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THE NEXT GENERATION OF WILDLAND FIREFIGHTING TOOLS: USING UAV SWARMS FOR FIRE ATTACK

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THE NEXT GENERATION OF WILDLAND FIREFIGHTING TOOLS: USING UAV SWARMS FOR FIRE ATTACK

by

Robert C. Hutchens

March 2022

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Wildland fires pose a direct threat to homeland security because of the severe personal, economic, and social stress they cause to those affected. As unmanned aerial vehicle (UAV) swarms become more ubiquitous in use, they will likely find a place as a frontline firefighting aerial asset, increasing the operational pace of aerial suppression flights and consequently increasing the safety of firefighters. This thesis explored the concept of using UAV swarms as a method for fire attack by comparing theoretical swarms to a conventional aerial asset within a realistic fire scenario and then using a systems engineering approach to define pressure points for implementing UAV swarms in the wildland space. The findings of this research support continued development of UAV swarms and clearly define areas that must be addressed before implementing large-scale UAV swarm flights. The firefighting UAV swarm system shows great promise due to its relative portability and ability to provide an aerial firefighting option to areas without ready access to conventional firefighting aircraft. It will be critical, however, to address logistical and communications constraints of UAV swarm systems before implementation to ensure positive outcomes.

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THE NEXT GENERATION OF WILDLAND FIREFIGHTING TOOLS: USING UAV SWARMS FOR FIRE ATTACK

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Submitted in partial fulfillment of the
requirements for the degree of

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ABSTRACT

Wildland fires pose a direct threat to homeland security because of the severe personal, economic, and social stress they cause to those affected. As unmanned aerial vehicle (UAV) swarms become more ubiquitous in use, they will likely find a place as a frontline firefighting aerial asset, increasing the operational pace of aerial suppression flights and consequently increasing the safety of firefighters. This thesis explored the concept of using UAV swarms as a method for fire attack by comparing theoretical swarms to a conventional aerial asset within a realistic fire scenario and then using a systems engineering approach to define pressure points for implementing UAV swarms in the wildland space. The findings of this research support continued development of UAV swarms and clearly define areas that must be addressed before implementing large-scale UAV swarm flights. The firefighting UAV swarm system shows great promise due to its relative portability and ability to provide an aerial firefighting option to areas without ready access to conventional firefighting aircraft. It will be critical, however, to address logistical and communications constraints of UAV swarm systems before implementation to ensure positive outcomes.

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LIST OF ACRONYMS AND ABBREVIATIONS

AGL	above ground level
AI	artificial intelligence
ARSENL	Advanced Robotics Systems Engineering Laboratory
BVLOS	beyond the visual line of site
COA	certificate of authorization
DHS	Department of Homeland Security
FAA	Federal Aviation Administration
GPS	global positioning system
HQ	headquarters
ICS	Incident Command System
LAT	large air tanker
MAFFS	Modular Airborne Firefighting System
MBSE	model-based system engineering
NATO	North Atlantic Treaty Organization
NICC	National Interagency Coordination Center
NPS	Naval Postgraduate School
NTSB	National Transportation Safety Board
NWCG	National Wildfire Coordinating Group
ODF	Oregon Department of Forestry
OSFM	Office of the State Fire Marshal
POSE	position and orientation
SEAT	single-engine air tanker
UAV	unmanned aerial vehicle
UGV	unmanned ground vehicle
USFS	United States Forest Service
VLAT	very large air tanker

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EXECUTIVE SUMMARY

Wildland fires pose a clear and present danger to American homeland security because of the impact on natural resources, decreased economic stability for people who make their living from the forest products industry, loss of property and homes, and potential loss of life. It is critical to take the threat of wildland fires seriously and seek to implement technological advances that increase safety and security. The next significant advance in wildland firefighting tactics may be using swarms of unmanned aerial vehicles (UAVs) to perform fire attacks on wildland fires.

