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Abstract

The Middle-Class Tax Relief and Job Creation Act created the Public Safety Communications Research (PSCR) Division at the National Institute of Standards and Technology (NIST) to investigate interoperability for public safety by improving wireless and broadband communications for first responders. The Public Safety Trust Fund established from this legislation and subsequent congressional funds enabled PSCR to conduct research through prize challenges to explore the potential of technology and the impact of Uncrewed Aircraft Systems (UAS) on public safety operations. Prize challenges help bring together industry leaders and experts to solve technology problems for first responders. Challenges have focused on performance, endurance, and technology-specific use case scenarios with requirements specific to first responder needs. This report provides a general overview of the PSCR UAS Portfolio, the history of PSCR UAS prize challenges, and the UAS prize challenge structure.

Keywords

Broadband; Drones; First Responders; Prize Challenge; Public Safety; Public Safety Communications; Search and Rescue; Uncrewed Aerial Vehicle; Uncrewed Aircraft Systems; Wireless Communications

Note to Readers

The PSCR UAS Program Overview report is part of a technical publication series focusing on the UAS program, research, and prize challenges. This document serves as the lead introductory manuscript for the publication series and provides an executive summary of each manuscript in the series. Reading each publication in series order may provide additional context; however, if read out of order, the reader does not need prior knowledge of the other documents. Below is a list of publications and data sets in this series:

1. PSCR UAS Program Overview (this document)
2. PSCR UAS Flight Payload and Endurance Prize Challenges
3. PSCR UAS 3.0 First Responder UAS Triple Challenge
4. PSCR UAS First Responder Indoor UAS Challenges

Note: Publications two (2) through four (4) are forthcoming.

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1. PSCR UAS Program Introduction

Since 2015, PSCR has investigated deployable technologies and innovations to provide communications coverage and situational awareness during first responder events. First responders identified Uncrewed Aircraft Systems (UAS) as plausible mechanisms to assist in mission and training activities and potential communication tools. Over a relatively short time, the power and potential of using UAS in first responder organizations have proven valuable resources for many public safety agencies. The impact of the small UAS industry on United States (U.S.) commercial markets began in earnest as a hobbyist craft for entertainment and by the military in defense applications. The military utilized uncrewed aircraft for many years; however, these specialized, expensive platforms were inaccessible to public safety organizations. Due to their increasing cost-effectiveness, ease of use, and agility, small, uncrewed aircraft are now a valuable tool for first responders to use in hard-to-reach areas. Public safety agencies nationwide were each starting their own UAS program, and new uses emerged for firefighters, law enforcement, and other emergency responders to produce valuable data. Because of this increasing interest, PSCR responded by investigating technology gaps, design tradeoffs, and potential UAS use cases for public safety. Since UAS requires disciplines in multiple technology areas, PSCR recognized that research goals would be best met through internal projects, prize challenges, and external researchers.

- PSCR utilized its internal, state-of-the-art research labs, facilities, and test sites to perform world-class research in UAS deployable technologies.
- PSCR sought expertise from other NIST laboratories and partnerships with other federal, state, and local government agencies to advance public safety UAS goals.

- Prize challenges formed contractual research opportunities with industry leaders, other research laboratories, and academic partners who are foremost experts in UAS technologies.
- UAS prize challenges attracted competitors from multiple disciplines, both domestic and international, and provided multiple perspectives to solve a common research challenge.

PSCR created a UAS-specific program portfolio to study first responders' use of UAS technology after initially researching its use as a deployable tool for enhanced communications capabilities. The current mission of the UAS portfolio is to advance UAS capabilities to provide safe, effective, and reliable solutions through cutting-edge research for first responders and emergency response operations.

The PSCR UAS portfolio utilizes prize challenges to engage with external experts, researchers, and innovators to help solve gaps initially identified by internal researchers and first responders. The technological gaps may vary based on the public safety agency or discipline and include uses such as effective communications in cellular-denied areas, flight endurance for carrying heavy payloads, lack of AI-based image detection, and other tools providing real-time or near real-time delivery of information. These prize challenges create a forum for collaborative partnerships among technology stakeholders while furthering awareness of public safety needs. The program integrates UAS studies and market research into program deliverables and prize challenges by exploring other industries' state-of-the-art technologies for addressing public safety issues.

Research obtained through prize challenges enhances awareness among industry and first responder stakeholders and drives economic development with interest groups and national communities. While the research goal is to produce measurable technical outcomes, the larger goal is to make impacts to industry, government, and academia. An early impact from this research demonstrated the design tradeoffs necessary to support long endurance flights using hybrid fuel sources, and another notable example exhibited original ideas to improve flyability for the UAS and pilot when flying indoors in challenging confined spaces, both enhancing situational awareness and a speed to accomplish the mission. The PSCR UAS portfolio designs its prize challenges to award innovators for their expertise and innovative functional prototypes that may be developed further for practical use in first responder activities. As a result, research entities and academics can learn new approaches to research methods and engage in interdisciplinary partnerships between entities. At the same time, government agencies, including public safety, can use the data and scientific metrics to support new use cases and increase economic development. These innovations can lead to new businesses, industry standards, and partnerships among innovators and first responders.

