Rapid Prototyping: Accelerating the Design Process

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ABSTRACT

Prototyping techniques have significantly advanced in the last decade, providing engineers with quick ways to iteratively modify designs of parts and systems with greater precision and at lower cost than ever before. The Research and Exploratory Development Department (REDD) at the Johns Hopkins University Applied Physics Laboratory (APL) has made the most of these advancements, using rapid prototyping tools and quick-turn manufacturing that was not possible a decade ago to achieve success in many applications. Examples highlighted in this article include human–machine interfaces conceived through a Navy program called Tactical Advancements for the Next Generation (TANG), confined-area autonomous mapping devices like the Enhanced Mapping and Positioning System (EMAPS), and personal protective equipment to help prevent the spread of COVID-19 during the unprecedented and uncertain times of the early pandemic. These three case studies demonstrate the benefits of rapid prototyping.

INTRODUCTION

Sponsors rely on APL engineers and scientists to produce high-quality, intelligent solutions to complex problems, even when projects have incredibly short timelines. Although some projects require years of intricate planning and testing for one final hardware deliverable, other projects need to go from concept to reality in a matter of weeks. Regardless of design needs and schedules, by relying on rapid prototyping (RP) hardware, APL teams can decrease the cost of design and shorten the time to deliver.

Prototyping hardware to develop novel and innovative designs is not a new concept. For centuries, humans have employed prototypes to convey design intent or provide an initial model of an object to test a design. Thomas Edison was said to have built more than 3,000 light bulb prototypes before arriving at the right design.[1] The Wright brothers tested more than 200 wing and airfoil models to optimize their design.[2] APL's founder, Merle A. Tuve, went through dozens of prototype iterations to ensure that the inner radio tube component in the famous VT fuze would not shatter under high forces when deployed.[3] Since its beginning, APL has successfully employed prototyping methods in its design and research process. Recent advances in RP methodologies, such as the use of additive manufacturing, metal additive manufacturing, quick-turn machining, and artificial intelligence in developing G-code, have changed the landscape of concept generation and project timelines for APL teams.

This article highlights how APL has leveraged mechanical RP and early-concept design methodology and used advanced design and fabrication methods not previously possible to rapidly develop prototype hardware that can meet or exceed sponsor expectations. It also provides examples of how design thinking and the application of iterative design and RP have enabled the creation of innovative solutions to sponsors' problems.

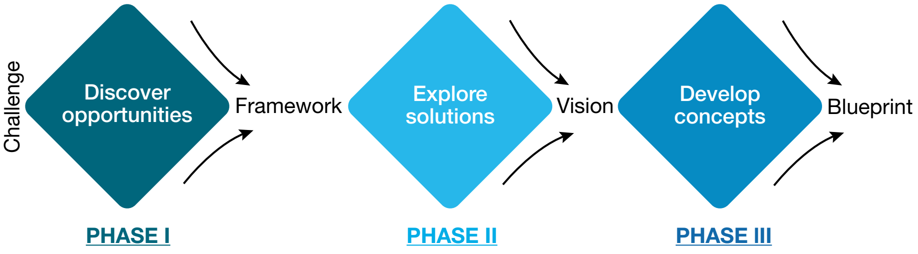

Figure 1. TANG's three-phased approach.

TANG: DEMONSTRATING IDEATION THROUGH EARLY PROTOTYPING

In 2011, the US Navy established the TANG Program (Tactical Advancements for the Next Generation) to leverage design and systems thinking methodologies to tackle human-centered and mission-focused challenges across the Department of Defense. The TANG Program is a multi-organizational program, led by APL, that aims to bring together diverse perspectives across end users, stakeholders, and subject-matter experts to create impactful solutions that address pain points across those communities.

The TANG Program focuses on challenges in the early stages of development, delivering front-end innovation solutions to sponsors. Through empathizing with the end user and developing a comprehensive understanding of the challenges and opportunity space, project teams work with end users, stakeholders, and subject-matter experts to design different human-centered solutions and prototype concepts rapidly. This RP enables sponsors to buy down risk in the long run, ensuring the right concept is being built before focusing on higher-fidelity and costly systems. The TANG methodology offers a unique capability to turn nascent ideas into reality by delivering high-quality "pretotypes" (a pretotype is a low-cost early prototype, as coined by Google's Alberto Savoia[4]). The example discussed below illustrates how pretotyping was injected into the process for creating a futuristic helicopter cockpit.

