Advancing Wildland Fire Response with NASA's Second Shift Capabilities

Hyo-Sang Yoo
Universities Space Research Association
NASA Ames Research Center
Moffett Field, CA USA
Hyo-Sang.Yoo@nasa.gov

Spencer Monheim
Aviation Systems
NASA Ames Research Center
Moffett Field, CA USA
spencer.c.monheim@nasa.gov

Lynne Martin
Human Systems Integration
NASA Ames Research Center
Moffett Field, CA USA
lynne.martin@nasa.gov

Robert Mcswain
Aeronautics Systems Engineering
NASA Langley Research Center
Hampton, VA USA
robert.g.mcswain@nasa.gov

***Abstract*—Novel "Second-Shift" capabilities—leveraging Uncrewed Aerial Systems and Optionally Piloted Vehicles—are identified that could extend wildfire aerial logistics support into night or low-visibility conditions. Expert elicitations with subject-matter experts informed the development of these conceptual capabilities and identified key challenges in wildfire logistics operations. Furthermore, the potential of these capabilities could extend beyond aerial logistics support, encompassing aerial suppression, observation, and emergency extraction support for wildland firefighting. An approach to development, implementation and validation of the novel capabilities is described.**

Keywords—Wildfire logistics, Uncrewed Aerial System (UAS), Optionally Piloted Vehicle (OPV), Advanced Capabilities for Emergency Response Operations (ACERO), Second Shift Capabilities (SSC)

I. Introduction

The risk of catastrophic wildfires is growing significantly. Compared to the average annual burned area between 1983 and 2016, the period from 2017 to 2021 experienced a 68% increase. The devastating impact was evident in 2023, causing immense economic losses and fatalities from Maui to the Great Smoky Mountains [1]. Climate change and other factors like continued population growth in the Wildland Urban Interface (WUI) are projected to further exacerbate the issue, causing more frequent and intense wildfires, stretching the wildfire season ever longer [2, 3].

While the wildfire risk has increased, the aerial support to firefighters on the ground has remained largely constrained to the same narrow window of approximately six to eight hours of Visual Meteorological Conditions (VMC) as when crewed aircraft first began supporting wildland firefighting over 90-years ago.

These escalating risks and the continuing large gaps in available aerial support necessitate innovative solutions for wildfire management. A promising development may lie in integrating Uncrewed Aerial Systems (UAS) and Optionally Piloted Vehicles (OPVs), in conjunction with advanced Air Traffic Management (ATM) technologies, into wildfire logistics support.

This integration could be particularly effective in challenging conditions like Degraded Visual Environments (DVE) caused by daytime smoke, inversions, and nighttime darkness and smoke, where traditional crewed aerial support remains largely absent. Research by the Department of Interior (DOI) from 2015 to July 2017 [4] found that nearly 19% of wildland fires were discovered outside traditional aerial firefighting hours. Of these, 66% are discovered between the end of flight operations and midnight, extending aerial support capabilities presents a significant benefit.

The primary contribution of the research work presented in this paper focuses on identifying key capabilities that enable safe and effective coordination and operations of UAS and OPV during DVE conditions. By leveraging these capabilities, we aim to significantly extend aerial logistics support for wildfire into this 'second shift.' This could lead to potential continuous 24/7 operations. Furthermore, these capabilities can be adapted for broader applications in wildland fire response, including aerial suppression, observation, and emergency extraction support for wildland firefighters and the community they protect.

The rest of the paper is organized as follows: the background section begins with an overview of the increasing threat of wildfires and the national push for modernization in response. It then introduces the NASA ACERO project and its focus on SSC in alignment with these objectives, followed by a brief description of current wildland fire management logistics. The methodology section outlines the approach used to identify SSC research areas, including literature reviews, expert interviews, and tabletop exercises. Key challenges in wildland fire logistics are presented in the results, alongside proposed solutions that could be addressed by SSC R&D efforts. The SSC R&D approach details iterative activities such as conceptual design, prototyping, testing, and community engagement to implement SSC solutions effectively, following NASA's system engineering principles. Lastly, the conclusion section is presented.

II. Background

A. Policy Emphasizing the Need for Modernizing Wildland Firefighting

The evolving landscape of wildfires necessitates a transformative approach to initial attack and extended attack suppression, logistics, observation, and emergency extraction improved by increased automation, integration of advanced capabilities, and enhanced collaboration across agencies and private sectors [5]. Recent federal investments acknowledge the critical need for improved wildfire management, providing significant funding. This includes the recent Bipartisan Infrastructure Law (BIL), which allocates nearly $200 million towards mitigating the escalating wildfire crisis in the United States [6].

Moreover, the President's Council of Advisors on Science and Technology (PCAST) report [5] advocates for expanding the nation's wildfire response capacity by leveraging advanced technologies, aligning with legislative initiatives like the John D. Dingell Jr. Conservation, Management, and Recreation Act [7, 8]. This legislation underscores the importance of leveraging cutting-edge technology for an increasingly effective and cost-efficient response to wildfires, emphasizing the establishment of a research, development, and testing program, including assessment of UAS technologies and OPV for modernized wildland fire management.

B. NASA's Advanced Capabilities for Emergency Response (ACERO) and Second Shift Capabilities (SSC)

Second Shift Capabilities (SSC) is an integral part of the NASA's Advanced Capabilities for Emergency Response Operations (ACERO) project. It is dedicated to developing, refining, showcasing, and transferring aviation technologies aimed at improving the safety, efficiency, and effectiveness of wildland fire management. These technologies encompass a variety of innovations, including UAS, airspace management, and advanced communication systems tailored for emergency situations.

ACERO endeavors to unite the wildland fire community with a vision for the future state of fire management. This involves crafting interagency Concepts of Operations (ConOps) to ensure operational consistency and technology adoption. Furthermore, ACERO considers importance of aligning programs with national needs and priorities.

