Johns Hopkins APL
TECHNICAL DIGEST
Volume 35, Number 3

Exploring Immersive Technology at APL

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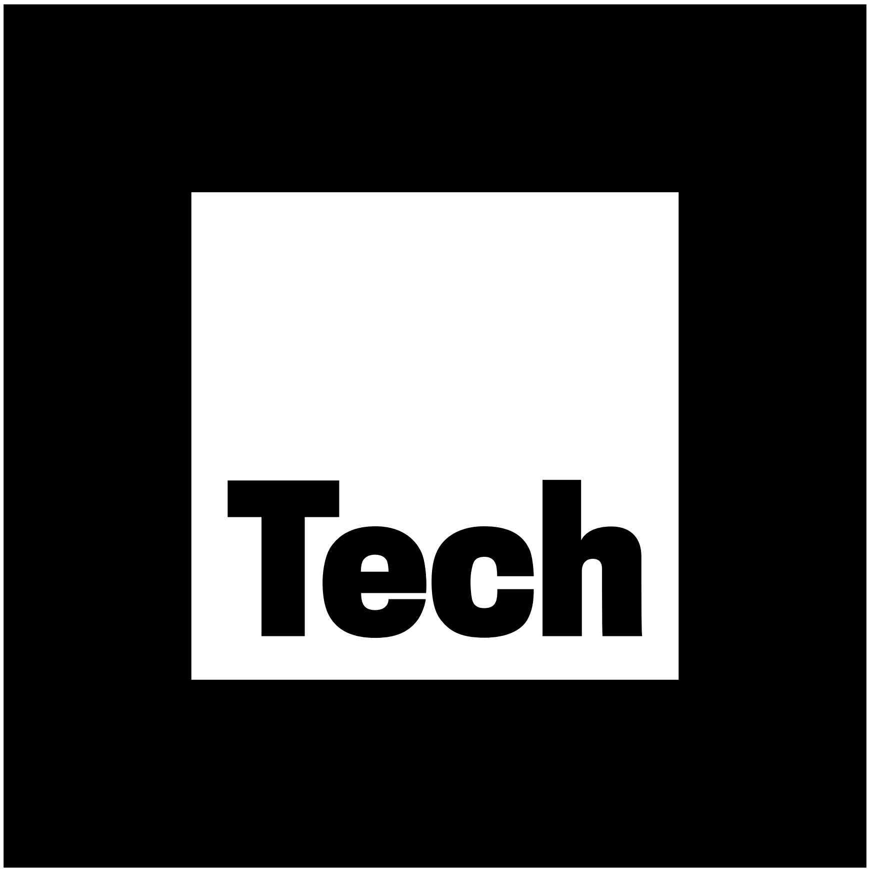

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XR for Advanced Prototyping of Spacecraft Mechanical Systems

Devin J. Hahne

AR VR MR

ABSTRACT

This article discusses how teams in the Space Exploration Sector at the Johns Hopkins University Applied Physics Laboratory (APL) are using XR as an advanced prototyping capability. Prototypes enable engineering and design teams to see or experience an object before committing resources to full-scale production. XR provides a means of digitally prototyping high-fidelity physical information in a nonmaterial form. The collaborative immersive qualities of XR appeal to human visual processing senses, enabling teams to quickly engage complex system information, make decisions, and confidently move from ideas to actions. The design intelligence gained through using XR enables teams to make faster decisions with greater confidence and less risk. APL teams introduced production-grade XR tools into mechanical design workflows in 2017, making critical contributions to Parker Solar Probe, Europa Clipper, and other programs. But XR is only a small part of a bigger picture challenging companies to rethink conventional business operations for the modern competitive global industrial ecosystem. Incorporating XR as part of a broader digital transformation (DX) strategy carves a path to greater advantages and opportunities that cannot be realized by XR alone.

INTRODUCTION

Human decision-making tends to be most expedient and robust when it involves collaborative hands-on or immersive experiences. Such experiences give humans the opportunity to use their multisensory perception and processing capabilities to leverage cognitive strengths such as pattern recognition and data relationship identification. XR is a broad term categorically referring to the expansive variety of immersive technologies including virtual, augmented, and mixed reality (VR, AR, and MR, respectively), as well as others. XR contributes to improved human decision-making by reducing cognitive load and cognitive distance. Cognitive load is the effort required to absorb and process a given type of information. Cognitive distance is the gap between information form and context (e.g., 3-D information delivered as a slide presentation).