PSCR initially studied first responder deployable use cases to include low-cost offerings, e.g., between $5,000 and $20,000 per UAS, to meet state, county, and local agency budgets while looking to improve UAS performance and endurance. The use case was to establish voice and data services for emergency crews on the ground in non-serviced or cellular-denied areas, resulting in enhanced situational awareness. Over time, PSCR has closely collaborated with public safety agencies nationwide to recognize new use cases and identify gaps in UAS hardware and design capabilities. PSCR also studied using supplementary devices in UAS, such as Internet of Things (IoT) sensors, to align with industry advancements. Specific technologies included alternative energy sources for UAS, onboard sensors to increase system fidelity, advanced optics for search and rescue operations, resilient UAS for indoor and confined space operations, and three-dimensional (3D) mapping for analysis of indoor spaces. PSCR also recognized artificial intelligence (AI) as a driving factor for ease of control, operator assistance, and enhanced autonomy in UAS. In the future, PSCR will continue looking at new use cases, including emerging UAS technologies that benefit first responder operations.

2. PSCR UAS Research Methodologies

First responders employ UAS for various purposes, including search and rescue, situational awareness, delivering medical supplies, and disaster response. The exact date a first responder first used an aerial drone is challenging to pinpoint, as the use of aerial vehicles in emergencies has evolved. One of the earliest extensive uses of aerial drones by first responders was in 2005 following Hurricane Katrina in the U.S. [1] The Louisiana Army National Guard used aerial drones to help assess the damage and locate survivors in the aftermath of the hurricane. Since then, many public safety agencies have adopted uncrewed aircraft for preventive safety measures, operational missions, and other emergency use cases.

As UAS manufacturers integrate increasingly autonomous features, control and navigation have improved to lessen the burden of remote aircraft operation. Ease-of-control allows first responder pilots to focus more attention on the mission and less on controlling the aircraft, making aerial drones more reliable tools. While these improvements have helped UAS adoption in public safety organizations, first responders have unique requirements many commercial UAS cannot meet. Special purpose-built UAS for industrial and military use are often costly and contain unnecessary capabilities for widescale adoption by local public safety agencies. Likewise, hobbyist and prototype UAS are challenging to operate in hazardous environments and cannot meet the high reliability that public safety demands. Social, economic, regulatory, and political barriers also limit commercial vendors' interest in adapting products for this environment, making it difficult for public safety to plan for and adopt UAS programs. PSCR addresses these challenges by establishing a UAS-specific research portfolio dedicated to advancing UAS technologies in public safety. The mission of the PSCR UAS portfolio is to advance the capabilities of UAS and provide safe, effective, and reliable solutions to first responders in their crucial missions by conducting cutting-edge research for emergency response operations.

2.1. PSCR Resilient Systems and Open Innovation Research

PSCR initially investigated deployable communication systems for first responder use cases in its resilient systems research. [2] Many of the deployable systems analyzed in this research included small form-factor servers that could host a Long-Term Evolution (LTE) core and Radio Access Networks (RANs) to provide cellular coverage in areas where service is unavailable or degraded. Solutions analyzed included ground-based systems, such as Cell on Wheels (CoWs), mobile rackmount systems, and portable backpack systems for quick and efficient first responder deployments. PSCR also evaluated using UAS as a deployable system to expand cellular communications networks. In a 2018 study, PSCR created a proof-of-concept UAS carrying a small cellular system that could provide mission-critical voice, data service, and text messaging. [3] After the resilient systems research concluded, PSCR recognized the need to continue researching deployables, specifically UAS, as a valuable tool for communications systems and day-to-day first responder activities. Concurrently, with influence from public safety and emergency management agencies, the U.S. Congress Appropriations Committee requested that NIST pursue research on UAS in public safety. This recognition by Congress demonstrated to PSCR the value and endorsement of past PSCR achievements of UAS for emergency response and the need to continue research of perceived gaps in making UAS practical tools for public safety.

A challenging aspect in the initial years of UAS research was conceptualizing use cases for first responders in a developing technological field while public safety agencies also established UAS programs. It was not possible to stay ahead of the curve on aerial drone development. However, simultaneously, a unique research process emerged that promoted crowdsourcing in the form of prize challenges to quickly find people from around the world with similar technology interests and skills to help solve a problem statement. PSCR utilized open innovation methods to facilitate interoperability research and leveraged the America Competes Authority to drive the economic growth of the UAS industry. [4] [5] By hosting prize challenges as a crowdsourcing methodology, PSCR collaborated with UAS enthusiasts and experts. This approach allowed for the development of unique ideas and rewarded solvers with monetary prizes.

2.2. Market Research Studies

PSCR utilizes market research studies to discover market offerings that meet first responders' requirements. Various market research reports have been produced internally by NIST employees, associates, and research companies contracted by PSCR. These studies help PSCR discover specific requirements or technology gaps, define UAS challenges in a first responder scenario, and locate experts in a particular technical field. PSCR also uses market research studies to help find trends that may identify potential use cases in first responder UAS challenges.

From 2018 to 2019, PSCR employed the services of Yet2, an open innovation research group. Yet2 conducted market research, identifying market trends that supported the first two UAS prize challenges in evaluating UAS payload, endurance, and other design tradeoffs. [6] Yet2 produced a pivot report identifying UAS that could carry communications devices to provide coverage for first responders in areas without reliable communications. In this report, Yet2 found 41 potential companies that manufactured a UAS that could carry a 15 lb payload for a minimum of 30 minutes. These selections classified UAS into power source categories, tethered/untethered configurations, and rotor-type arrangements. Power sources included commonly used types, such as battery and gas, and novel solutions, such as hydrogen fuel cell, solar-powered, and hybrid. This report's research predicted many solutions tested in the UAS 1.0 and 2.0 challenges, as described in sections 4.1 and 4.2 of this document.