With trends of increased global warming and longer fire seasons, it is critical to foster innovation in the arena of wildland firefighting to ensure maximal impact by firefighting forces while simultaneously increasing the safety of firefighters. In a retrospective study, Butler found that from 2000 to 2013, 78 deaths of wildland firefighters, or 26.2 percent, were related to aviation.[1] The National Interagency Fire Center reports that over the past 10 years, "there were an average of 62,693 wildfires annually and an average of 7.5 million acres impacted annually."[2] The National Fire Protection Agency estimates that the annual cost to suppress wildland fires is now $1.6 billion annually.[3] Despite all of these facts, the availability of resources to combat these fires has remained essentially the same over those years.[4] With the threat of wildland fire exposing citizens to property loss, high monetary costs for suppression, and potential loss of life, exploring UAV-based fire suppression is warranted at this time. UAV swarms may perform the critical task of aerial fire suppression more efficiently and more effectively than current aerial assets.

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[1] Corey R. Butler, Mary B. O'Connor, and Jennifer M. Lincoln, "Aviation-Related Wildland Firefighter Fatalities—United States, 2000–2013," *Morbidity & Mortality Weekly Report* 64, no. 29 (2015): 793, https://doi.org/10.15585/mmwr.mm6429a4.

[2] Katie Hoover and Laura A. Hanson, *Wildfire Statistics*, CRS Report No. IF10244, version 49 (Washington, DC: Congressional Research Service, January 2021), 1, https://crsreports.congress.gov/product/pdf/IF/IF10244/49.

[3] Jesse Roman, Angelo Verzoni, and Scott Sutherland, "The Wildfire Crisis: Greetings from the 2020 Wildfire Season," *NFPA Journal*, November/December 2020, http://www.nfpa.org/News-and-Research/Publications-and-media/NFPA-Journal/2020/November-December-2020/Features/Wildfire.

[4] Hoover and Hanson, *Wildfire Statistics*, 1.

UAV swarms are semi-autonomous groups of aerial vehicles deployed under specific parameters to complete a mission. The aircraft are assisted in launching and recovering by a human controller but are then allowed to complete a mission within specific parameters. UAV swarms could prove to be quick-to-deploy aerial assets to find and suppress fires before ground forces arrive. The utilization of UAV swarms for fire suppression operations can increase safety for firefighters and the public by keeping fires small and manageable, providing early detection and suppression of wildland fires, and freeing up traditional aerial assets for deployment on critical fires.

Using conventional fixed- and rotary-wing aircraft to suppress fires has limitations, namely, the aircraft's inability to fly in heavy smoke conditions, weather events, and the darkness of night. Flying aircraft in an uncontrolled environment close to an active wildland fire allows for no margin of error, and the results can be catastrophic. The utilization of UAVs and UAV swarms could allow for a higher operational pace due to their ability to fly at night and in many conditions that crewed aircraft cannot. Committing to UAV swarms for aerial fire suppression might reduce the number of firefighter deaths from aerial accidents while keeping fires smaller and more manageable.

This thesis aimed to answer the question of how emerging UAV swarm technology could be implemented as a method of fire attack in the wildland setting. The research design employed a three-pronged method. The first was a proof-of-concept methodology facilitated by participating in actual UAV swarm flight missions with the Advanced Robotics Systems Engineering Laboratory (ARSENL) and the Consortium for Robotics and Unmanned Systems Education and Research groups at the Naval Postgraduate School. We flew swarms of multiple types of UAVs and integrated unmanned ground vehicles into the swarms during testing. Practical testing informed the feasibility for deployment of UAV swarms in the wildland space and highlighted issues that must be addressed before full deployment.

The second methodology was a comparative analysis performed between a 50-aircraft UAV swarm and conventional single-engine air tanker (SEAT) aircraft, attacking a theoretical fire. This analysis allowed for a comparison of the UAV swarm and the conventional aircraft in attacking a fire over a specific time. The metrics included the amount of suppression agent dropped and the projected cost of operating each asset. This information was used to complete a cost comparison between the UAV swarm and the traditional aircraft. Finally, the Innoslate 4 (V 4.5.1.0) model-based systems engineering software and modeling system was employed to model the flight scenarios for the UAV swarm and the air tanker using accurate flight, refuel, and reload cycle times. These flight scenarios allowed for (a) identification of pressure points of implementation, (b) an understanding of the limitations and benefits of UAV swarms and SEAT aircraft, and (c) identification of the critical relationships between UAV swarm operations and the ground support personnel necessary to ensure successful missions.