This article describes a few examples of how APL teams used XR advanced prototyping to solve engineering problems in spacecraft mechanical design and integration for the Parker Solar Probe and Europa Clipper missions. For context, it begins with brief overviews of the Fourth Industrial Revolution (4IR), Industry 4.0, and

Digital Transformation (DX). These trends, along with others, are disrupting business operations across economic sectors worldwide and are the background for XR. This article does not rigorously examine these trends, nor does it offer return-on-investment predictions for technology adoption. Instead, it briefly discusses how XR has become part of mechanical design in the APL Space Exploration Sector's Mechanical Systems Group and how this narrow slice of industry possibly sheds light on higher-level business operations.

THE FOURTH INDUSTRIAL REVOLUTION

The first three industrial revolutions were characterized by mechanization, mass production, and computation, respectively. Klaus Schwab, in his seminal work about the Fourth Industrial Revolution (4IR), characterizes this newest revolution as ubiquitous mobile internet in combination with many complementary technological breakthroughs—specifically, artificial intelligence, robotics, the Internet of Things (IoT), autonomous vehicles, 3-D printing, nanotechnology, biotechnology, materials science, energy storage, and quantum computing. The key point to recognize is the interconnectivity of the physical, digital, and biological domains and how, together, they are changing not only what we do and how we do it but also who we—as humans—are.[1,2]

INDUSTRY 4.0

The terms *Industry 4.0* and *4IR* are often used interchangeably. This is a disservice to both terms. 4IR centers on the economic, societal, and technological forces disrupting global industries. Industry 4.0 is more about strategic initiatives to gain competitive advantage by using 4IR technologies. For instance, outfitting value chains with sensor and information systems can lead to real-time decisions, which could reduce costs as well as increase production from machines and workers. Industrial IoT (IIoT) systems could track a product's status, as well as the status of the machines operating on the product. When combined with artificial intelligence tools that look for indicators of needed maintenance and asset scheduling optimizations, as well as integrated data consoles and XR displays, enterprises can gain unprecedented awareness of their operations, enabling them to be more responsive to customer demands and more adaptable to value chain events.[3–6]

DIGITAL TRANSFORMATION

What would it look like if all our information and communications systems worked well to create new opportunities and more value? In 2018 the Department of Defense announced, "To help ensure continued U.S. technological superiority, the Department is transforming its engineering practices to digital engineering, incorporating technological innovations into an integrated, digital, model-based approach."[7] DX can be viewed as using technology to "solve traditional business challenges and create new opportunities. . . . It requires acceptance of entirely new ways of working and delivering value to customers."[8] In other words, DX is the tactical implementation of Industry 4.0 and 4IR trends to reduce costs and deliver better value. It involves imagining entirely new business operations and establishing integrated information systems. For instance, the computer-aided design (CAD) models of a complex assembly could become the visual foundation of an XR cyber-physical system digital twin that could be used, for example, to display modeling and simulation data and deliver status reports of component procurements and testing.

XR IN SPACECRAFT MECHANICAL DESIGN

The core responsibility of the mechanical designers in the Mechanical Systems Group in APL's Space Exploration Sector is ownership of the mechanical design of spacecraft structures. From a systems engineering standpoint, this is where requirements are converted into components within systems of systems. Mechanical design sits at the nexus of all stakeholder concerns. The engineers responsible for thermal and stress analysis, manufacturing, radiation, electromagnetics, electrical wire harness, integration and testing (I&T), etc. all depend on seeing their interests reflected in the mechanical design.

Designers use CAD models to create manufacturing drawings for hardware fabrication and inspection. Traditionally, non-designers engage with the design by reviewing drawings, screenshots of CAD models, or lightweight viewable CAD models—all of which are 2-D derivatives of 3-D data. For instance, 3-D PDFs are relatively easy to create and distribute, but they often are not user friendly. Additionally, a sense of component sizes can be easily lost in these derivatives, and this can lead to ill-fated situations such as components being too large to fit though doorways and hallways and complications with lifting operations.

AR tools are making it possible for all team members—engineers, technicians, systems engineers, system assurance managers, etc.—to access high-fidelity design data within context that is relevant to their particular functions. The two AR engineering tools that have been most effective for teams in APL's Space Exploration Sector are ProtoSpace and Vuforia. ProtoSpace is an AR CAD model visualization tool developed by, and licensed from, NASA's Jet Propulsion Laboratory Operations Laboratory (JPL Ops Lab). It converts high-fidelity 3-D CAD models of top-level spacecraft assemblies into AR experiences. It delivers the AR experiences via the Microsoft HoloLens head-mounted display platform. Vuforia is a commercial tool licensed from PTC. It delivers CAD data as AR experiences to phone- and tablet-based devices as well as to head-mounted displays. Vuforia most easily consumes PTC Creo CAD files and can even incorporate IoT sensor streams into AR experiences. Currently Vuforia's most noteworthy capabilities are its ability to target physical objects to anchor the AR experiences and then to perform occlusion culling so that the AR experience appears to be obstructed by the model target.