From April to July 2019, PSCR surveyed 183 first responders to understand how they used UAS in public safety operations. [7] The survey targeted responders from diverse geographical areas and focused on the current state of their UAS programs. The questions addressed UAS flight endurance and payload capability and the plausibility of using a UAS to help provide communications in first responders activities. This study reflected the goals sought in the UAS 1.0 and UAS 2.0 challenges.

In 2022, PSCR funded Ensemble to conduct a market research study on the current state of the UAS industry, domestically and internationally. Ensemble subcontracted this study to Ezassi, a technology research company. Ezassi utilized its technology landscaping software platform to gather records and data sources from grants, patents, trademarks, scientific journals, news, web monitoring, and conference data. [8] This study examined industry-wide applications of UAS and specific UAS use cases in public safety agencies. Figure 1 below shows an increase in UAS-focused research records and data over 11 years, reflecting emerging UAS technology trends and societal use. It also highlights when the FAA launched its pilot program for placing regulations on hobbyist aerial drones, recognizing the FAA's interest in this emerging technology and evaluating its impact on U.S. airspace. This data shows the overall growth of UAS in all industries, including public safety.

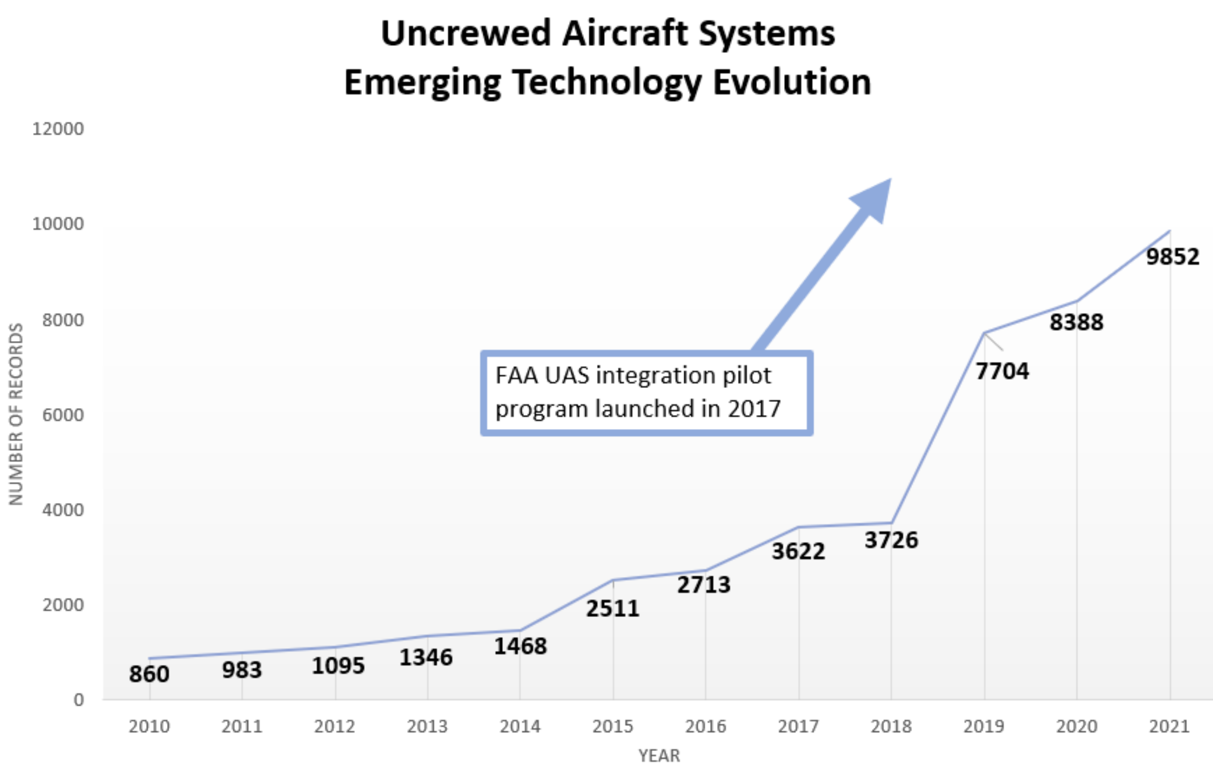

Figure 1. UAS Emerging Technology Evolution. Source: Ezassi. [8]

Ezassi found that, over this short time, technological advances improved the ease of use of UAS and reduced costs, leading to wider-scale adoption. Likewise, the UAS industry developed special-purpose applications due to advances in flight stability systems, obstacle avoidance, and component monitoring that helped overcome inherent flight control and performance issues.

2.3. Technological Gaps and Limitations in First Responder-Focused UAS

Numerous UAS products are available for purchase by public safety organizations; however, only a limited number sufficiently accommodate every public safety use case. Companies compete to serve a broad customer base and maximize profits, but doing so may not meet public safety needs. Adding features to a UAS to satisfy a public safety need may not serve the broader market or strategically align with business objectives. Building a product for current technological trends or a niche market, such as public safety, may be cost-prohibitive for most businesses.