C. Current Wildland Fire Management Logistics Operations

Wildland fire response logistics operations encompass planning, acquisition, storage, transport, and delivery. It relies on a multi-tiered National Dispatch and Coordination System (NDCS). This system connects over 250 Local dispatch centers to ten Geographic Area Coordination Centers (GACCs), and the National Interagency Coordination Center (NICC). This structure ensures efficient communication, resource allocation, and a collaborative response across agencies and regions, critical for tackling boundless wildfire incidents [9, 10].

III. Methodology

This study utilized a structured research approach to gain insights into wildland fire response logistics operations and identify challenges where the SSC could enhance the wildland fire response logistics operations. The methodology consisted of three main steps: literature review, expert elicitation, and use-case analysis through focused sessions with Subject Matter Experts (SMEs) facilitated with scenario simulations.

Firstly, a comprehensive literature review was conducted to understand the current state of wildland fire response logistics and ongoing modernization efforts in wildland fire response management. This review encompassed a variety of sources, including scholarly articles, and agency reports, including National Wildfire Coordinating Group (NWCG) documents. SMEs also provided valuable guidance, suggesting relevant documents and highlighting recent publications from other NWCG member agencies. This review not only provided a foundational understanding of challenges, available technologies, and best practices in the field but also mainly helped formulate questions for subsequent semi-structured interviews.

Subsequently, 26 one-on-one semi-structured interviews were conducted with wildland fire response logistics experts from Federal, State and Local agencies, including National Oceanic and Atmospheric Administration (NOAA), Federal Emergency Management Agency (FEMA), California Department of Forestry and Fire Protection (Cal Fire), the United States Forest Service (USFS), etc. These experts held key roles in wildland logistics operations (e.g., logistics chiefs, UAS pilots, Helicopter pilot, and smokejumpers) and have extensive experience.

Each interview lasted approximately one hour, with the goal of understanding challenges in wildland fire response logistics operations and to gather insight on improvements needed in logistics support. The interview questions were structured around three main themes: understanding the interviewees' experiences and opinions on current logistics operations, soliciting their suggestions for improvements in logistics operations, and exploring their vision for the future state of logistics operations.

The findings from the literature review and interviews were analyzed to identify challenges and corresponding solutions. This guided researchers' development of an initial, high-level concept of operations and prototype requirements for the SSC .

To gain initial feedback on the proposed concepts and requirements from other NWCG members, a use-case analysis was conducted during tabletop activities, held in May 2024, using scenario-based simulations. Tabletop activities simulate exercise where participants discuss and evaluate proposed plans, procedures and concepts. Leveraging NASA's World Wind capability, a free open-source software development kit that allows users to visualize and interact with geospatial data on a virtual 3D globe [11], these activities demonstrated the use of SSC to support UAS and OPV in performing resource delivery operations at the wildland fire incidents, even during DVE conditions, where crewed aerial support operation are largely non-existent.

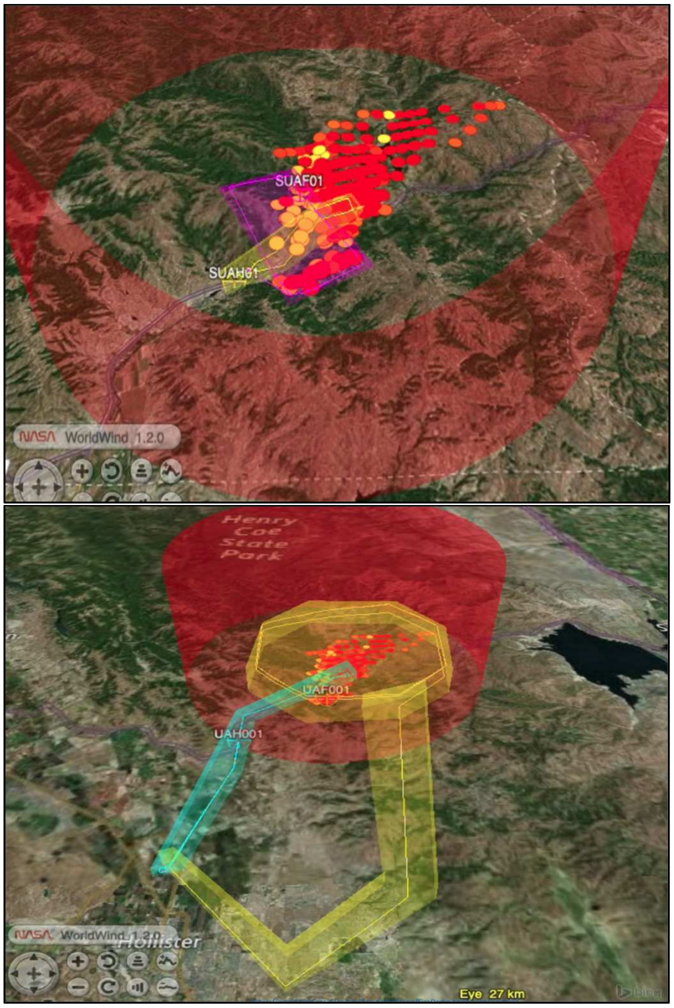

Fig. 3. Scenario-based simulation screenshots (top: sUAS supporting last-leg delivery; bottom: OPV supporting mid-leg delivery)

The screenshots in Fig. 3 illustrate a wildfire simulation scenario near Hollister, CA. Rugged terrain and inaccessible routes significantly hinder firefighting efforts. Due to DVE conditions, including limited visibility and nightfall, all crewed aircraft have been grounded within the Temporary Flight Restriction (TFR) airspace, indicated by the red circle geofence in the image.