As a result of this research, it is believed that UAV swarms can critically contribute to aerial fire suppression in the wildland setting. UAV swarms show great promise through their relative portability and their limited barriers to entry for fire protection districts. While a swarm of 50 UAVs may not be feasible for every forest protection district, having access to even a few firefighting UAVs could keep low- to moderate-intensity fires in check until ground forces can attack them. However, before that occurs, many pressure points must be addressed to fully implement UAV swarm-based fire suppression. Some of those issues include developing and implementing clear policies and procedures for flying UAV swarms, reviewing current Federal Aviation Administration rules regarding UAV swarm operations, developing logistical best practices to support UAV swarm operations, and ensuring positive communication links to guarantee complete control of UAV swarms. Finally, should the United States embrace the concept of using UAV swarms for both wildland firefighting and other commercial operations, it is critical to support UAV and UAV swarm infrastructure and UAV-specific education focusing on building, programming, and operation.

The concept of using UAV swarms in the wildland environment has definite value for increasing the safety and productivity of firefighting operations. While there are hurdles to overcome, the future of wildland firefighting will heavily involve UAV swarms. It is expected that multiple operators will seek to move to the forefront of UAV swarm building and operations both as a business opportunity and an opportunity to assist in combating an increasing wildland fire problem. While it is unlikely that UAV fire suppression will supplant conventional aerial firefighting soon, the ability to use UAV swarms as another aerial firefighting tool, especially during the night when conventional aircraft do not fly, should offer fire managers yet another means of mitigating fires quickly and more safely.

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I must first acknowledge the sacrifice that my family—Lenika and Flynn—has made in allowing me to pursue this graduate degree. It was only through their continued support and willingness to allow me the time to complete this thesis that it came to fruition. The completion of this degree is a testament to our family's belief in higher education.

United States Navy Commander Kathleen Giles, PhD, acted as my advisor for this project, bringing her wealth of knowledge of swarm operations through the ARSENL group and as a systems engineer. I would not have achieved the deep understanding of UAV swarm operations and infrastructure without her willingness to assist in this journey. I appreciate your work and your willingness to assist a firefighter from Oregon in trying to understand the complex nature of this project.

I must thank members of CHDS Cohort 2005/2006. As my family dealt with some unexpected issues during this program, they supported me and my family and kept me on track through an extremely challenging time. Finally, I must thank the DC Basement group, who would not allow COVID to derail our in-residence time together by gathering on our own both in Washington, DC, and Santa Cruz, California. Your support kept me in the program. I appreciate you all.

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I. INTRODUCTION

The next significant advance in wildland firefighting tactics may be using swarms of unmanned aerial vehicles (UAVs) to perform fire attacks on wildland fires before they burn out of control. Swarms are autonomous teams of UAVs deployed under specific parameters to complete a mission. Swarms of UAVs are permitted to make autonomous and cooperative decisions within the mission parameters while under supervisory control by a single operator. This ability contrasts with current UAV operations, which require a pilot for each aircraft. The utilization of UAV swarms for fire suppression operations has the potential to increase safety for firefighters and the public, provide early detection and suppression of wildland fires, and free up traditional aerial assets for deployment on critical fires.

A. MOTIVATION FOR RESEARCH

Wildland fires pose a clear and present danger to American homeland security because of the impact on natural resources, decreased economic stability for people who make their living from the forest products industry, loss of property and homes, and potential loss of life. The danger that large-scale wildland fires represent is so severe that fire managers must attempt to suppress them using all available tactics, including direct and indirect fire-attack methods. These techniques require placing firefighters in harm's way to slow or stop the fire progression. Between 2010 and 2019, 134 firefighters were killed in the line of duty while battling wildland fires.[1] The National Interagency Fire Center reports that over the past 10 years, "there were an average of 62,693 wildfires annually and an average of 7.5 million acres impacted annually."[2] However, the availability of resources to combat these fires remained the same over those years.[3] With

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[1] Department of Homeland Security et al., *Firefighter Fatalities in the United States in 2019* (Emmitsburg, MD: U.S. Fire Administration, 2020), 9, https://www.nfpa.org/-/media/Files/News-and-Research/Fire-statistics-and-reports/Emergency-responders/FFF-2020.ashx.