Human resources and operational budgets are significant factors, and current low-cost UAS offerings require at least one person to set up, launch, operate, and coordinate constricting time in a situation where every second counts. The industry responded by offering stand-alone solutions requiring little human intervention, e.g., drone in a box. Although future advances in autonomy aim to reduce the burden placed upon the operator, UAS missions still require active coordination during an evolving incident. However, many of these systems require thorough investment into a single company solution, require skilled in-house or contracted staff for integration and maintenance, or may involve custom-built and often experimental solutions.

Many existing UAS solutions share the same traits of limited cost-effectiveness, special training requirements, lack of technological advancements specific to emergency response, limited deployment and response times, or little-known information about the technology. While the overall UAS industry continues to advance, developers are retrofitting crucial technologies and sensors from other industries for first responders. These technologies and sensors are either in the testing and prototyping stages or are limited in practical use due to regulatory constraints.

3. Research through Prize Challenges

The PSCR UAS program takes a unique stance in public safety research by seeking stakeholder input and innovation through prize challenges. PSCR's UAS prize challenges were authorized under the America COMPETES Reauthorization Act of 2010, Pub. Law 111-358, title I, § 105(a), Jan. 4, 2011, codified at 15 U.S.C. § 3719 amended by the American Innovation and Competitiveness Act of 2016 (Pub.L.No. 114-329) (hereinafter "America COMPETES Act.") [4]

PSCR engages public safety entities, government, academia, and industry to identify innovation opportunities and foster technology advancements for public safety communications. The Public Safety Trust Fund and subsequent ongoing congressional funds have helped PSCR identify and define gaps and limitations in public safety technology and provide financial awards to incentivize solvers to participate in publicly held activities. Challenges, such as the UAS series of challenges, produce engagements and collaborations among technology professionals and first responder users. These groups can collaboratively develop innovative ideas that meet specific needs and the high demands of first response. NIST PSCR benefits from the resulting output from challenges, producing proof of concepts, performance benchmarks, guidance documentation, and standard test methods that industry leaders can utilize. Accordingly, research conducted through prize challenges allows contestants to retain their intellectual property and further develop their prototypes with the aim of commercialization or contribution to academic research or industry progress.

3.1. Challenge Structure for UAS Challenges

The PSCR UAS Prize Challenges are structured to produce outcomes from solvers and external researchers worldwide. The challenges are designed for competitors to succeed while providing outcomes that may benefit public safety. Rules must follow the provisions of the America Competes Act. While the PSCR UAS prize challenges utilize scientific methodologies where possible, results from these challenges may require additional study and verification for validation.

All contestants in PSCR UAS prize challenges must meet eligibility requirements outlined in the America Competes Act. For full disclosure, refer to each contest's rules at https://www.challenge.gov.

3.1.1. Milestones and Incentives

PSCR UAS challenges are built using a temporal-linear approach that defines achievable milestones. Requirements may specify one or more milestones, each with defined deadlines. Contest organizers typically incorporate these milestones into contest stages and evaluate contestant entrants' progress at the end of each stage. PSCR rewards contestants who pass the evaluation with a cash prize as an incentive to reinvest in accomplishing further milestones in subsequent stages. PSCR does not award competitors who do not pass evaluations; however, judges may invite them to proceed to the next stage with remediation contingencies or as returning contestants.

3.1.2. Experts and Judges

Prize challenges utilize Subject Matter Experts (SME) to evaluate contestant progress and judges to decide on prize awards; judges may also assess submissions. SMEs review contest criteria against submitted materials, analyze results, and provide consultation to judges. PSCR selects SMEs and judges from various industry, government, and academic disciplines to ensure high-quality and diverse viewpoints. Knowledge of UAS, expertise in first responder technologies, and professional experience as a first responder are favorable considerations for SME and judge selections, where the number of reviewers and judges varies based on the number of contestant submissions.

3.1.3. Outreach/Marketing/Registrations

PSCR uses multiple online resources and social media sites to announce up-to-date UAS prize challenge activity. Interested parties can access current and past PSCR challenges on the PSCR website at https://www.pscr.gov or the official federal registry at https://www.challenge.gov. PSCR promotes UAS prize challenges through stakeholder outreach events, such as conferences, first responder training events, and news articles. Interest groups, such as professional organizations, standards groups, university programs and clubs, and meetup groups, are solicited for challenge participation or collaboration. PSCR also invites stakeholders to tour their state-of-the-art laboratory at the NIST campus in Boulder, Colorado, and their Public Safety Immersive Test Center in the First Responder Network Authority (FirstNet Authority) facility in Boulder, Colorado.

Challenge.gov provides notification services for PSCR UAS prize challenges. The General Services Administration (GSA) supports federal agencies in maturing and scaling the use of prize challenges to advance their missions. [9] The GSA manages the challenge website and learning portal (https://www.challenge.gov) to empower federal agencies and the public to participate in open innovation projects and help identify solutions to critical issues. Solvers can learn about PSCR's UAS challenges at https://www.challenge.gov, where they can find links to register on the PSCR and challenge websites.

Interested parties can find notifications about up-to-date UAS events on the following social media platforms:

- https://www.linkedin.com/company/uaschallenges
- https://x.com/uaschallenges
- https://instagram.com/uaschallenges
- https://www.facebook.com/uaschallenges

Note: Web page availability, social media posts, and web links are subject to change. Please refer to https://www.pscr.gov/ for the most current information on PSCR prize challenges.