The colored volumes (yellow, purple and cyan) represent a concept for segregated airspace designated for different Uncrewed Aerial Vehicle (UAV) types (small UAV; sUAV and Optionally Piloted Helicopters; OPH). This concept aims to minimize the risk of mid-air collisions by separating the airspace used by various UAV/OPH/OPV. Segregated airspace is a commonly practiced method in the ATM world to ensure safe separation between aircraft and safely perform their missions. During the tabletop activity, SSC effectively supporting this airspace management concept was discussed.

In the simulated scenario, last-leg delivery could be utilized to support the provision of essential resources such as water and food directly to ground firefighting crews stationed on hard-to-reach elevated terrain. These last-leg delivery operated by sUAV operations would save the crews from having to scale difficult terrain repeatedly when receiving these resources. Mid-leg delivery by OPH could involve the transport of a large pallet of water or other supplies (e.g., chainsaw parts) from a nearby location to a coordinated delivery point.

These activities enabled community feedback to be incorporated into the SSC conceptual design and prototype development.

IV. Results

The methodology above produced results in the form of a refined set of the SSC, informed by a more comprehensive (or detailed, or wide-ranging, or whatever) set of key challenges.

A. Key Challenges and Proposed Solutions

Wildland fire response logistics may encounter challenges throughout the supply chain management cycle. However, this paper is specifically focused on the challenges during the active phase of the wildfire response, and only these key relevant challenges are summarized:

- **Difficulty in Resource Allocation:** Strategically planning and assigning firefighting personnel, equipment, and supplies to multiple locations and tactically reallocating them during high-demand periods and shifting priorities remains challenging.
- **Cross-Regional Resource Utilizations:** Certain resources are often approved for use at a local or state level but may not meet the criteria for a different or even neighboring region. Even when those local or state resources meet all the requirements of the lead agency on a fire, they may not have had the opportunity to have had that compliance validated by the agency managing the fire and therefore cannot be used. This hinders more efficient use of all available resources.
- **Limited Accessibility:** Remote or rugged terrain often poses obstacles to resource delivery. Aerial support (e.g., helicopters) is often used to provide supplies to ground crews, but aerial logistics operations are typically available for only one-third of each 24-hour period and are frequently grounded for multiple consecutive days due to DVE, low visibility, nighttime darkness, adverse weather conditions, or operational safety concerns.
- **Safety Protocols and Emergency Extraction:** Ensuring safety protocols for evacuating personnel and equipment, as well as establishing refuge areas during intensified wildfires, can be challenging due to the scattering of resources.
- **Limited Common Operating Picture (COP):** Real-time monitoring is limited due to inadequate availability of accurate wildfire maps, impacting decision-making and coordination.
- **Last-Mile Connectivity Issues:** Challenges in providing continuous and reliable communication hinder effective logistics coordination in remote or rugged terrain.

Our proposed solutions to the challenges identified during interviews and literature reviews are presented in Table 1. These solutions emerged from collaborative discussions with SMEs, reflecting their envisioned future capabilities and directly aligning with the goals of our SSC R&D effort. This effort also corresponds with the recent PCAST recommendations [5] to leverage advancements in autonomous systems for wildfire management. The solutions utilize UAVs and other technologies to achieve these goals.

TABLE I. PROPOSED SOLUTIONS TO WILDFIRE LOGISTICS CHALLENGES USING UAS AND OPV

Challenge	Solution
Difficulty in Resource Allocation	Utilize UAS and OPV equipped with advanced sensors and imaging for real-time reconnaissance and mapping, and resource tracking, enhancing situation awareness and enabling safer and more efficient resource movements
Cross-Regional Resource Utilizations	Establish standardized protocols for UAS and OPV utilization and advanced airspace coordination system across jurisdictions, ensuring consistent, safe, and efficient coordination of operations
Limited Accessibility	Deploy UAS and OPV equipped with advanced sensors to access challenging terrain and visual conditions, providing aerial support and transportation of essential equipment and supplies to hard-to-access locations even during DVE conditions. These operations could be supported by an advanced airspace management system to ensure safe vehicle operations
Safety Procotols and Emergency Extraction	Utilize UAS and OPV for aerial monitoring and emergency planning, providing real-time information and support for safety protocols during intensified wildfires. Incorporate OPV.
Limited COP	Integrate UAS with imaging and mapping capabilities to create a comprehensive and accurate COP, enhancing decision-making based on (near) real-time aerial data
Last-Mile Connectivity Issues	Implement UAS as a communication relay or equip OPV with communication systems to address last-mile connectivity challenges, ensuring continuous and reliable communication

B. *Second-Shift Capabilities (SSC)*

The methodology described in Section III refined the initial (or rudimentary, or candidate) ideas for potential SSC into a vetted list of developed concept elements as follows: 1) Advanced Airspace Management, 2) Communication, 3) User Interfaces, 4) Decision support, and 5) Aircraft autonomy

1) Advanced Airspace Management System ("UTM-in-a-box")

A portable advanced airspace management system could be developed to support safe and efficient operation of UAS and OPV during wildfire. Its portability ensures flexible deployment in remote and dynamic wildland fire environment. Currently, there is no existing ATM system capable of supporting the scaling UAS and OPV operations for wildland fire response. This system must function effectively under various conditions, including situations where internet access is unavailable, or bandwidth is restricted, or overwhelmed with first responder agencies working the wildfire. For example, in the absence of connectivity to cellular data network, users can rely on radio-based networks and communication to coordinate operations to ensure separation between vehicles. The radio-based network and communication layer could be supported using visual aids and audible cues, to augment the ability of vehicles and their operators to stay within the coordinated airspace and receive pertinent alerts, such as when a non-participatory operation enters the coordinated airspace.