XR on Parker Solar Probe

The Parker Solar Probe spacecraft launched on August 12, 2018, from Cape Canaveral, Florida.[9] Four major science investigations are riding aboard the observatory. It will fly within about 4×10^6 km of the sun and face temperatures of nearly 1,400°C (2,500°F). A 2.4-m-diameter shield, called the Thermal Protection System, protects the observatory from the intensity of the sun. Two of the core questions the mission is working to answer are why the corona is so much hotter than the photosphere and how the solar wind is accelerated. On December 4, 2019, the first results of the mission were published.[10] Parker Solar Probe is the first APL-managed mission to take advantage of the application of production XR during the I&T phase of the life cycle. Some of the use cases described below were first reported by Hahne et al.[11]

High-Gain Antenna Installation Rehearsal

The Parker Solar Probe high-gain antenna (HGA) is responsible for transmitting all science data back to Earth. It comprises a 0.6-m-diameter carbon fiber parabolic reflector mounted on a 1-D rotating actuator and is fed radio frequency (RF) signals via rectangular waveguides from telecom subsystem components. Flexible waveguides cross the actuator joint, connecting the rigid waveguides on the spacecraft with the antenna's feed assembly. Although the HGA assembly is not particularly large and its installation onto the spacecraft is not particularly complex, the installation is by no means trivial. The easy part is transferring the assembly from its tabletop stand to the exterior surface of the spacecraft. The hard part is avoiding all the components already mounted to the spacecraft as well as accessing the mounting fasteners obstructed by the reflector itself.

A team—comprising engineers, technicians, and system assurance managers—used ProtoSpace to rehearse the installation steps spelled out in a work instruction document. The immersive experience helped the team discover unexpected challenges and inspired edits to the instructions. At least three major discoveries directly led to improved actions when handling the flight hardware: First, no fewer than two technicians were required to carry the HGA because of the awkwardness of handling the component. Second, those two technicians determined the best path to approach the spacecraft with the HGA and avoid interfering with other components. Finally, a third technician determined the best position to access the mounting fasteners behind the reflector with the HGA held against the spacecraft (see Figure 1). Before this rehearsal, the team had assumed that interference with other spacecraft components was inevitable. The AR immersion rehearsal allowed the team to discover a safe and certain installation sequence (see Figure 2).

Figure 1. HGA XR installation rehearsal. The team used XR to rehearse the installation steps described in a work instruction document and discovered several "gotchas" during the process, leading to revisions that improved the instructions.

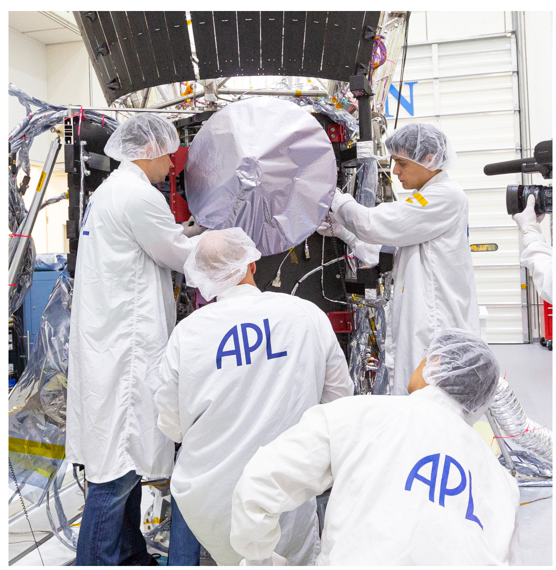


Figure 2. HGA flight hardware installation. The XR installation rehearsal led to the discovery of an installation sequence that avoided interference with other components—something the team had assumed was impossible before the rehearsal.

Figure 3. The integration team, comprising participation from APL and external partners, using XR to inspect the combined third-stage payload adapter and spacecraft assembly. Left, Users test umbilical access in AR. Right, User demonstrates clearance to vibe table in AR.

Spacecraft Vibe, Match Mate, and Dynamics Flow

The most critical interface for the entire mission is the interface of the spacecraft with the third-stage payload attachment fixture. This interface was mated for the first time at APL in preparation for vibration testing and match mate testing, and it presented a significant challenge. The packaging of the instruments and solar arrays obstructed access to torque fasteners and mate/de-mate of the umbilical wire harness connectors. This mating operation was a collaborative effort between APL and the stage team. The APL team was familiar with the spacecraft hardware located around the launch vehicle separation plane and needed to impart information to the third-stage team so that they would be equally familiar. Because nearly all the observatory's instruments are situated near this interface with the third stage, any error or inadvertent contact with sensitive hardware could result in devastating consequences to those components and to the mission.

The entire operation was classified as both hazardous and critical and, like other operations, required thorough planning. The teams needed to identify potential show-stopping issues and develop contingency plans to best reduce the risk of damaging hardware and impacting the mission cost and schedule. While viewing the CAD model on a computer screen gave them sufficient information to talk through some processes, it quickly became clear that a ProtoSpace exercise could help the teams better understand the interface and better prepare for the upcoming spacecraft environmental tests. Operations could be planned in such a way as to avoid collisions and interferences between tools and instruments. ProtoSpace enabled the teams to learn about the location of hardware, as well as tool access and motion paths, and better plan ahead for the mating operations. Figure 3 depicts the integration team inspecting the combined third-stage payload adapter and spacecraft assembly. Participants from both organizations were able to express concerns about their particular areas of responsibilities and expertise and to help develop steps and processes that were crucial to the mating operation's success. Lessons learned from these ProtoSpace sessions and these tests were also incorporated into the procedures to mate the spacecraft and the launch vehicle during launch processing and made the final mating before launch an extremely successful event.

Unexpected Illumination on the V5 Antenna

At closest approach, the Parker Solar Probe observatory is protected from the intensity of the sun by an umbra created by the Thermal Protection System. Any component protruding beyond the umbra at that time will be damaged. Parker Solar Probe uses state-of-the-art autonomy and flight software along with solar limb sensors to detect umbra violations due to spacecraft attitude errors. The solar limb sensors' heads are designed to be the first objects that see sunlight in the

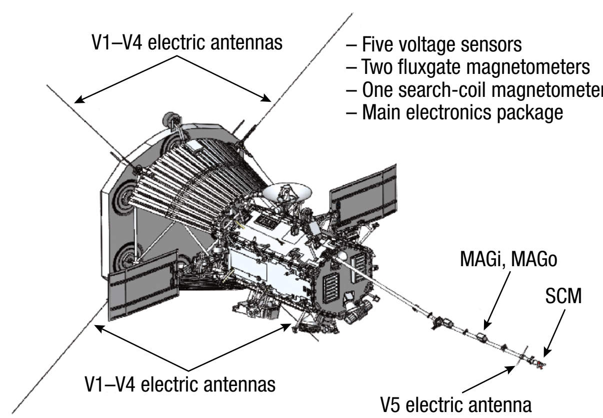


Figure 4. Model of Parker Solar Probe showing the FIELDS antennas, specifically the V5 voltage sensor.[13] An early test indicated that the V5 antenna was being hit by solar illumination when it was supposed to be in shadow. Studying telemetry data, CAD models, and 2-D drawings helped the team form hypotheses about why this was happening, but only through an immersive experience could the team confidently confirm one of the hypotheses.

event of an excursion away from sun pointing. During observatory commissioning—after launch but before the first solar encounter, when the solar illumination was at a safe level—the team tested this subsystem by intentionally tilting the spacecraft in a number of directions off the sun line. They monitored inputs from the V5 FIELDS antenna (Figure 4), which is mounted at the end of the magnetometer boom, as a check to determine whether the boom was deployed correctly. All components, except the solar limb sensors, are supposed to signal that they are inside the umbra. However, during the test, the V5 antenna telemetry signal indicated it was being hit by solar illumination when it was supposed to be in shadow.

Engineers studied the spacecraft configuration using telemetry data, CAD models, and 2-D drawings, attempting to visualize the situation. Ultimately they arrived at plausible explanations—suspecting that the illumination could be caused by a glint off a solar array—but they could gain only so much confidence by rotating CAD models on a computer screen, and thus they wanted further confirmation. The team used ProtoSpace to take an immersive look at this scenario. Once the model was loaded and oriented such that a user could visually align the V5 antenna with one of the solar arrays, suspicions of the glint hypothesis were immediately confirmed. Simply put, the conclusion was visually apparent. Additionally, the team recognized that the testing configuration positioned the solar array wings fully deployed—fully outside the umbra—whereas during solar encounter, they are withdrawn and much closer to the spacecraft body. By reducing cognitive distance, the XR experience provided the team a level of certainty that CAD models and 2-D images could not, and the engineers were able to proceed into the first solar encounter with assurance that the observatory would function properly.