3.2. Prize Challenge Stages

PSCR UAS challenges consist of three to four main stages with multiple milestones and sub-tasks within each stage. Stage goals may include a draft concept paper, one or two technical design reviews, a build progression evaluation, a technology demonstration, and a final in-person flight contest. Depending on the contest objectives, PSCR may include a culminating stage for additional build progression, business acceleration, and testing.

3.2.1. Contestant Selection and Prizes

Each UAS challenge schedule is temporal-linear in design and typically one year in duration (excluding prelaunch activities), with each successive stage building upon the previous stage. Each challenge stage uses design specifications, submission requirements, performance metrics, and desired outcomes to evaluate contestants' UAS prototypes and their unique solutions to solving a public safety UAS problem statement. Solutions that meet contest rules may progress to the next stage, but meeting minimum requirements does not guarantee advancement. SMEs review submissions, and judges determine how well the proposed solutions address challenge goals and UAS design specifications. SME consultation, key metrics, and defined test procedures assist judges in ranking submissions based on contest rules and safety goals. Teams can earn monetary awards at the conclusion of each stage, which they can reinvest in their UAS for the subsequent stage. The number of award recipients diminishes with each stage while the monetary prizes increase for the top performers in each stage. If permitted, contestants who fail to meet requirements may advance without a prize or receive invitations to participate in later stages. The number of contestants to progress, new entrants allowed at mid-competition, or return competitors, and the monetary amounts vary in each challenge to reflect the challenge goals.

3.2.2. Stage 1: Concept Paper

Stage 1 entrants draft a concept paper presenting each team's unique solution. The concept paper must address the first responder use case and the requirements outlined in the challenge rules document. The Stage 1 paper typically includes a cover page, abstract, project description, team qualifications, and letters of support or references. SMEs evaluate concept paper submissions based on the team's approach to the problem statement, strategic alignment with the provided first responder use case, potential technical outcomes, benefits, or unique attributes offered by their solution. Based on these evaluations, SMEs rank teams using a defined point system that addresses each category and present these results to judges who decide on the winning teams. The number of solutions accepted for Stage 1 is open to all eligible contestants; however, only a select number may receive monetary awards and invitations to advance to the next stage. At the end of Stage 1, organizers provide individual team debriefs to contestants selected to advance, discussing their results, next steps, and recommended actions.

3.2.3. Stage 2: Design Review, Video Test and Safety Evaluation

Stage 2 is an intermediate stage where contestants build and develop initial prototypes based on their Stage 1 proposal. PSCR UAS challenges typically divide Stage 2 into two sub-stages: a design review and a video evaluation.

In the design review, contestants present their plans to SMEs who assess the prototype design against the concept paper and the contest's design specification table. SMEs review hardware and software components by evaluating the bill of materials, component procurement sources, total system cost, and logistical planning and construction details, ensuring a solid plan for meeting flight requirements by the final stage. Contestants also present their team skills, build progress, and technical specifications on how their solution meets the contest goals.

After the design review, organizers give contestants a three- to four-month development period that concludes with a recorded video evaluation. In this period, contestants build, test, and fly their UAS; in some cases, new walk-on teams can compete by joining this stage. At the end of this period, teams submit a video showing their prototype, conduct a safety review, and explain any modifications or outstanding tasks from the original design review. Teams also provide a performance demonstration to prove flightworthiness and functionality. In some challenges, the organizers instruct teams to construct a flight measurement apparatus using NIST standard test methods to evaluate flight and operator performance. SMEs assess each team's flight video submission and supporting documentation against the defined rules. Contestants' measurements derived from the NIST test procedures provide evidence to prove their capabilities. From this evidence, SMEs advise judges on the outcomes to determine which teams to advance to the next stage.

3.2.4. Stage 3: Live Test Evaluation

Stage 3 is a live, in-person event where teams demonstrate their UAS performance. Contestants commonly have two to three months between stages 2 and 3 to prepare prototypes and make minor changes before the final Stage 3 flights. Any significant design changes may result in disqualification if not communicated to and approved by contest organizers.

During Stage 3, the organizers give contestants multiple objectives to evaluate their aircraft's and pilots' ability to fly in a live scenario and solve the contest's public safety use case. On the first day of Stage 3, the contestants run UAS prototypes through a series of static technical tests. These tests include procedures used in Stage 2 video submissions, such as safety checks, analyses of bill of materials, capabilities testing, and performance demonstrations. The remaining days of the event typically include a live scenario with a series of tests that closely replicate a disaster or other emergency response operation. This stage is a head-to-head competition with strict scoring metrics; however, remediations are discretionarily allowed if a contestant's UAS crashes or fails to meet the objectives or required operation, with the team incurring penalty points. Winning categories typically include first, second, and third place, best-in-class awards for specific features or functionalities, and a first responders' choice award.

3.2.5. Stage 4: Solution Accelerator

Stage 4 is a solution accelerator stage for the top winners and best-in-class awardees from Stage 3. The UAS 5.0 challenge introduced this final stage, consisting of two milestones, to enhance their UAS solution or small business. The first milestone asks contestants to write a solution plan with attainable goals for developing their UAS prototype or small business with requirements to solicit support from a public safety partner. The second milestone educates and guides teams to further the commercial application or technical research of the contestant's Stage 3 UAS solution. Unlike in previous stages, contestants do not compete against each other; instead, performance is individually evaluated based on project completion and satisfaction criteria. The goal of Stage 4 is to help contestants build a marketable product or improve their aircraft system through partnerships, strategies, and additional resources. While commercialization is the goal, contestants decide if the strategy of their solution plan is to advance their business or academic goals beyond the contest period. The final Stage 4 evaluation culminates with each contestant providing a closing presentation and UAS test evaluation in a live scenario. Note that NIST does not provide recommendations for or against products, services, or vendor selections based on challenge outcomes.