Putting the TANG Approach to Work

Upon learning about the benefits of human-centered design to inform future requirements, a sponsor approached the TANG Program to charter a project to explore the cockpit experience of a future rotary wing aircraft. After framing the challenge with the sponsor, the team launched into Phase I of the process (Figure 1): discovering opportunities. The team conducted immersive ethnographic research with the user community, interviewing and observing pilots in the field in order to identify pain points and opportunity areas in the current cockpit. This was the first step of a three-phased design approach: discover opportunities, explore solutions, and develop concepts (Figure 1). In Phase II, the team explored the technology space and took inspiration from analogous human–machine pairings, such as NASCAR and video game interfaces. This inspiration was fed into a workshop with end users, stakeholders, and subject-matter experts during which over 40 concepts were designed in the following future technology areas:

- Controls
- Haptics
- Artificial intelligence
- Virtual and augmented reality (VR/AR)
- User interface and user experience (UI/UX)
- Modularity

This approach ultimately led to a cross-Laboratory and multi-organizational collaborative Phase III effort to develop different concepts, relying on the technical experts in each technology area to contribute to various prototyping efforts. Prototyping has been used extensively for every aspect of the project, including creating life-size virtual test environments for demonstrations and creating real tactile devices and visual interface concepts for users to quickly test. The article by Crane et al., in this issue, expands on these capabilities.

Virtual and Augmented Reality

One aspect of envisioning the future flight experience was understanding physical constraints and space within the cockpit, ranging from overall dimensions to visibility to the number of operators it would accommodate. Through research, synthesis of user needs, and brainstorming on the vision for the future cockpit, the team identified initial design parameters. Engineers quickly developed solid models of the cockpit that could be 3-D-printed for handheld demonstration. However, this approach was not very immersive and did not provide operators with a way to "step into" the cockpit for themselves.

Figure 2. Example VR/AR environment for user experience testing of current cockpits. Haptics creates a greater sense of immersion, enabling the user to feel the elevation changes throughout the experience.[5]

To enhance the user experience, the team created a first-iteration flight simulator using gaming chairs, commercial off-the-shelf (COTS) projectors, and perforated foam to create a panoramic view of the external environment. They then overlaid the solid 3-D model of the cockpit airframe into the environment.

With a COTS AR headset, pilots were able to sit in their virtual cockpit and look around to provide feedback on how they imagined themselves working in the space, considering factors such as field of view, position of equipment, and digital information layout, to make the experience more intuitive. Since the software model is highly modifiable in digital space, engineers can quickly implement design changes in the software to instantaneously provide operators with updated concepts. By using commercially available software and readily accessible materials, interested parties can easily make their own virtual environment to test without traveling long distances, reducing travel costs.

Haptics

The Cockpit Experience team also researched how to enhance operators' situational awareness using haptic feedback. In pursuit of a rapid hardware solution and a low-fidelity proof of concept, they leveraged COTS hardware and software to prototype concepts such as enemy threat tracking, horizon line indicators, and elevation alerts using active haptic feedback. For example, they created a virtual experience that placed the user within a cockpit flying over a simulated environment (Figure 2). The addition of haptics created a greater sense of immersion, allowing the user to feel the changes in elevation throughout the experience (for more details, see the article by Crane et al., in this issue).

These examples of prototyping hardware solutions are just a few used in TANG projects. Without the use of quick, low-cost prototyping, realizing the TANG vision to develop various human-centered designs would not be possible. With its main goal to reduce cost while providing an all-immersive experience, the future cockpit project is no exception, and the use of low-fidelity, high-quality prototyping hardware is critical to the validity of user and expert feedback studies.

EMAPS: ITERATIVE DESIGN FOR A GROWING PROJECT

During research and development, evaluation kits or stock electronics obtained from equipment manufacturers are often used to develop platforms to complete novel tasks. As the design grows, so does the hardware, and engineering teams are forced to reengineer and integrate the parts they must use. Using an iterative RP design process allows for faster and more cost-effective modification and integration.

The Enhanced Mapping and Positioning System (EMAPS)[6,7] is an example of a successful program that continued to grow and change for several years. Developed for the Defense Threat Reduction Agency, EMAPS is a portable device that can be used to automatically create annotated maps in tight spaces where GPS is not readily available, such as in underground areas and on ships. This system, worn in a backpack, greatly improves range, maneuverability, and mapping ability compared with mapping-robot counterparts. The mapper's main objective is to measure, analyze, and capture a continuous detailed survey of the operator's surroundings and interpret these data to build a comprehensive map through the use of point clouds and photographs.

The form-fitting outer protective enclosure was made of acrylonitrile butadiene styrene (ABS) via the fused

Figure 3. EMAPS backpack-mounted mapping sensor head version 1. Initial prototypes incorporated quick-turn sheet metal components and heatsinking plates to support and dissipate heat from the COTS electronics and imaging systems.

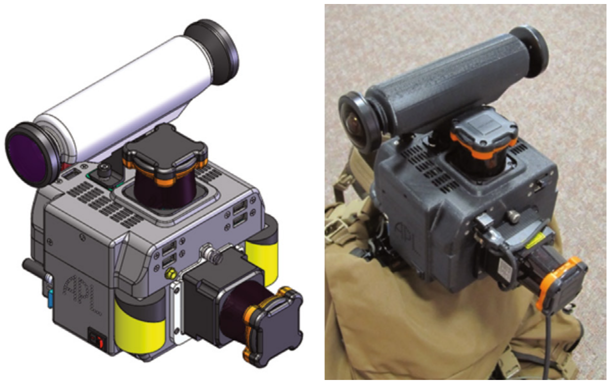

Figure 4. EMAPS backpack-mounted mapping sensor head versions 2 and 3. The design evolved to include different lidar modules and cameras, as well as antennas and other sensors.

deposition modeling additive manufacturing process to provide a compact and lightweight device. Initial prototypes for the unit incorporated quick-turn sheet metal components and heatsinking plates to support and dissipate heat from the COTS electronics and imaging systems (Figure 3).

Unsurprisingly, the design continued to evolve, using different light detection and ranging (lidar) modules and cameras, as well as antennas and various other sensors (Figure 4). Each design iteration added requirements, such as electromagnetic interference shielding and increased mechanical robustness. As APL's additive capabilities continued to expand, a different additive manufacturing method was used for the fourth- and fifth-generation housings. These final two versions used selective laser sintering (SLS) nylon for its ability to serve as both the primary structural support and the protective housing for the electronics. The final housing included both a plated lower section for electromagnetic interference shielding and an unplated upper section for radio frequency transparency, as shown in Figure 5. APL's continual investment in emerging manufacturing technology, such as laser sintering additive manufacturing, allowed for improved precision and resolution in fabricated parts.

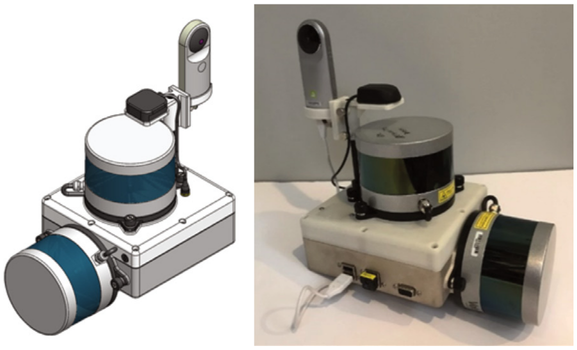

Figure 5. EMAPS backpack-mounted mapping sensor head version 5. This final version included both a plated lower section for electromagnetic interference shielding and an unplated upper section for radio frequency transparency.

As the overall system design progressed, so did the need to rapidly accommodate more capable sensors and user convenience features. The design was upgraded to include two lidar units and two ultra-wide-lens cameras, as well as several ports for external sensors. The enclosure was quickly redesigned to accommodate the new hardware and connector interfaces, so it remained composed of ABS 3-D-printed plastic for several iterations.

After creating five EMAPS backpack devices, the APL team reached its final product. Using EMAPS, nontechnical operators can capture environmental information while they carry the ~6-in., 4-lb cube in a backpack. Lidar sensors scan an area with narrow beams of light coming from every angle. The distances between objects are quickly recognized and translated into detailed views of the area being scanned while providing real-time graphical feedback to the operator through a handheld tablet. The basic system has a 270° laser scanner that measures distances to environmental elements, such as walls. A second laser scanner enables the capture of 3-D data, and an inertial sensor enables detection of the user's steps by measuring the system's roll, pitch, and yaw. The unit can also house a removable camera to obtain omnidirectional images, a GPS receiver to geo-register collected data, and a solid-state hard drive to process and store data in real time.[6]

EMAPS has generated maps of APL office buildings, ship engine rooms, and museums. By using RP parts and off-the-shelf components, the team was able to focus the design and associated costs on the electronics prototyping hardware, allowing for further and faster development of usable prototypes. APL's Tech Transfer Office recently licensed EMAPS to an external company to be mass-produced for government use.

POWERED AIR-PURIFYING RESPIRATOR REDESIGN: PROTOTYPING IN A RACE FOR A CRITICAL INVENTION

March 2020, the onset of the COVID-19 pandemic, was unlike any other March: work-from-home mandates began, materials shortages for manufacturing loomed, and hospitals quickly hit maximum capacity. Soon thereafter, the shortages affected production of medical personal protective equipment, and supplies trended toward a dangerously low inventory.

A Johns Hopkins radiology nurse—who also happened to be married to an APL engineer—mentioned to her husband that medical facilities were close to having no powered air-purifying respirator (PAPR) hoods left. PAPR hoods protect health care personnel who are directly exposed to aerosolized pathogens that cause acute respiratory conditions.[8] In late March, because

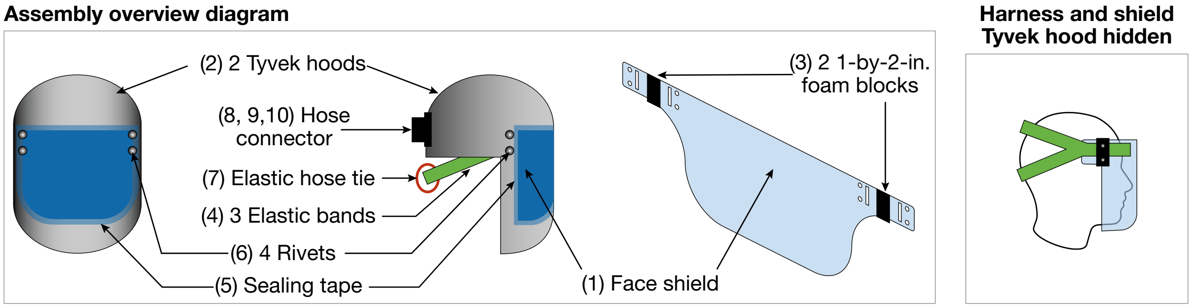

Figure 6. Final design concepts for the PAPR hood. The APL team explored may design concepts and materials before landing on this final design.

of material sourcing limitations, health care personnel were already being forced to sanitize and share hoods. A small APL team formed to develop a design using an alternative material for PAPRs, as well as an agnostic hook-up nozzle design so that the newly designed PAPR could be used in any health care setting.

The team collaborated with a local engineering company, which worked on the air filtration portion. Members met virtually since in-person meetings risked virus transmission. The team swiftly defined the parameters to drive design efforts remotely (see Zinn et al.[9] for more on how APL staff members adapted to a rapidly changing work environment). First, the hood had to be made of a soft material that needed no additional sewing so that anyone could construct the PAPR. Second, a connector for the back of the PAPR needed to connect to certain air circulation blowers. There are several different blowers with different connector interfaces, and ideally, the new PAPR could serve as a host connector that could attach to various types of systems and therefore work in any hospital, anywhere.

Using online video conferencing and slideshow software, the team drew initial concepts on human heads. They then convened to collaboratively decide on design paths, and after reaching consensus, they worked on their design ideas independently. They conducted market searches on state-of-the-art PAPR technology to inform their design decisions and collected and shared information using cloud platforms. The APL team then split into two subteams, each focusing on a specific subtask: (1) the hood and shield assembly and (2) the agnostic connector.

To design the hood, the team searched for materials similar to those used in current PAPR hoods. They began by exploring COTS materials, but traditional Tyvek materials for PAPRs were sold out everywhere. They found Tyvek house wrap and tried sewing and taping it in their first design iteration, but the design was unsuccessful because of the material's stiffness. The team continued searching, trying several materials they were able to source from retailers, when they happened upon Tyvek-based hairnets. Although this material prevented them from producing PAPRs in large quantities, it did allow them to make individual hoods at a significantly low cost. After successfully developing the hood, they moved on to developing the shield. Relying on other open-source RP part design that was being developed, the team was able to quickly create shield holders that were adaptable to the hood. These were connected to a thin polycarbonate shield that was selected after they had ordered many extremely inexpensive materials of different textures and thicknesses (acrylic, polyvinyl chloride film, perfluoroalkoxy, polyester, and polycarbonate) to reduce design time. The final design concept is shown in Figure 6.

The connector design was not as straightforward: it required knowledge of the blower interface dimensions, and this information was not available. As a result, it took several iterations to correctly create the curvatures and surface interfaces. The team turned to 3-D-printed RP as a manufacturing method in lieu of traditional injection molded parts because the traditional method, with a mold manufactured and parts produced, can require a lead time of weeks to months. In addition, specific features for the air blower connection required geometries that were too complex for

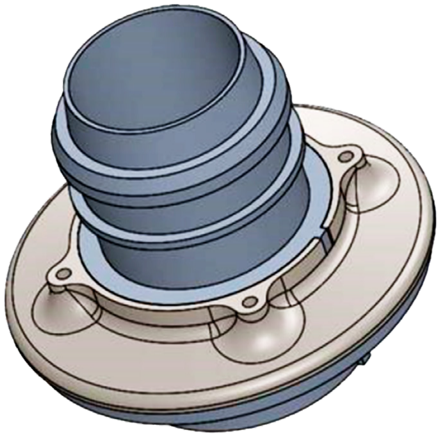

Figure 7. Final design of agnostic PAPR connector. The connector design was not straightforward. The team used 3-D-printed RP as its manufacturing method, saving both time and cost.

injection molding. The approach to 3-D-print multiple individual test designs reduced the design iteration time by several months and reduced cost by several orders of magnitude. The team was able to bypass significant delays from external 3-D printing vendors by using APL's in-house 3-D printers. Each design iteration was drafted via computer-aided design (CAD) at night, 3-D-printed overnight, and hand-delivered by the next day between designers' houses to avoid contact between workers. Each design iteration was completed and tested within 2 days. Figure 7 shows the final design.

Integrating the device had its challenges, an all the team members worked in parallel during the integration phase: one dropping off the valve iterations, one dropping off COTS supplies, and one constructing the hood. The pieces were then integrated, and the hood was delivered to Johns Hopkins Hospital for testing. After working many late nights, the team developed a deployable prototype within 6 weeks by relying on RP technologies and using virtual environments to ideate and collaborate. Not only was the design readily usable and easy to make, but this work resulted in an intellectual property disclosure for the hood design and a patent application for the connector.

CONCLUSION

Prototyping hardware is a powerful tool to bring a product to life. From conceiving ideas and concepts to producing full-fledged designs, prototyping can be used throughout the design process to ensure success. Recent advances in RP and quick-turn part manufacturing have allowed APL researchers to meet sponsor needs by iteratively designing systems at lower cost. Using RP parts and COTS technologies and ideating with low-cost materials allows teams to work faster than was imagined possible a decade ago. These advances in prototyping parts development have helped APL achieve real results: fieldable products, patents and intellectual property disclosures, and sponsor demonstrations that keep the Lab at the forefront of innovation.

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REFERENCES

[1] E. Palermo and C. McKelvie, "Who invented the lightbulb?" *Live Science*, Nov. 23, 2021, https://www.livescience.com/43424-who-invented-the-light-bulb.html.

[2] K. Sands (Ed.), "Overview of the Wright Brothers invention process," NASA, last updated May 10, 2021, https://wright.nasa.gov/overview.htm.

[3] J. Holmes, *12 Seconds of Silence: How a Team of Inventors, Tinkerers, and Spies Took Down a Nazi Superweapon*. Boston, MA: Mariner Books, 2020.

[4] A. Savoia website, https://www.albertosavoia.com/ (accessed Jan. 20, 2022).

[5] "Airbus brings cockpit to you with new Virtual Reality Flight Trainer," English translation, *Immersive Learning News*, Dec. 16, 2019, https://www.immersivelearning.news/2019/12/16/airbus-brings-cockpit-to-you-with-new-virtual-reality-flight-trainer/.

[6] G. Ellrich, "APL's mini-mapper captures intel in tight spots," *JHU Gazette*, May 2013, https://hub.jhu.edu/gazette/2013/may/news-roundup-all-mini-mapper-system/.

[7] G. Ellrich, "Backpack mapping system captures intelligence in tough-to-get-to places," press release, APL, Mar. 27, 2013, https://www.jhuapl.edu/PressRelease/130327.

[8] "Considerations for optimizing the supply of powered air-purifying respirators (PAPRs) for healthcare practitioners (HCP)," Centers for Disease Control and Prevention, updated Nov. 3, 2020, https://www.cdc.gov/coronavirus/2019-ncov/hcp/ppe-strategy/powered-air-purifying-respirators-strategy.html.

[9] D. A. Zinn, M. Ginther, K. A. Griffin, K. N. Kelly, T. T. Miles, and J. M. Paulson, "COVID-19 impact on fabrication and design in APL's Concept Design and Realization Branch," *Johns Hopkins APL Tech. Dig.*, vol. 36, no. 4, pp. 453–459, 2023, https://secwww.jhuapl.edu/techdigest/Content/techdigest/pdf/V36-N04/36-04-Zinn.pdf.

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