[2] Katie Hoover and Laura A. Hanson, *Wildfire Statistics*, CRS Report No. IF10244, version 49 (Washington, DC: Congressional Research Service, January 2021), 1, https://crsreports.congress.gov/product/pdf/IF/IF10244/49.

[3] Hoover and Hanson, 1.

trends of increased global warming and longer fire seasons, it is critical to foster innovation in the arena of wildland firefighting to ensure maximal impact by firefighting forces while simultaneously increasing the safety of firefighters.

1. Augmenting Firefighting Tactics with Swarm Technology

The concept of using single UAVs to assist in intelligence collection on wildland fires is familiar territory. For most large wildland fires, single UAVs may be used to observe the location and movement of the fire or monitor a fire that has escaped control lines. The intelligence produced by UAVs becomes a critical factor in fire prediction and operational planning for the upcoming operational periods. However, UAVs have not been deployed for direct fire-suppression activities, nor have swarms of UAVs been deployed on wildland fires. Swarm technology is in its infancy and will need additional development to be a viable option to apply to suppression operations.

The term "UAV swarm" refers to multiple UAVs operated by one controller. A controlled swarm is a team of UAVs programmed for a specific mission, operated by a single controller. A semi-autonomous swarm is a team of UAVs assisted by a controller to launch and recover. The semi-autonomous swarm has specific mission parameters whereby it can identify a mission, decide which members will complete the mission, complete the mission, and recover to a base station while deconflicting among the members to ensure successful completion.[4]

The notion of using single UAVs for direct fire attacks has neither been significantly explored nor studied due to the necessity of placing a large suppression payload of water or retardant on the fire. However, with the potential of UAV swarm technology that allows many smaller payloads to be placed on station and the advancement of heavy-lift UAV systems that carry as much as 100 pounds, swarms of many UAVs may be effective in suppressing fires. Using a UAV swarm rather than one traditional aircraft

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[4] Moulay A. Akhloufi, Nicolás A. Castro, and Andy Couturier, "UAVs for Wildland Fires," in *Proceedings of SPIE Defense and Security*, ed. Michael C. Dudzik and Jennifer C. Ricklin, vol. 10643, *Autonomous Systems: Sensors, Vehicles, Security, and the Internet of Everything* (Bellingham, WA: International Society for Optics and Photonics, 2018), M9, https://doi.org/10.1117/12.2304834.

could be the next dramatic advance in wildfire suppression. The technology to perform this job is being developed, yet it is neither practical nor scalable at this time.

2. Wildland Fires Are Becoming More Prevalent and Destructive

Wildland fires must be viewed with a wide-angle lens as a homeland security issue. Many courses of action can be undertaken concurrently to decrease wildland fires' frequency, severity, and intensity. It will be necessary not to focus on one solution as a panacea to the wildland fire problem but rather to embrace innovation and technology to meet the challenge of decreasing these destructive fires.

Wildland fires directly threaten U.S. homeland security due to large fires' extreme economic, social, and emotional impact. The cost to combat these fires continues to increase in monetary expenditures and human costs, both in the lives of firefighters and citizens who have succumbed to wildland fires. The National Fire Protection Agency estimates that the annual cost to suppress wildland fires is now $1.6 billion annually.[5] Historically, there has been a designated "fire season"; however, large-loss wildland fires happen in all months of the year, causing some western states to abandon the notion of a fire season.[6]

As wildland fires continue to present challenges for firefighters and those living in the urban–wildland interface, exploring more efficient and cost-effective methods of combating these destructive fires becomes critical. One cannot escape the fact that global warming is changing the susceptibility of forests to burn more readily. These tinder-dry conditions have created situations in which multiple lives have been lost because the fire progressed at such a rapid rate. A clear example is the Camp Fire in California in 2018, where 85 people lost their lives, and 18,804 structures were lost, primarily in the first five

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[5] Jesse Roman, Angelo Verzoni, and Scott Sutherland, "The Wildfire Crisis: Greetings from the 2020 Wildfire Season," *NFPA Journal*, November/December 2020, http://www.nfpa.org/News-and-Research/Publications-and-media/NFPA-Journal/2020/November-December-2020/Features/Wildfire.