4. PSCR UAS Challenge Summaries

As of this publication, PSCR has produced seven UAS prize challenges that have addressed various first responder situations and use cases. The summaries below provide insight into each challenge; however, future publications will cover these in greater detail.

4.1. PSCR UAS 1.0: Unmanned Aerial Systems Flight and Payload Challenge

The inaugural UAS challenge took place in 2018 in Fredericksburg, Virginia. In this challenge, PSCR examined how engineering design tradeoffs for flight time and endurance capabilities affect the UAS while carrying a communications payload. This use case examined how a UAS could extend cellular network coverage to “boots on the ground” first responders in a communications-denied location. The challenge was to incorporate a payload that would mimic the weight of a small cellular system on a deployable UAS.

UAS were required to achieve 90 minutes of hovering flight endurance while carrying defined payloads of 10, 15, and 20 lb (4.5, 6.8, and 9.1 kg), the typical weights for a small communications system. The total weight of the flight vehicle at liftoff had to be less than 55 lb (24.9 kg) to ensure portability and compliance with FAA regulations. The UAS also had to complete maneuvering and positioning tests as required in the NIST Open Test Lanes and Scenarios test methods with the various attached payloads. [10] The Open Test Lanes methodologies helped simulate and evaluate flight maneuvers, such as position-hold and yaw movements, that a UAS pilot may observe in a responder event. Evaluators used 2D and 3D fiducials as reference points and ground truths to assess each UAS with repeatable and measurable results. By performing these test procedures in an outdoor venue, PSCR could closely replicate the environment that a UAS may encounter while carrying essential communications equipment.

In the UAS 1.0 challenge, PSCR found that hybrid fuel solutions, such as a battery and gasoline combination, performed the best. Multi-rotor and aircraft frames supportive of Vertical Takeoff and Landing (VTOL) greatly influenced the performance and accuracy of the aircraft's flight. Deficiencies that PSCR observed were mainly in the form of aircraft control and the need for further tuning of flight software to maintain and hold position. Essential loiter functions and automated flight mechanisms were challenging to maintain, possibly due to the developing UAS marketplace, the device’s prototype nature, and the design of the payload transport functionality.

4.2. PSCR UAS 2.0: First Responder UAS Endurance Challenge

The UAS 2.0 challenge continued the objectives of UAS 1.0 but focused more on endurance. Weight limitations were increased to include larger UAS with the expectation of better control, longer endurance, and innovative ideas. The use case for UAS 2.0 closely matched the communications functions presented in UAS 1.0 but contained an additional use case for long-duration search and rescue scenarios.

The key design requirements in UAS 2.0 included a single payload weight of 10 lb (4.5 kg), which simulated the smallest available cellular network device. The final event took place between 2020 and 2021. Due to the global COVID-19 pandemic, each contestant performed the final event tasks and measurements within their team locality. The NIST-designed payload provided to the contestants for their final flights comprised an independent position data capture and dissemination system for test measurement and validation. As in UAS 1.0, contestants performed a hover endurance test and used the NIST Open Test Lanes as a ground truth measurement system as evaluation methodologies. Larger UAS sizes, up to 100 lb (45.3 kg), were permitted with the expectation of greater endurance, longer flight times over 90 minutes, and increased aircraft stability. Contestants had to provide evidence of airspace authorizations for aircraft weight and height operation exceptions from their respective governing authorities, e.g., FAA Certificate of Authorization.

Mirroring the results of the first challenge, UAS with propulsion systems and multi-rotor hybrid battery-gasoline solutions performed the best. Novel propulsion systems, such as hydrogen fuel cells, were also demonstrated in the final event. Some contestants proposed fixed-wing VTOL UAS in the early competition stages, but these ideas failed to progress past theoretical design due to engineering complexity. Flight control and stability functions were also improved with a standard payload, providing more aircraft design flexibility. PSCR found that contestants who started with existing designs early in the competition or those who tested early and frequently had better success in later stages. The winning UAS solution consisted of a hex-rotor design with a hybrid electric-gasoline engine propulsion system. The maximum flight time of this solution in the final test event was approximately 112 minutes, with a total takeoff weight of 54.9 lb (24.9 kg.)

4.3. PSCR UAS 3.0: First Responder UAS Triple Challenge

The UAS 3.0 challenge aimed to create a multi-use, multi-payload UAS platform for first responder search and rescue use cases. The challenge comprised three distinct research challenges that ran concurrently. The final stage of these competitions took place concurrently in June of 2022 in Starkville, Mississippi.

4.3.1. PSCR UAS 3.1: First Responder UAS Triple Challenge: FastFind

The design goals of UAS 3.1 focused on the use case of finding missing persons quickly in heavily forested areas. In this challenge, UAS required optical systems that could penetrate thick forest canopies and withstand environmental conditions and hazards. The UAS had to be rapidly deployable and endure the mission's duration.