XR on Europa Clipper

Europa Clipper is set to launch in the early 2020s.[12] The spacecraft comprises a primary structure that is nearly 6 m high and 1.5 m in diameter, with a solar array wingspan that almost covers a typical basketball court. Its mission is to orbit Jupiter and make flyby observations of Europa, one of Jupiter's moons. The suite of science instruments will study this icy ocean world and look for signs of microorganisms. This mission is a collaboration between APL and JPL (in Pasadena, California). JPL is managing the overall program as well as delivering the avionics module. APL is providing the propulsion module, which includes the solar arrays, as well as the RF module. Europa Clipper was still very much in its design development life cycle as the XR contributions to Parker Solar Probe were becoming clear. The benefits of XR captured the attention of the Europa Clipper team, motivating team members to think harder about incorporating XR into this mission as well.

ICEMAG Payload Harness

The Europa Clipper ICEMAG payload harness was a bundle of wire harnesses, coaxial cables, and fiber optic cables. A number of requirements make it nearly impossible to install this harness onto the propulsion module. For instance, the fiber optic cables are delicate to handle, requiring a large bend radius, and they must be shielded from radiation in a rigid copper pipe and also must be thermally coupled with the propulsion module to reduce heater power. The propulsion module–hosted segment of this bundle routes from a connector bulkhead high up on the avionics module to a field joint bracket down on the propulsion module lower cylinder. Along the way, the harness must navigate the congested exterior of the avionics module, cross the avionics module–propulsion module interface, avoid the heat redistribution system fluid lines, navigate between solar array bipods along the propulsion module surface, cross the interface between the upper and lower cylinders, and make a sharp turn to interface with the lower field joint bracket.

The team members could not fully realize the breadth of all these challenges; no one knew all the unknowns. Even when the APL and JPL teams met face to face and manipulated CAD models on a projection screen for all to see, they could not achieve a confidence-inspiring solution. In May 2018, the APL and JPL teams used ProtoSpace to participate in a shared non-colocated AR exercise (see Figure 5) to examine this routing in more detail. The immersion experience reduced cognitive distance and load, allowing the whole team to really see and understand the details of the problem. As more of the unknown unknowns were converted into known unknowns, subject-matter experts were able to begin considering creative alternative solutions to the problems.

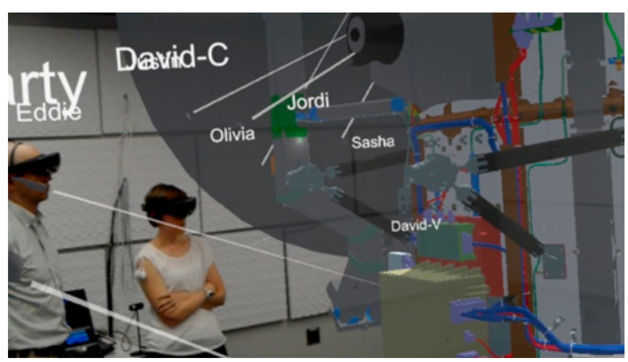


Figure 5. APL–JPL non-colocated collaboration using XR. Avatars of the non-colocated team members appear as HoloLens graphics with pointers and names floating above. The two teams used this XR solution to collaboratively solve challenges regarding installation of the Europa Clipper ICEMAG payload harness.

Preliminary Design of the Propulsion Module Harness Fabrication Fixture

The electrical wire harness for Europa Clipper's propulsion module requires a fabrication fixture. Completed harness bundles can be quite stiff, making it difficult to fabricate them flat and then try to bend and conform them onto the cylindrical propulsion module. Thus, the harness must be fabricated such that wire can be routed and wrapped in-shape with all its complex twists and turns and branches. Fabrication of the fixture required the industrial capacity of the APL in-house sheet metal shop. But the harness itself was going to be fabricated in a harness lab in a different APL building. The scheme to transport the harness fixture from the sheet metal shop to the harness lab was a key driver in the design of the fixture's structure. For instance, fully assembling the fixture in the shop versus delivering the upper and lower cylinders separately and assembling the fixture in the lab required completely different accommodations for transportation, tools, clearance in the doors and halls and rooms, scheduling with technicians, etc. Even fundamental mechanical design decisions about bolted and riveted joints were driven by the transportation scheme.