These features—developed as part of NASA's Scalable Traffic Management for Emergency Response (STEReO) Project [12]—and the lessons learned are being leveraged for the current research effort. The STEReO's capabilities include notifying UAS pilots or other airspace users with an audible cue when an aircraft equipped with ADS-B Out enters user-defined areas, providing enhanced situation awareness. However, this approach has limitations. ADS-B signals are susceptible to attenuation by terrain, especially lower altitudes critical for aerial firefighting operations like dropping fire retardant/suppressant/water. Additionally, FAA regulations under Part 107 [13] specifically prohibit UAS from using ADS-B Out due to concerns about cluttering airspace data and potentially interfering with crewed aircraft that rely on ADS-B for navigation and situation awareness.

To address these limitations and improve overall airspace management during wildfire, STEReO's aerial asset tracking capability could be enhanced by exploring additional methods for tracking all aerial assets. This would provide a comprehensive picture of everything operating in and around wildland fire incident airspace. With complete and up-to-date information on the location and status of all aerial assets, decision-makers could make more informed choices.

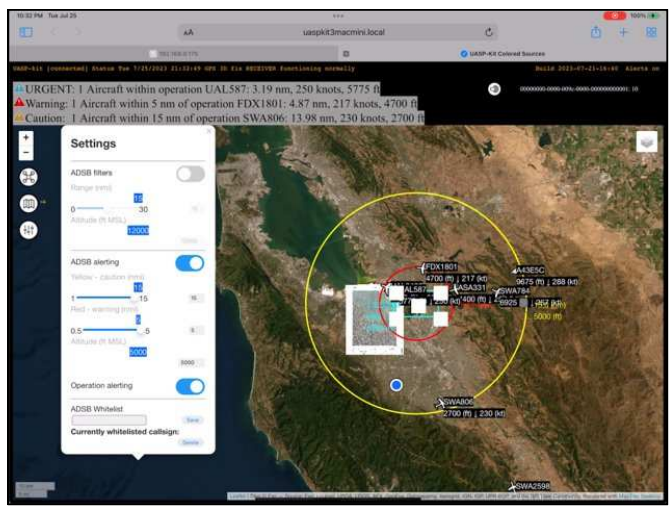

Fig. 5. Offline support: Visual aid and audible cue

When there is last-mile connectivity enabling information exchange between the multiple UTM-in-a-box systems, key elements from UAS Traffic Management (UTM) [14]—like Operational Intent Sharing, Strategic deconfliction, and Conformance monitoring capabilities—can be facilitated.

Operational intents, which are four-dimensional data (4D) (time and space) specifying an aircraft's intended location during a mission, can be submitted by UAS/OPV pilot for either trajectory-based or area-based operations to personnel with incident airspace authority responsible for coordinating and approving these operations. The size and shape can flexibly support various mission phases and types, like using a trajectory for transit but area-based for surveillance type of missions.

Efficient use of operational intents relies on users sharing only the minimum volume of operational intents required to ensure safe operation but with high confidence that their vehicle can stay within its designated boundaries. This operating practice is to promote efficient and fair airspace utilization.

The strategic deconfliction function aids in identifying temporal and spatial conflicts with other submitted Operational intents, assisting in coordination and decision-making processes.

Conformance monitoring is intended to support UAS pilots and other relevant positions that require continuous monitoring of UAS performance and operations for enhanced situational awareness. It is designed to notify the user(s) when a UAS leaves its designated Operational Intent boundary.

The advanced airspace management capability may enable efficient communication with the Extensible Traffic Management (xTM) [15] system, ensuring interoperability. UAS Service Supplier for Public Safety (USS-PS) is a proposed service within the xTM system environment that provides airspace restriction management services. It manages and disseminates airspace restrictions, including TFRs, from the Civil Aviation Authority (CAA) or Air Navigation Service Provider (ANSP). These restrictions are communicated through notices to Airmen (NOTAMs), ensuring that local UAS operators, nearest Air Traffic Control facilities, and the public are promptly informed about any temporary airspace limitations or operational changes.

By effectively communicating TFRs and other airspace restrictions for emergency usages, USS-PS may support the secure and efficient movement of aerial assets for logistics support within and outside the wildland fire incident area. This capability is important for maintaining airspace safety and compliance during critical operations, such as firefighting efforts and emergency response activities.

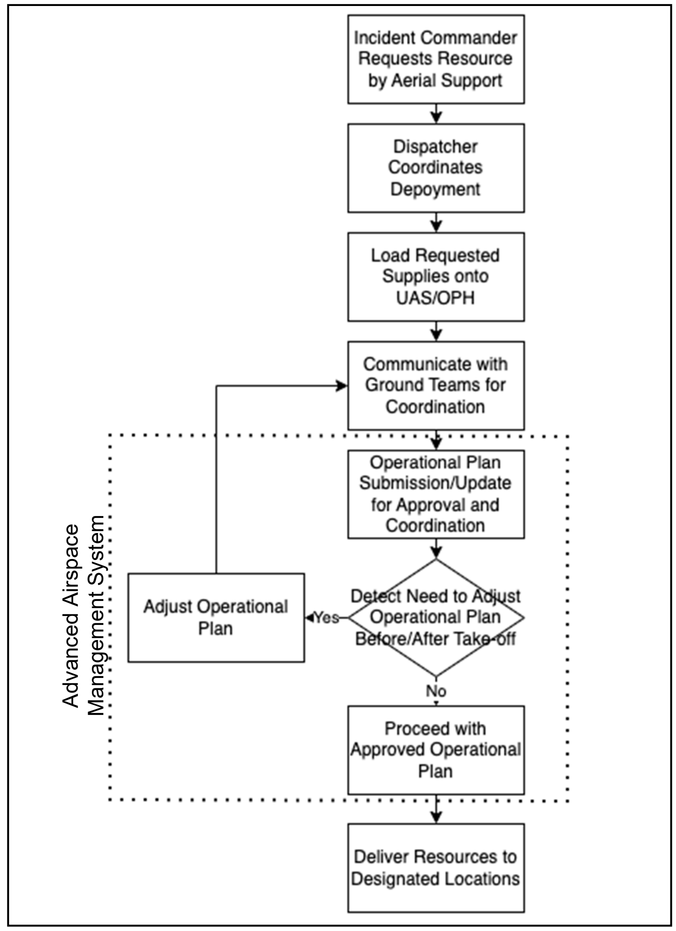

Fig. 6. A Notional sequence of steps: streamlining UAS and OPV deployment with UTM-in-a-box