In the UAS 3.1 challenge, flight vehicles had to meet a weight requirement of 55 lb (24.9 kg) or less, including attachments or payloads. A five-point scale evaluated the flight autonomy of the aircraft, with each level describing a range of independence that required less pilot intervention. Additionally, real-time video had to be transmitted to the pilot's ground control station, while onboard recording was mandatory on the aircraft. The vehicles had to demonstrate the capability for degraded takeoff and landing while operating in environments not typically suited for standard flight operations, such as areas with uneven surfaces, dirt, or gravel. The final scenario required all competitors to find multiple designated targets within a 60-minute timeframe.

In the final event, contestants used adaptive search technologies, including real-time computer vision, machine learning, and human verification, to assist in finding targets. Competitors used one or multiple camera technologies, including infrared, thermal, and neutral-density optical filters, digital filters, and telephoto optical systems, to help expedite recovery time. One contestant utilized a novel technique called Airborne Optical Sectioning, which incorporates a form of synthetic aperture imaging to integrate multiple camera technologies to suppress occlusions computationally. [11] Environmental factors at the test location, including high heat and humidity, negatively affected the contestant's aircraft performance and the optical systems' efficiency. These conditions also generated false positive matches by computer vision algorithms used in the search.

4.3.2. PSCR UAS 3.2: First Responder UAS Triple Challenge: LifeLink

UAS 3.2 LifeLink evaluated techniques using a UAS to provide continuous broadband communications in a service-denied area. The UAS carried a communication relay system to extend communications with first responder stations on the ground.

UAS 3.2 contained identical UAS requirements for weight, autonomy, takeoff, and landing conditions as UAS 3.1. Specific to the LifeLink challenge, each UAS was required to have a wireless Wi-Fi transceiver to transmit internet protocol data to responders on the ground and to a NIST-provided bandwidth measurement server. A Wi-Fi antenna or array attached to the UAS could enhance coverage by optimizing signal power and direction. Each contestant's UAS was not limited beyond FAA Part 107 requirements; contestants could choose the optimal testing height for their solution.

UAS designs in UAS 3.2 contained Wi-Fi configurations that could transmit simulated voice and data streams up to 800 ft (244 m) from the aircraft. Omnidirectional antennas provided optimal coverage and higher bandwidth speeds for areas with more first responders in a small, circular geographic area. Directional antenna configurations offered the best coverage for distance-focused applications when correctly oriented. When combined with repeater technology, the Wi-Fi signal could transmit further, but each added repeater would diminish the bandwidth speeds. High heat, humid weather conditions, and forest foliage negatively impacted coverage, distance, and bandwidth speeds.

4.3.3. PSCR UAS 3.3: First Responder UAS Triple Challenge: Shields Up!

UAS 3.3 Shields Up! explored one specific component of UAS with an attempt to bring awareness and ideas to UAS cybersecurity. The goal presented to contestants was to design both an attack and mitigation of the attack using open-source UAS navigation and control software. By developing both aspects of the attack, contestants thoroughly understood the problem a UAS operator might face when failing to take preemptive countermeasures to remediate the threat.

Competitors had to display a successful UAS control takeover, document the attack process, and show how a first responder or cybersecurity specialist could mitigate the attack.

As with the other UAS 3.0 challenges, competitors had to design a flight vehicle weighing less than 55 lb (24.9 kg). Autonomy, degraded takeoff and landing, and real-time video were optional but beneficial if used in part of the attack and remediation demonstration.

In the final event, contestants found vulnerabilities that exploited many UAS primary and secondary systems. UAS wireless transmitters and receivers without encryption allowed for eavesdropping and man-in-the-middle attacks. In one contestant's demonstration, they captured video data transmitted between the aircraft and the flight controller without alerting the pilot. Another demonstration showed how a bad actor could take control of a UAS by mimicking the trusted flight controller. Similarly, another contestant showed how spoofing GPS signals could alter the position and location of a UAS and provide false information to the pilot control station and flight controller. Default setup parameters and out-of-box settings were also exploited in demonstration attacks, permitting take over control of the UAS.

4.4. PSCR UAS 4.0: First Responder UAS Indoor Challenge

UAS 4.0 deviated from previous challenges to focus on the indoor application of UAS in first responder operations. The goal of UAS 4.0 was to design, build, and fly a cost-effective UAS solution that could help search and rescue teams locate missing person(s) and life-threatening obstacles in an indoor, low-light, and Global Positioning System (GPS)-denied environment. UAS designs in this challenge targeted flyability, ease of control, high durability, and a high-quality video signal to detect human life and assess environmental hazards.

UAS evaluation involved a series of accuracy and alignment tests to display aircraft capabilities. These features included light-emitting diode illumination, night vision, or infrared cameras while keeping system costs under $5,000. Optionally, contestants could implement an auto-flip feature to orient the aircraft upright if it crashed upside down, two-way audio, and a perching capability to help preserve battery life and gain situational awareness. All contestants were required to perform in a live scenario obstacle course within a 30-minute timeframe.

In the final evaluation, UAS with enhanced stability features and position-holding capabilities performed the best. Additionally, UAS outfitted with protective frames and propeller guards were more effective at avoiding hazards, which is crucial in indoor environments. Pilot experience and skill also played a crucial role in successful indoor navigation. Another finding was that aerial drones with gimbaled or vertical pan cameras gave pilots a better ability to identify hazards and accomplish search and rescue goals.

4.5. PSCR UAS 5.0: First Responder UAS 3D-Mapping Challenge

UAS 5.0 continued the indoor UAS first responder use case but included a 3D mapping element as the main deliverable. This challenge tasked competitors to design a 3D mapping aerial drone to provide first responders with real-time maps of potentially dangerous or unknown areas.