The team used ProtoSpace to study what it would look like if the propulsion module harness fabrication fixture were delivered from the sheet metal shop fully assembled. Figure 6 shows the team transiting the AR model down the hall as if it were on a cart and maneuvering it into the door of the harness lab. This exercise helped the team realize that, although there were solutions to bring the fully assembled fixture into the lab, the fixture would completely dominate the space and conflict with other work in that space at the same time.

Fabrication of the Propulsion Module Harness

Before the Europa Clipper program, APL had never used CAD modeling to design the routings of a spacecraft harness subsystem. Traditionally, harness technicians do not have the opportunity to participate in the design phase, and routing accommodations can be easily overlooked. In the traditional process, at the end of the design phase, when everything is locked down and further changes are prohibited, a full-scale high-fidelity mock-up of the complete mechanical system is fabricated and delivered to the harness technicians. The technicians then have to design the routings on the physical mock-up.

CAD modeling of the Europa Clipper harness routing assemblies has made it possible for technicians to contribute throughout the design phase, ultimately resulting in better integration between the harness and mechanical subsystems. Although the modeling effort demonstrated that the complexity of the harness subsystem necessitates a fixture on which to fabricate the harness assemblies, the experience also revealed that the approach could be simpler than a typical high-fidelity mock-up. The process of discovery, the creative process in which the routing paths were chosen, occurred within the CAD modeling tool. The team is able to clearly recognize which features of the propulsion module structure are actually relevant to the harness assemblies, allowing them to ignore other features.

The CAD models of the harness routing assemblies were then incorporated into AR experiences to aid technicians during harness fabrication. This was the first time APL used CAD modeling to design harness routing and also the first time APL used AR for harness fabrication. Using the object targeting and occlusion culling capabilities of PTC's Vuforia AR tool, the team superimposed CAD models of the harness routing assembly on the fabrication fixture so that the fabrication technicians could visualize the design of the routing before cutting wire (Figures 7 and 8).

These tools certainly helped the technicians when fabricating. Anecdotally, as there is a scarcity of highly

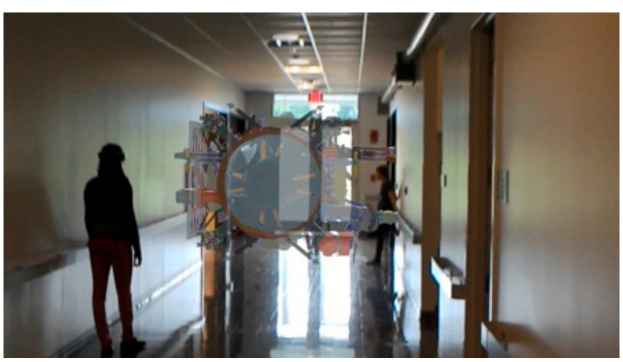


Figure 6. XR used to analyze transport of the Europa Clipper propulsion module harness fabrication fixture. The Europa Clipper harness team used XR to examine the issues involved with transporting a full-scale model of the fixture through the halls of an APL building and rounding a corner to enter the harness fabrication lab.

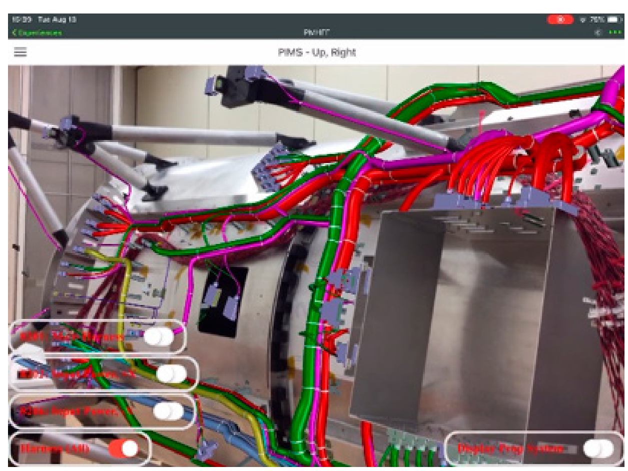


Figure 7. CAD models and AR used to aid in fabrication. This screenshot from PTC's Vuforia tool shows the digital harness superimposed on the fabrication fixture.

Figure 8. Prefabrication review using CAD model and AR tool. This photo shows engineers and fabrication technicians using Vuforia, with the CAD models superimposed on the physical fixture, to review the placement of the harness routing before the technicians begin to cut and place wire.

skilled spacecraft harness technicians who understand the art of harness routing, these two tools, together with parametric schematic modeling tools, are critical to help newer technicians visualize the routing, effectively reducing risk to the mission.

HGA Installation Accessibility

The Europa Clipper HGA must be installed no fewer than three times. It will first be installed at APL for telecom subsystem functional testing and then it will be removed for shipping to JPL. Then it will be installed at JPL for flight system I&T and then removed again for shipping to the Kennedy Space Center. It will then be installed a final time at the payload integration facility at the Kennedy Space Center. The HGA has structural mounting locations, holding it to the propulsion module, as well as waveguides that connect to antenna feed RF inputs in the middle of the back of the HGA. These waveguides are difficult to access because of their location and the tiny space behind the HGA.

To solve these challenges, and others, the team used ProtoSpace to prototype the accessibility for technicians who would be using a scissor lift at APL. They tested two scenarios: (1) mating and de-mating the RF waveguides connecting the RF panel assembly with the HGA feed; and (2) access to the RF panel assembly electrical connector field joint, for installation of ground support cables as well as the flight harness. The technician maneuvered the lift around the model in the high bay until it was near the edge of the model but did not interfere with the model (see Figure 9, left). The technician then elevated and extended the lift above the model to determine which components could reach (see Figure 9, right). Testing ultimately proved that the lift was too wide for the space available to get close enough to the flight hardware to enable the technician to complete the required operations. The team is using the information it gained from this exercise to develop alternative supports that will allow technicians to reach these joints.

CONCLUSIONS

This article describes a few examples of how APL teams have used XR in the mechanical design process and the benefits they have experienced. Demonstrating the value of XR is difficult, because there is no perfect way to define or measure "value." One approach might be to plan a rigorous I&T campaign, use XR to reduce risk and simplify steps, and then compare the actual campaign with the plan to try to assess the difference XR made. But there will be noise in this approach, because XR is not an isolatable line item. Throughout the life cycle of a program, many factors interfere with a pure calculation of return on investment.

What is clear, however, is that XR can be embedded in the design and engineering process, can be used to get more out of meetings and collaborations that would occur regardless, and can be used to resolve unforeseen disruptions (e.g., the Parker Solar Probe V5 antenna). XR reduces cognitive distance and load, increasing teams' awareness of the mechanical system and helping them make decisions with greater confidence. Since

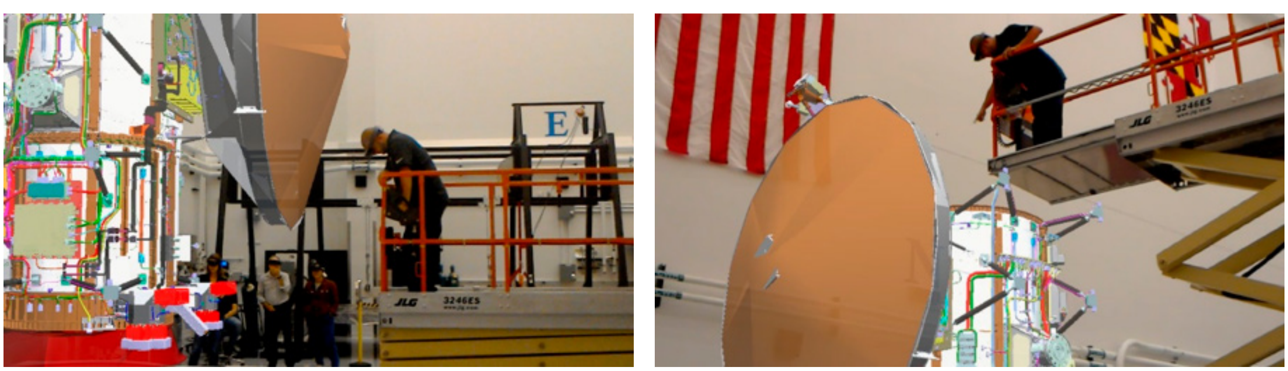


Figure 9. Left, A technician drives the scissor lift to align with the edge of the AR model, creating the distance available for I&T operations. Right, A technician elevates the scissor lift to clear the propulsion module solar array struts and performs a "reach analysis" to assess accessibility to the RF waveguide and connector interfaces.

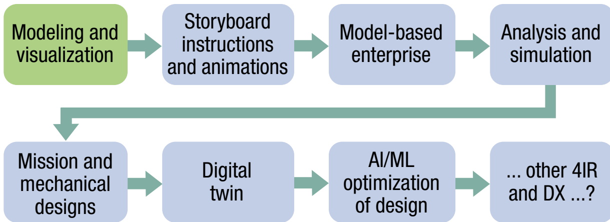


Figure 10. Possible mechanical engineering DX path. This pathway is one option for taking the XR efforts even further to unlock opportunities to apply DX upstream and downstream of the mechanical design systems.

2017, APL-managed space missions have enjoyed benefits from APL staff members' grassroots developments in the realm of XR. These efforts have typically been small localized proof-of-concept and/or pilot projects. Some tools, like ProtoSpace and Vuforia, have been rolled into production and are beginning to scale up.

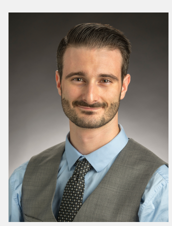
The selected anecdotes described in this article are from a narrow niche of XR applied to spacecraft mechanical design. There is tremendous untapped creative potential for applications outside this niche—applications that haven't even been imagined. Still, as exciting as XR is, focusing only on it could obscure the bigger trends of 4IR and DX. These disruptive forces on global societies and economies challenge organizations to reimagine their business operations, customer engagement, competitive advantage, and relevance in an increasingly competitive and technologically advanced world. APL's XR grassroots efforts—leveraging both commercial tools as well as bespoke software capabilities—have led to meaningful solutions to difficult problems. But just as mechanical design is a small part of a spacecraft program, XR is a small part of DX. Applying DX upstream and downstream of the mechanical design systems will lead to even more advantages. Figure 10 shows one possible pathway for realizing this potential. APL teams have already taken the first step of visualizing 3-D models in immersive experiences.

Manufacturing is still a major economic force for any nation. Manufacturing is a major force within APL. APL is a world-class systems engineering organization. One thing that gives APL an edge is that its teams actually makes things. And not just things, but highly complex systems of systems. The trend of competitiveness appears to be bending toward data-infused products, cyber-physical systems, and digital twins. So in the future, the significance of the things APL makes will be largely affected by the flow of data around these things. We are excited to be contributing to this transformation at APL and beyond.

ACKNOWLEDGMENTS: We thank the NASA Living With a Star program office and the NASA Heliophysics Division for the opportunity to develop these AR capabilities for Parker Solar Probe. Thanks to Jackie Perry for filling in details about the Europa Clipper harness activities. Thanks to Jim Kinnison for filling in details about the Parker Solar Probe V5 antenna illumination exercise. Thanks to the software development team at the NASA JPL Ops Lab for creating the ProtoSpace AR tool.

REFERENCES

1. K. Schwab, *The Fourth Industrial Revolution*, Currency, New York, 2017.
2. World Economic Forum, "World Economic Forum Annual Meeting 2016, Mastering the Fourth Industrial Revolution," World Economic Forum, Davos-Klosters, Switzerland, 2016.
3. S. Pfeiffer, "The Vision of 'Industrie 4.0' in the making—A case of future told, tamed, and traded," *NanoEthics*, vol. 11, no. 1, pp. 107–121, 2017.
4. R. Y. Zhong, X. Xu, E. Klotz, and S. T. Newman, "Intelligent manufacturing in the context of Industry 4.0: A review," *Engineering*, vol. 3, no. 5, pp. 616–630, 2017.
5. PTC Inc., "Quantifying the value of digital transformation in manufacturing," White Paper, 2019, https://resources.ptc.com/c/quantifying-the-value-of-iiot.
6. G. Büchi, M. Cugno and R. Castagnoli, "Smart factory performance and Industry 4.0," *Technol. Forecast. Soc. Change*, vol. 150, 119790, 2020.
7. Office of the Deputy Assistant Secretary of Defense for Systems Engineering, "Digital Engineering Strategy," Department of Defense, Washington, DC, 2018.
8. J. Lang and D. Immerman, "The state of industrial digital transformation," PTC Inc., Needham, MA, 2019.
9. "Parker Solar Probe." Johns Hopkins University Applied Physics Laboratory. http://parkersolarprobe.jhuapl.edu/ (accessed Jan. 1, 2019).
10. "Staring at the Sun," *Nature*, vol. 576, no. 7786, 2019.
11. Content draws heavily, and in some cases verbatim, from D. Hahne, J. F. Ruiz, A. Fagan, and N. DeMatt, "Risk reduction of integration and testing operations using augmented reality on Parker Solar Probe," in *Proc. 30th Space Simulation Conf.*, 2018.
12. C. B. Phillips and R. T. Pappalardo, "Europa Clipper mission concept: Exploring Jupiter's ocean moon," *Eos Trans. AGU*, vol. 95, no. 20, pp. 165–167, 2014.
13. J. Smith, "Solar Probe Plus," Presentation, 2016. https://sites.nationalacademies.org/cs/groups/ssbsite/documents/webpage/ssb_174885.pdf.



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