[6] "2021 Incident Archive," Cal Fire, accessed January 14, 2022, https://www.fire.ca.gov/incidents/2021/.

hours of the fire.[7] A more recent example is the Marshall Fire outside of Denver, Colorado, on December 30, 2021, where two people lost their lives, and 991 structures were lost in just a few hours. This fire was fueled by dry conditions and winds of more than 90 miles per hour.[8] Exacerbating these fires is the fact that there are limited resources to combat them in terms of personnel, aircraft, and funds to hire additional assistance. Scarcity of resources has become a significant problem, especially during the heart of fire season when multiple fires are burning and expanding rapidly. During the last few fire seasons, there were times when there simply were not enough resources to commit to firefighting. Fire managers must make difficult decisions to write off sometimes thousands of acres or hundreds of homes when that happens.

3. Global Warming and the Threat to the Wildland

What were previously believed to be unprecedented fires and fire behavior have become commonplace seemingly every summer. Global warming significantly impacts the wildland environment, creating hotter and dryer climates that perpetuate fire growth. Current and legacy policies of where, how, and when fires are suppressed have increased the fuel loading of American forests. It will take decades for forest management policies to catch up to the current fuel load in American forests.[9] Global warming and climate change initiatives may take decades to impact forests positively. According to the Insurance Information Institute, approximately 10.1 million acres burned in the United States in 2020, and U.S. homes at high or extreme risk of wildfire totaled 4.5 million.[10]

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[7] Alexander Maranghides et al., *A Case Study of the Camp Fire—Fire Progression Timeline*, NIST Technical Note 2135 (Gaithersburg, MD: National Institute of Standards and Technology, 2021), 3, https://doi.org/10.6028/NIST.TN.2135.

[8] Kyle Cooke, "'A Horrific Event': 991 Structures Destroyed, Three Missing in Marshall Fire," Rocky Mountain PBS, December 30, 2021, https://www.rmpbs.org/blogs/news/superior-louisville-grass-fire-colorado-evacuations/.

[9] Lee E. Frelich and Peter B. Reich, "Will Environmental Changes Reinforce the Impact of Global Warming on the Prairie–Forest Border of Central North America?," *Frontiers in Ecology and the Environment* 8, no. 7 (September 2010): 371, https://doi.org/10.1890/080191.

[10] Cal Fire, "Facts + Statistics: Wildfires," Insurance Information Institute, accessed October 26, 2021, https://www.iii.org/fact-statistic/facts-statistics-wildfires.

It is essential to acknowledge the negative impact of global warming and climate change on the wildland environment. The most significant effect global warming has on forests is drought and higher average daily temperatures. These higher temperatures have two significant effects on vegetation. The first is creating lower long-term fuel moistures (taking moisture out of the fuel). The second creates a vapor pressure deficit within the environment (taking the moisture out of the air), making the vegetation more susceptible to fire.[11] The drier the fuel, the more susceptible it is to ignition when exposed to heat. Both climate change effects work in conjunction to dry fuels and then keep them dry.

The second impact of global warming is the erratic weather patterns that climate change fosters, bringing large amounts of rain during the rainy season and hotter and drier conditions in the summer months.[12] The rain propagates the growth of light vegetation in the spring, increasing the overall fuel load. When the hotter, drier summer months arrive, the new growth is susceptible to drying. This vegetation is now “cured” and ready to carry a fire, especially when exposed to wind. The fuel volume increases for the next fire season if the vegetation does not burn that season. The weather patterns that global warming influences have an exponential impact on wildland fires by first increasing the fuel load and then severely drying the areas, making them more susceptible to fire.[13] Forest management policies of allowing heavy undergrowth to accumulate have created conditions within the forest environment that promote fires to burn hotter, faster, and more intensely.[14] The failure to act on global warming initiatives and little prescribed burning have created unhealthy forest ecosystems.