Like UAS 4.0, the aircraft had to perform indoors and contend with confined spaces, debris, and obstacles. In addition, the UAS had to provide accurate mapping information with a real-time rendering speed greater than or equal to 2 (two) ft/s (0.609 cm/s). Contestants also had to provide a completed post-flight map, which was deliverable on portable media storage for further analysis. Objects within the environment had to be resolvable to minimize surface coverage gaps and the smallest degree of area and volume possible. The preferred dimensions of resolvable objects were less than or equal to 64 in^3 (162.56 cm^3) or 16 in^2 (40.64 cm^3) with a surface gap of less than or equal to 12 in^2 (30.48 cm^3). The UAS also had to include flight enhancement and usability features that allow for a one- or two-person deployment and operation, navigation, and human detection capability. Optional capabilities included one- or two-way audio and auto-flip functionality. Blue/Green UAS compliance was another optional capability that competitors could implement in their UAS. Blue UAS is a Department of Defense (DoD) program that rapidly evaluates and scales commercial UAS technology, meeting high cybersecurity and supply chain requirements. [12] Green UAS is a certification program developed by the Association for Uncrewed Vehicle Systems International (AUVSI) that assesses and verifies commercial UAS using criteria similar to Blue UAS. [13] In this criteria, the competitor's UAS only had to meet the component manufacturer's source requirements outlined in the contest's Blue/Green UAS requirements.

Mirroring the results from UAS 4.0, stability, position-hold, and autopilot capabilities enhanced UAS navigation for indoor flight. While puck LiDAR vehicles produced the best maps, this type of heavy sensor impacted endurance and flight duration. Fixed LiDAR systems were lighter but required additional UAS maneuvering to map a full 360-degree view. 3D stereoscopic and vision-based sensor solutions were lighter; however, they produced lower-quality maps and required greater processing onboard the aircraft or at the ground station. A combination of fixed LiDAR and 3D stereoscopic UAS solutions proved to be the most efficient regarding endurance and map quality.

Stage 4 of UAS 5.0 includes a solution or business accelerator component focusing teams on improving their technology or marketing their product. Contestants receive third-party consultation on achieving commercialization and must present their product in a presentation. The final event also provides a unique platform for teams to test and evaluate their UAS using NIST-standardized test methods. As of this writing, Stage 4 of UAS 5.0 has a completion date of September 2024.

5. Conclusion

Initially, PSCR investigated UAS as a deployable asset that first responders could use to extend and enhance communications in cellular-denied locations. Over the past seven (7) years, as UAS became more affordable, accessible, and easier to use, PSCR expanded its research into additional technology areas to help advance the state-of-the-art for first responder UAS. Utilizing prize challenges for UAS research allows PSCR to define UAS specifications with associated metrics while pushing innovators to develop solutions for first responder operations and bring awareness to the unique needs of public safety entities.

PSCR found that stakeholder engagement and partnerships provide the most insight toward building successful prize challenges with quality outcomes. These engagements offer PSCR staff and prize challenge innovators consultation and guidance for how first responders employ UAS now and in the future.

With the regulatory landscape changing, PSCR will include challenge requirements and metrics in future prize challenges that align with federal regulations and first responders' interests. As such, industry advancements will allow new use cases to emerge, particularly in artificial intelligence, sensor integration, and onboard data processing. Today, AI-enhanced technologies are making significant technological advancements, highlighting new strategies that may benefit UAS and PSCR research areas for public safety. For example, the advantages and implications of autonomy used in flight operations and the human-machine interactions necessary to achieve public safety mission goals. These topics will help guide PSCR's understanding of AI and data management risks while offering situational awareness for all public safety disciplines. Specific UAS and AI technologies may include AI-assisted user interfaces, human and hazard identification applications, Drone as First Responder, and flight operations for Beyond Visual Line-of-Sight involving fewer human interactions. The recent launch of UAS 6.0: First Responder UAS Wireless Data Gatherer Challenge and future prize challenges may reflect these topics by including requirements for increased AI functions and a cybersecurity analysis. The resulting analysis may provide potential mechanisms that inform first responders of these capabilities, impact public safety operations, and advise PSCR's future research.

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Appendix A. Glossary

Contestants
Individuals or teams (also referred to as “innovators,” “teams,” “solvers,” “competitors,” “entrants,” or any combination thereof) that innovate solutions to solve technology problems presented by NIST, PSCR for awards.

Organizers
The individuals or groups responsible for planning, coordinating, and overseeing prize challenge events and activities. This publication refers to NIST, PSCR, or entities under the contract of NIST, PSCR as “organizers,” “contest organizers,” or “challenge organizers.”

Prize Challenge
A challenge (also referred to as “challenge,” “competition,” “prize competition,” “contest,” or any combination thereof) that allows the public to solve technology problems presented by federal agencies and receive awards for the best solutions. [9]

Uncrewed Aircraft System
An uncrewed aircraft system consists of an uncrewed aircraft and the equipment necessary for its safe and efficient operation. [14] This document also uses the original acronym expansions of “unmanned aircraft system” and “unmanned aerial system.”

Uncrewed Aerial Vehicle
The aircraft component of a UAS capable of sustained flight. This document also refers to it as an “unmanned aerial vehicle,” “unmanned aircraft vehicle,” “unmanned aircraft,” “aerial drone,” or any combination that substitutes unmanned with uncrewed.