Fig. 6 depicts an initial, high-level proposed processing flow for utilizing UAS and OPVs for resource delivery. This notional model is proposed to serve as a reference point for collaborative decision-making with wildland fire community during the system development process, particularly regarding the integration of UTM-in-a-box technology. The intention is to achieve a standardized streamlined flow while minimizing disruption to existing organizational structures (e.g., roles and responsibilities).

The SSC R&D efforts are not limited to tool development; they include producing tool requirements and recommendations for standardized procedures. These guidelines, informed by this notional processing model, would facilitate the deployment and utilization of UAS and OPV, ensuring efficient and coordinated operations in various challenging conditions and across regional boundaries.

2) Communication

Effective aerial support in wildland fire response requires continuous and reliable communication to ensure COP across all involved entities, encompassing logistics, suppression, and all other aspects. Interviewees emphasized the need for persistent communication, particularly regarding last-mile connectivity challenges in remote areas for logistics support. While potential future solutions include ground-based mobile platforms like wheeled robots equipped with cellular repeater technology, their deployment flexibility could be hampered by factors like rough terrain. Additionally, reliable remote control of these robots from distance might be challenging, hindering their effectiveness in communication. Aerial platforms, on the other hand, may prove to be a preferable solution due to their ability to overcome these ground-based limitations, and the interviewees were supportive of our concept pursuit in leveraging them for this purpose. (see Fig. 7)

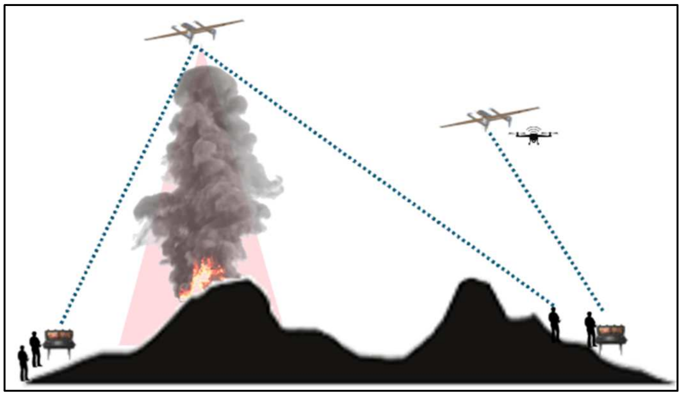

Fig. 7. Schematic view of UAS providing last-mile connectivity for persistent communication

Currently, radio communication is the essential and common form of communication for wildland fire response. However, radio signals are limited by terrain and topography, as they only travel to receivers within the “line-of-sight” (LOS) of the transmitter. One of the current solutions to this LOS issue is the use of repeaters, which receive the original signal and retransmit it to extend its range. Firefighters often use mobile repeater stations that can be quickly assembled or disassembled to connect multiple entities via radio communications by placing repeaters at terrain peaks [16]. However, accessing these peaks can often be challenging.

To overcome these challenges, the SMEs recommended NASA explore the use of aerial-based repeater systems, including low, medium, and high-altitude UAS platforms [17, 18, 19, 20]. By creating a layered mesh network with these aerial-based repeaters, the SSC could better ensure redundancy and increased reliability, providing more persistent communication.

Additionally, the SMEs indicated that the use of aerial platforms for providing cellular connectivity in remote areas should be investigated. This is essential for transmitting data between the asset base, dispatch center, and incident command. Technologies like Starlink [21] could be considered to enable cellular connectivity in these remote areas. The PCAST report [5] emphasizes the need to assess existing technologies available within the federal arena, the private sector, and allied nations that could be integrated into each stage of the wildland fire response cycle. The Dingell Act Resource Tracking (DART) team [22, 23] has recently tested various resource tracking capabilities with low-bandwidth mesh networking radios (i.e., goTenna Pro X [24] and Beartooth MK II radios [25]) and Satellite internet service (i.e., Starlink [21]), demonstrating the potential for enhanced connectivity.

The present research highlighted a need for more rigorous testing and understanding of the currently available innovative communication capabilities for field deployment by conducting assessments and reporting performance requirements in conjunction with other SSC systems, such as the aforementioned advanced airspace management systems. Moreover, these efforts may include developing standardized data formats and protocols for exchanging fire information data, incorporating UAS remote sensing capabilities to provide real-time geospatial wildfire information. This information includes the location, extent, fire behavior, and surrounding environmental conditions (e.g., wind), enhancing wildfire logistics and safety outcomes, such as evacuation and extraction operations.

The importance of standardized data formatting and establishing data pipelines is emphasized by the PCAST report [5] and the Dingell Act [7]. Currently, there is an ongoing development effort on the Interagency Data Management Environment (IDME) [26]. The initiative is to develop an interoperable data architecture supporting the wildland fire community. Aligning the SSC's R&D efforts with broader data management initiatives and leveraging collaborative efforts could help streamline information integration.