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[11] Robinson Meyer, “The Most Important Number for the West’s Hideous Fire Season,” *Atlantic*, September 15, 2020, https://www.theatlantic.com/science/archive/2020/09/most-important-number-for-the-wests-wildfires-california/616359/.

[12] A. Park Williams et al., “Observed Impacts of Anthropogenic Climate Change on Wildfire in California,” *Earth’s Future* 7, no. 8 (2019): 894, https://doi.org/10.1029/2019EF001210.

[13] “Climate Change Indicators: Wildfires,” Environmental Protection Agency, accessed March 9, 2022, https://www.epa.gov/climate-indicators/climate-change-indicators-wildfires.

[14] Courtney A. Schultz, Matthew P. Thompson, and Sarah M. McCaffrey, “Forest Service Fire Management and the Elusiveness of Change,” *Fire Ecology* 15, no. 1 (2019): 2, https://doi.org/10.1186/s42408-019-0028-x.

The ability to accurately define what is contributing to global warming and climate change specific to their effects on wildland fire will continue to attract public attention for years to come. The effects of global warming are on display every year with the large wildfires that burn in the western United States and other parts of the globe. These large fires will require fire managers to embrace technology and policies that can potentially limit the growth of future fires. Moritz notes that the national understanding of the role of wildfire in global warming is changing. He states that between 2003 and 2007, the question typically asked during large wildland fires was "Who is to blame here?" Conversely, now the question asked is, "Are these fires due to climate change?"[15] Perhaps recognizing that wildfires are an extreme result of global warming will influence policies that positively impact global climate change.

4. Utilization of Aerial Assets in the Wildland Environment

With the threat of wildland fire exposing citizens to potential loss of life, high monetary costs for suppression, and the emerging potential from other fields of UAV study, exploring UAV-based fire suppression is warranted at this time. It is essential to understand the role of aircraft in fighting wildland fires. Using firefighting helicopters and fixed-wing airplanes has become an integral part of the current overall fire suppression plan, especially on large, fast-moving wildland fires. In general, fire managers use aircraft to leverage their speed and ability to quickly put out a fire before it expands to a significant fire. Rarely, if ever, are aircraft able to suppress a fire entirely. It ultimately takes the firefighters on the ground to fully contain wildland fires. Essentially, aircraft are used to "buy time" for other firefighting forces to be obtained and deployed.

However, using aircraft is an extremely costly method of fighting fires. The U.S. Forest Service (USFS) establishes contract rates for aircraft by type and ability. During the contracting period between 2018 and 2021, Type 1 helicopters (the most powerful and capable of dropping the most water) were contracted at rates between $4,000 and $8,000

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[15] Max A. Moritz, "Wildfires Ignite Debate on Global Warming," *Nature* 487, no. 7407 (2012): 273, https://doi.org/10.1038/487273a.

per flight hour, depending on the aircraft type.[16] Costs for fixed-wing retardant-dropping aircraft can be between $7,100 and $13,500 per flight hour, not including the retardant cost.[17] The USFS spent "approximately $607 million on contract aircraft in 2018," including rotor and fixed-wing aircraft.[18] In an era of tight budgets, one must consider the cost-effectiveness of using aircraft to fight fires. If using UAVs to suppress fires can prove less costly and as effective as—or even more effective than—traditional aerial assets, the utilization of UAVs should be explored in depth.

Employing both fixed- and rotary-wing aircraft to suppress fires has limitations, namely, the aircraft's inability to fly in heavy smoke conditions, weather events, the darkness of night, limitations on pilot flight hours, a limited and specialized group of people who can pilot these aircraft, and the inaccessibility of aircraft during required maintenance. Flying aircraft in an uncontrolled environment close to an active wildland fire allows for no margin of error, and the results can be catastrophic. A significant number of firefighters have been killed in aircraft accidents while engaged in fire suppression operations. In a retrospective study, Butler, O'Connor, and Lincoln found that from 2000 to 2013, 78 deaths of wildland firefighters, or 26.2 percent, were related to aviation.[19] In such cases, highly skilled firefighters and pilots are lost, and the airframe they are flying is usually destroyed. While fire managers seek to minimize risk for firefighters and aircrews, unfortunately, placing men and women in harm's way to slow or stop a wildland fire remains an effective tactic.

UAVs and UAV swarms may replace crewed aerial assets for fire identification and direct fire suppression in the coming years. The utilization of UAVs and UAV swarms

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[16] "Helicopter Services Hourly Flight Rates, Fuel Consumption, and Weight Reduction Chart," U.S. Forest Service, February 16, 2019, https://www.fs.usda.gov/sites/default/files/media_wysiwyg/flt_chrt_awarded_2018-2021.pdf.

[17] "FAQs–Austin Airtanker Base," Texas A&M Forest Service, accessed January 13, 2022, https://tfsweb.tamu.edu/uploadedFiles/TFSMain/Preparing_for_Wildfires/Contact_Us(4)/FAQs-updated%20July%2019.pdf.

[18] U.S. Forest Service, *Aviation Annual Report 2020* (Washington, DC: U.S. Forest Service, 2021), 7, https://www.fs.usda.gov/sites/default/files/2021-06/CY2020_USFSAviationReport_Final_1.pdf.

[19] Corey R. Butler, Mary B. O'Connor, and Jennifer M. Lincoln, "Aviation-Related Wildland Firefighter Fatalities—United States, 2000–2013," *Morbidity & Mortality Weekly Report* 64, no. 29 (2015): 793, https://doi.org/10.15585/mmwr.mm6429a4.

allows for a higher operational pace due to their ability to fly at night and in multiple conditions that crewed aircraft cannot. Additionally, UAVs can theoretically fly missions for a full 24 hours and are constrained only by required maintenance, rest requirements for pilots, and fire conditions that are so severe they do not allow for flight operations. Committing to UAVs and UAV swarms could potentially reduce the number of firefighter deaths from aerial accidents and keep fires smaller and more manageable.

B. RESEARCH QUESTION

How can emerging UAV swarm technology be implemented as a method of fire attack in the wildland setting?

C. METHODOLOGY AND RESEARCH DESIGN

This thesis explores how UAV swarms could be a novel approach to direct fire-attack operations by suppressing or retarding a fire from growing beyond the incipient phase, allowing conventional firefighting forces time to arrive, control, and suppress the fire before it grows to a significant wildland fire. A proof-of-concept methodology was used by participating in actual UAV swarm flight missions with the Advanced Robotics Systems Engineering Laboratory (ARSENL) and the Consortium for Robotics and Unmanned Systems Education and Research groups at the Naval Postgraduate School. These flights informed the validity of scenario studies used to develop missions with practical applications in the wildland setting. Practical testing informed the possibility of deployment and highlighted issues that must be addressed before full deployment. Additionally, we analyzed current utilization models of commercial UAV swarm users to define their applications in relation to their potential integration into wildland firefighting operations.

To illustrate the potential value of UAV swarms for direct fire attacks, this thesis utilized a theoretical fire in the Tillamook State Forest in western Oregon. The fire is “attacked” using both a 50-aircraft UAV swarm and a single-engine, fixed-wing air tanker. The single-engine air tanker (SEAT) is a conventional aircraft traditionally used to attack the fire. A comparative analysis was performed between a UAV swarm and conventional SEAT aircraft attacking this fire. Innoslate 4 (V 4.5.1.0), the Department of Defense

Architectural Framework–compliant systems engineering modeling software, was employed to model the flight scenarios for the UAV swarm and the air tanker using accurate flight, refuel, and reload cycle times. For comparison, the flights were constrained by one normal fuel cycle of the SEAT. The fire attack methods were compared through the lenses of the total firefighting product delivered and comparative cost per gallon dropped for both resources. This information led to conclusions about the viability of using UAV swarms as firefighting assets either in place of or as adjunct to conventional aerial firefighting equipment. