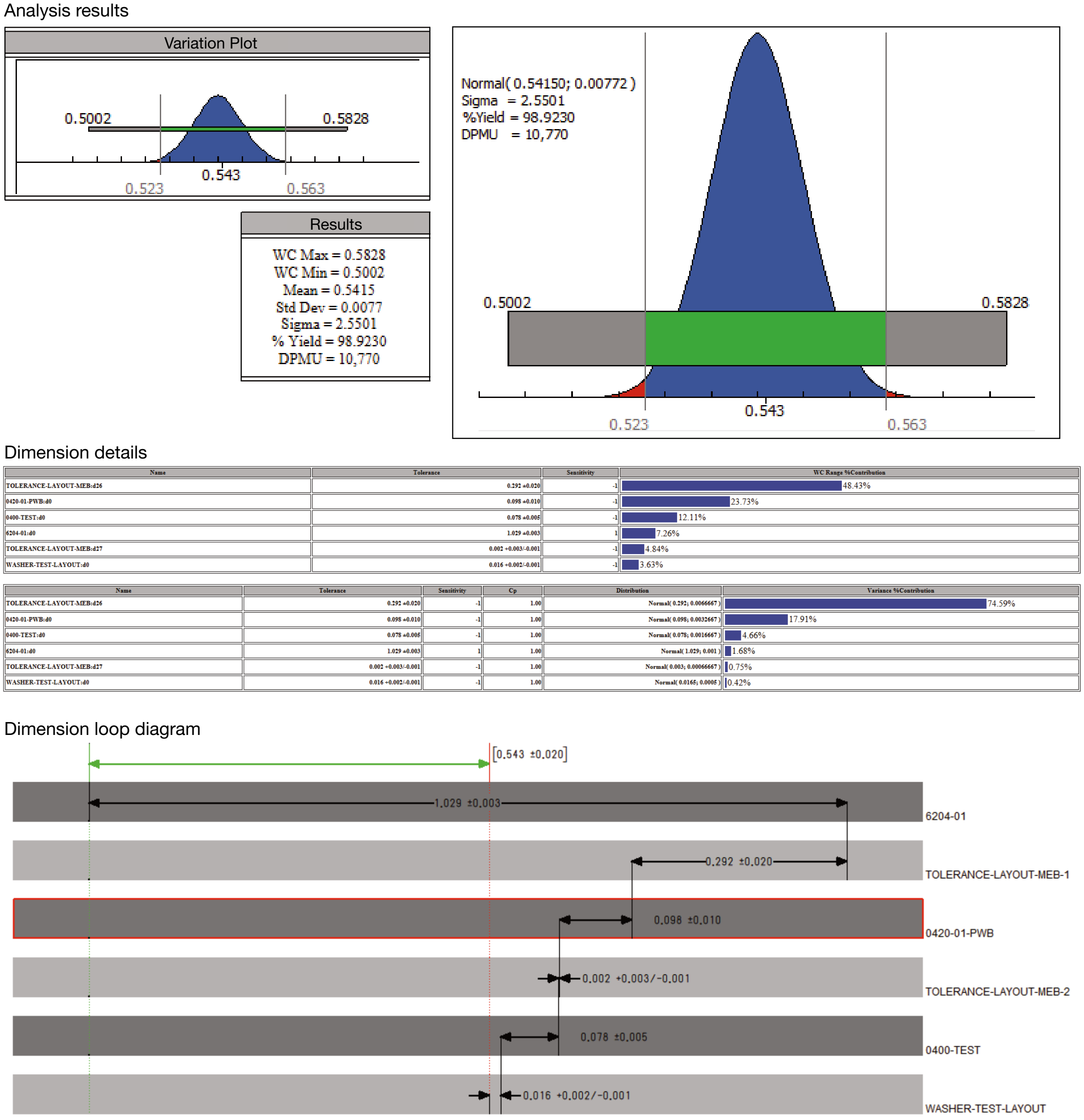


Figure 10. Example of assembly tolerances that influence a tolerance stack-up analysis. The visualization aids in determining the length of the four shoulder screws to ensure that the proper amount of preload is applied by the Belleville washers.