3) *User Interfaces*

In 2014 and 2015, during the Department of the Interior’s (DOI) Optionally Piloted Helicopter (OPH) wildland fire demonstration flights, the KMAX helicopter (see Fig. 8) showcased its ability to deliver four designated cargo loads to GPS-designated locations in a single flight using a four-point carousel rig [27]. The demonstration also included flying over a designated route that avoided simulated firefighter positions and incorporated an inflight update to one of the drop locations, which it executed flawlessly.

Fig. 8. KMAX OPH delivering cargo demonstration [27]

UAS and OPH like the KMAX hold promise for disaster response cargo delivery. However, full deployment and scaling of these technologies may necessitate standardized user interfaces (UIs) and operating procedures for safe and efficient field operations. The SSC is currently developing requirements and recommendations for such UIs and procedures, with a focus on minimizing user workload and maximizing situational awareness in the demanding environment of wildland fire response.

DVE conditions, where traditional crewed aircraft are grounded, offer an initial opportunity to simplify operations and test UIs. This testing ensures readiness and smooth interoperability when UAS/OPH/OPV are integrated with crewed aircraft in more mature stages.

To develop effective UIs, the SSC can employ a user-centered design approach. This involves focused research and interviews with experienced UAS and OPH pilots to understand their information needs during cargo delivery missions. Wireframes for pre-flight planning, including cargo manifests and GPS-designated routes, can be created and iteratively refined through user testing and demonstrations.

The design process could also include creating wireframes for pre-flight planning, which may encompass a cargo manifest, and route overview with GPS-designated delivery locations. These wireframes could be used to develop prototypes, which could undergo iterative testing and demonstration to refine the UI design.

4) *Decision Support*

Efficient UAS and OPH cargo delivery operations can be significantly enhanced by decision support tools. These tools could assist users during both the pre-flight planning and inflight phases by importing and processing information such as Digital Elevation Models (DEMs) [28]. The following describes the core functionalities proposed for these two phases (pre-flight planning phase and inflight phase):

For the pre-flight planning phase, optimal route generation could be developed by leveraging past NASA UAS package delivery algorithm development efforts and lessons-learned [29]. The decision support capabilities could help generate the shortest and safest routes, considering waypoints, terrain elevation, airspace restrictions, and weather forecasts.

For the inflight phase, a real-time flight status monitoring feature could be developed to provide a visual display of the UAS and OPH's location, altitude, airspeed, and remaining fuel or battery. NASA's previous research efforts in battery state of charge estimation research efforts for electric aircraft [30] could be leveraged to provide UAS system status monitoring, which is necessary to ensure safe Beyond-Visual-Line-of-Sight (BVLOS) operations. The display can be overlaid with the planned flight path for real-time progress monitoring, enhancing the operators' ability to track and manage the flight effectively.

Moreover, decision support capabilities could facilitate the necessary coordination processes for inflight route changes in response to the dynamic mission environment. During resource delivery, the system can display a real-time drop zone based on GPS coordinates, wind speed and direction, and the altitude of the UAS and OPH. It can also provide visual cues or instructions to assist the pilot with precise cargo release, ensuring accurate and efficient delivery.

These core decision-support functionalities could be integrated into the user interface design effort mentioned in the previous section, to better support users with performing resource delivery missions safely and efficiently, enhancing overall mission success in challenging environments.

5) *Aircraft Autonomy*

Advanced hazard detection and avoidance capabilities are needed for the safety and reliability of BVLOS UAS operations within a TFR above a wildfire incident. The development of these capabilities could be supported by improving the aforementioned aerial asset tracking capabilities for UAS localization and leveraging technology such as the Independent Configurable Architecture for Reliable Operations of Uncrewed Systems (ICAROUS), developed by NASA Langley Research Center [31].

ICAROUS is comprised of a distributed software architecture with well-tested algorithms that enable path planning, obstacle detection, collision avoidance, geofence handling, and decision making. It interfaces with the autopilot system through a publisher-subscriber middleware [31]. Integrating technology like ICAROUS could aid in Hazard Detection and Avoidance for UAS, ensuring safe and reliable operations, especially in challenging and dynamic conditions like DVE or rugged terrain.

V. RESEARCH AND DEVELOPMENT STRATEGIES

This research results now moved the SSC from Technology Readiness Level (TRL) 1 to TRL 2 [32], following the NASA system engineering approach [33]. This approach emphasizes a structured development process with a focus on requirement management, risk mitigation, and stakeholder involvement. The strategy for transitioning SSC from TRL 2 to TRL 6 is comprised of three elements as described next.

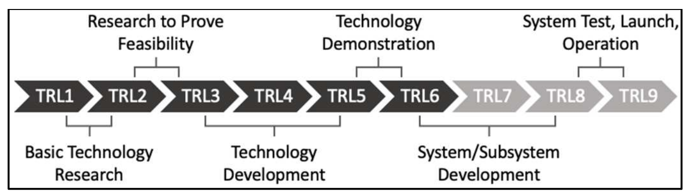

Fig. 9. NASA Technology Readiness Level (TRL) Process [32]

A. *Conceptual Design and Prototying*

The initial phase of this research effort focused on conceptual design, gathering high-level requirements from community engagement, and defining technological solutions needed for the development. Next, the prototyped capabilities are being/will be developed and used to help validate design concepts, development of feasible concept of operations, test functionalities and gather more feedback from the potential users. This phase corresponds to NASA's TRL 1 to 3, which involves conceptualization, feasibility studies, and technology exploration. Structured interviews, a workshop and tabletop activities with use-case analyses could be conducted iteratively to evaluate various technological ideas, concepts of operation, and gauge the community engagement with their acceptance.

B. *Field Test/Demonstration*

Moving forward, field tests and demonstrations could be planned for technology validation and operational readiness of SSC. Aligned with NASA's TRL 4 to 6, this phase may focus on validating the SSC's functionalities, reliability, and safety under relevant real-world-like environments. The field tests and demonstrations could be conducted incrementally for multiple Technical Capability Levels (TCLs), each offering opportunities and iteration on the performance and identification of more detailed functional/non-functional requirements (e.g., reliability of the last-mile connectivity technologies' performance requirement to support the SSC functions) in wildland fire response scenarios.

Since current wildland fire aerial support operations are mostly limited to daytime and clear visual conditions, UAS and OPV operations during DVE conditions, including the "second shift" (nighttime operations), naturally provide a controlled environment for integrating UAS and OPV without jeopardizing interoperability with crewed aircraft already present in the field. Throughout the process, iterative improvements based on operational feedback could be made, enhancing the maturity and readiness of the SSC tools for wider deployment.

C. Community Engagement and Feedback

Effective community engagement and feedback are imperative for the successful adoption of the SSC tools. Currently, stakeholder engagement and interaction with wildland fire communities are being pursued to ensure acceptance and utilization of the SSC during the design and prototyping phases. Throughout the iterative process of refining concepts, prototypes, and field demonstrations, informational materials for the SSC could be documented. In the future, these materials may assist the wildland fire community in establishing standardized procedures for the SSC and could aid in their integration into wildland fire response logistics operations.

VI. Conclusion

This paper proposes key elements of the SSC aimed at improving wildfire response with advanced capabilities to integrate UAS and OPV for the logistics support. Literature reviews, SME interviews, and use-case analyses identified refined key challenges in wildfire logistics, leading to tailored concept design and requirements for the SSC. The outlined SSC implementation strategies adhere to NASA's proven system engineering approach. The outcome of this effort is expected to enhance our nation's wildfire response capacity by safely integrating more use of UAS and OPV, aligning with broader initiatives like those recommended by the PCAST report and other ongoing interagency activities. Furthermore, these SSC elements are adoptable beyond logistics support. They can be utilized to bolster other aspects of wildland fire response, including suppression activities using UAS and OPV for dropping water to support ground crews.

Acknowledgment

The authors extend their gratitude to the National Interagency Fire Center community members and interview participants for their valuable input on the Second Shift Capabilities conceptual design and prototype development. Special thanks to Advanced Capabilities for Emergency Response project, and its team members for their collaboration and support. The material is based upon work supported by the National Aeronautics and Space Administration under Contract Number NNA16BD14C, managed by the Universities Space Research Association.

References

[1] The Pew Charitable Trusts, "How States Can Manage the Growing Price of Wildfires," [Online]. Available: https://www.pewtrusts.org/en/research-and-analysis/fact-sheets/2022/11/how-states-can-manage-the-growing-price--of-wildfires [Accessed: June 03, 2024].

[2] Fires Pose Growing Worldwide Threat to Wildland-Urban Interface [Online]. National Center for Atmospheric Research (NCAR). Apr 16, 2024. Available: https://news.ucar.edu/132950/fires-pose-growing-worldwide-threat-wildland-urban-interface [Accessed: June 03, 2024].

[3] U.S. Department of Agriculture (USDA) Office of Measurement, Standards, and Research, "Study Finds Climate Change to Blame for Record-Breaking California Wildfires," [Online]. Available: https://www.drought.gov/news/study-finds-climate-change-blame-record-breaking-california-wildfires-2023-08-08 [Accessed: June 03, 2024].

[4] U.S. Department of the Interior [DOI], Relationship of Fire Discovery Times on the Timeliness of Aerial Firefighting Support, [Online]. Available: https://www.doi.gov/sites/doi.gov/files/uploads/doi_uas_report_relationship_of_fire_discovery_times_on_timeliness_of_aerial_firefighting_support_2017_0712.pdf [Accessed: June 03, 2024]

[5] Executive Office of the President President's Council of Advisors on Science and Technology. (2023, February). REPORT TO THE PRESIDENT Modernizing Wildland Firefighting to Protect Our Firefighters. [Online]. Available: https://www.whitehouse.gov/wp-content/uploads/2023/02/PCAST_Wildfires-Report_Feb2023.pdf

[6] USDA, "Biden-Harris Administration Invests Nearly $200 Million in Bipartisan Infrastructure Law and Inflation Reduction Act Funding for Wildfire Risk Reduction," Mar. 20, 2023 [Online]. Available: https://www.usda.gov/media/press-releases/2023/03/20/biden-harris-administration-invests-nearly-200m-bipartisan [Accessed: June 03, 2024]

[7] Congress.gov. (2019). S.47 - John D. Dingell, Jr. Conservation, Management, and Recreation Act. [Online]. Available: https://www.congress.gov/bill/116th-congress/senate-bill/47/text [Accessed: June 03, 2024]

[8] DOI Office of Aviation Services. (2019). OAS Information Paper - Previous UAS Work and Accomplishments Related to Section 1114 - Wildland fire Technology Modernization of the John D. Dingell Jr Conservation, Management, and Recreation Act. [Online]. Available: https://www.doi.gov/sites/doi.gov/files/uploads/oas_information_paper_previous_uas_work_and_accomplishments_related_to_section_1114_-_wildfire_technology_modernization_of_the_john_d_dingell_jr_conservation_management_and_recreation_act.pdf [Accessed: June 03, 2024]

[9] National Interagency Mobilization Guide. (n.d.). [Online]. Available: https://www.nifc.gov/sites/default/files/NICC/3-Logistics/Reference%20Documents/Mob%20Guide/Mobilization_Guide.pdf [Accessed: June 03, 2024]

[10] Interagency Standards for Fire and Fire Aviation Operations (aka the Red Book). (n.d.). [Online]. Available: https://www.nifc.gov/standards/guides/red-book [Accessed: June 03, 2024]

[11] Bell, D. G., Kuehnel, F., Maxwell, C., Kim, R., Kasraie, K., Gaskins, T., Hogan, T., & Coughlan, J. (2007). NASA World Wind: Opensource GIS for mission operations. In 2007 IEEE Aerospace Conference (pp. 1-9). IEEE.

[12] U.S. National Aeronautics and Space Administration (NASA), What is STEReO (Scalable Traffic Management for Emergency Response Operations)? - NASA [Online]. Available: https://www.nasa.gov/centers-and-facilities/ames/what-is-scalable-traffic-management-for-emergency-response-operations/ [Accessed: June 03, 2024].

[13] Code of Federal Regulations (CFR). "14 CFR Part 107 - Small Unmanned Aircraft Systems." [Online]. Available: https://www.ecfr.gov/current/title-14/chapter-I/subchapter-F/part-107?toc=1. [Accessed: June 03, 2024]

[14] Kopardekar, P., Rios, J., Prevot, T., Johnson, M., Jung, J., & Robinson, J. E. (2016). Uncrewed aircraft system traffic management (UTM) concept of operations. In AIAA Aviation and Aeronautics Forum (Aviation 2016).

[15] Jung, J., Rios, J. L., Xue, M., Homola, J., & Lee, P. U. (2022). Overview of NASA's Extensible Traffic Management (xTM) Research. In AIAA SCITECH 2022 Forum (p. 1916).

[16] National Interagency Fire Center, "National Incident Radio Support Cache Basic Radio Operation Training," National Interagency Fire Center Document, [Online]. Available: https://www.nifc.gov/sites/default/files/NIICD/docs/Printable%20NIRSC%20Basic%20Wildland%20Fire%20Radio%20Training.pdf. [Accessed: June 11, 2024].

[17] A. Sharma, P. Vanjani, N. Paliwal, C. M. W. Basnayaka, D. N. K. Jayakody, H. C. Wang, and P. Muthuchidambaranathan, "Communication and networking technologies for UAVs: A survey," *Journal of Network and Computer Applications*, vol. 168, p. 102739, 2020.

[18] P. S. Bithas, V. Nikolaidis, A. G. Kanatas, and G. K. Karagiannidis, "UAV-to-ground communications: Channel modeling and UAV selection," *IEEE Transactions on Communications*, vol. 68, no. 8, pp. 5135-5144, Aug. 2020.

[19] B. Li, Z. Fei, and Y. Zhang, "UAV communications for 5G and beyond: Recent advances and future trends," *IEEE Internet of Things Journal*, vol. 6, no. 2, pp. 2241-2263, Apr. 2018.

[20] G. K. Kurt et al., "A vision and framework for the high altitude platform station (HAPS)

[21] Starlink. Starlink. [Online]. Available: https://www.starlink.com/. [Accessed: June 11, 2024].

[22] Storymaps, "DART on the Tamarack Fire." [Online]. Available: https://storymaps.arcgis.com/collections/c193360ddf124e5e9ad70b344d40eb14?item=1. [Accessed: June 03, 2024]

[23] Storymaps, "DART on the Caldor Fire." [Online]. Available: https://storymaps.arcgis.com/collections/c193360ddf124e5e9ad70b344d40eb14?item=2.

[24] goTenna. "goTenna." [Online]. Available: https://gotenna.com/. [Accessed: June 11, 2024].

[25] Beartooth. "Beartooth MK II radios." [Online]. Available: https://gotenna.com/. [Accessed: June 11, 2024].

[26] Interagency Data Management Environment (IDME). (n.d.). [Online]. Available: https://www.wildfire.gov/application/idme-interagency-data-management-environment [Accessed: June 03, 2024]

[27] DOI Office of Aviation Services, "Optionally Piloted Helicopters - A Primer On A Potentially Game-Changing Technology That Promises To Save Lives, Property, And Money In Wildland Fire," [Online]. Available: https://www.doi.gov/sites/doi.gov/files/uploads/doi_uas_background_info_paper_gamechanger_the_promise_of_optionally-piloted_helicopters_in_wildland_fire_08_2018.pdf [Accessed: June 03, 2024]

[28] E. E. Papadopoulou, C. Vasilakos, N. Zouros, and N. Soulakellis, "DEM-based UAV flight planning for 3D mapping of geosites: The case of olympus tectonic window, Lesvos, Greece," *ISPRS International Journal of Geo-Information*, vol. 10, no. 8, p. 535, 2021.

[29] P. Pradeep, A. A. Munishkin, K. M. Kalyanam, and H. Erzberger, "Strategic deconfliction of small uncrewed aircraft using operational volume blocks at crossing waypoints," in *AIAA SCITECH 2023 Forum*, 2023, p. 1654.

[30] P. Pradeep, C. S. Kulkarni, G. B. Chatterji, and T. A. Lauderdale, "Parametric Study of State-of-Charge for an Electric Aircraft in Urban Air Mobility," in *AIAA Aviation 2021 Forum*, 2021, p. 3181.

[31] Consiglio, M., Duffy, B. J., Balachandran, S., Glaab, L., & Munoz, C. (2019). Sense and avoid characterization of the independent configurable architecture for reliable operations of uncrewed systems. In USA/Europe Air Traffic Management Research and Development Seminar (ATM2019).

[32] NASA. (n.d.). Technology Readiness Levels. [Online]. Available: https://www.nasa.gov/directorates/somd/space-communications-navigation-program/technology-readiness-levels/ [Accessed: June 03, 2024]

[33] National Aeronautics and Space Administration, "NASA Systems Engineering Handbook," Sep. 2018 [Online]. Available: https://www.nasa.gov/wp-content/uploads/2018/09/nasa_systems_engineering_handbook_0.pdf. [Accessed: June 11, 2024].