Results

WC Max = 0.5828
WC Min = 0.5002
Mean = 0.5415
Std Dev = 0.0077
Sigma = 2.5501
% Yield = 98.9230
DPMU = 10,770

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%

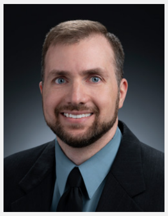
Figure 11. Visualization of each component's contribution to the overall stack-up. The contribution of each component's tolerance to the overall tolerance stack-up is shown as a percentage of the total in the histogram plot. The loop diagram is an alternative representation of the component contributions,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

Emily E. Crane, Research and Exploratory Development Department, Johns Hopkins University Applied Physics Laboratory, Laurel, MD

Emily E. Crane is a mechanical engineer and assistant supervisor in APL's Electrical and Mechanical Engineering Group. She earned a BS in mechanical engineering from the University of Maryland at College Park and an MS in mechanical engineering from Johns Hopkins University. She is an expert in computer-aided design (CAD), finite element analysis, hardware reverse engineering, and design for additive manufacturing. Her email address is emily.crane@jhuapl.edu.

Matthew S. Bailey, Research and Exploratory Development Department, Johns Hopkins University Applied Physics Laboratory, Laurel, MD

Matthew S. Bailey is a mechanical engineer in APL's Electrical and Mechanical Engineering Group. He earned a BS and an MS in mechanical engineering, both from Johns Hopkins University. Matthew's focus is mechatronics. His email address is matthew.bailey@jhuapl.edu.



Joseph C. Green, Research and Exploratory Development Department, Johns Hopkins University Applied Physics Laboratory, Laurel, MD

Joseph C. Green is a mechanical engineering designer in APL's Electrical and Mechanical Engineering Group. He earned an AAS in computer-aided design from Howard Community College. He has designed deployable systems for space programs and structures for flight and ground support equipment, as well as submarine systems. His expertise includes conceptual design, including modeling and drawing requirements, and integration support. His email address is joseph.green@jhuapl.edu.

Jennifer L. Herchek, Research and Exploratory Development Department, Johns Hopkins University Applied Physics Laboratory, Laurel, MD

Jennifer L. Herchek is a mechanical engineer in APL's Electrical and Mechanical Engineering Group. She earned a BS and an MS in mechanical engineering, both from Johns Hopkins University. Jenni specializes in mechanical design and analysis and is experienced with haptics, robotics, and design for additive manufacturing. Her email address is jenni.herchek@jhuapl.edu.

Joseph W. Hrivnak, Research and Exploratory Development Department, Johns Hopkins University Applied Physics Laboratory, Laurel, MD

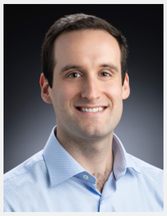
Joseph W. Hrivnak is a senior mechanical designer in APL's Electrical and Mechanical Engineering Group. He earned an AAS in engineering drafting and design from Delaware Technical Community College and is certified in geometric dimensioning and tolerancing (GD&T) by the American Society of Mechanical Engineers. His areas of expertise include component and assembly design, tooling and fixturing, and electronic packaging. His email address is joseph.hrivnak@jhuapl.edu.

Brian F. Massey, Research and Exploratory Development Department, Johns Hopkins University Applied Physics Laboratory, Laurel, MD

Brian F. Massey is a mechanical engineer in APL's Electrical and Mechanical Engineering Group. He earned a BS in mechanical engineering from Widener University. His experience in mechanical engineering includes designing aerospace and military systems and structures, such as spacecraft, payloads, electronic sensors, and more. He is experienced in a variety of computer-aided design (CAD) programs. His email address is brian.massey@jhuapl.edu.

Ryan D. Seery, Research and Exploratory Development Department, Johns Hopkins University Applied Physics Laboratory, Laurel, MD

Ryan D. Seery is a mechanical design engineer in APL's Electrical and Mechanical Engineering Group. He earned a BS in mechanical engineering from the University of Connecticut and an MS in mechanical engineering from Johns Hopkins University. His areas of expertise include computer-aided design (CAD), programming, fabrication, and assembly. His email address is ryan.seery@jhuapl.edu.



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

James N. Tobias is a mechanical engineer in APL's Electrical and Mechanical Engineering Group. He earned a BS and MS in mechanical engineering from the University of Rochester. He is experienced in computer-aided design (CAD) and reverse engineering, and he has worked on a variety of mechanical design projects, including mechanical structures, electrical and optical enclosures, fluid regulation mechanisms, and others. His email address is james.tobias@jhuapl.edu.

Harold R. White (Retired), Research and Exploratory Development Department, Johns Hopkins University Applied Physics Laboratory, Laurel, MD

Harold R. "Ray" White, who retired from APL in 2021, is a mechanical design engineer. He has over 42 years of career work experience. His experience in mechanical engineering and design includes designing aerospace and military systems, structures, and electro-mechanical packages. He is also experienced in a variety of computer-aided design (CAD) programs.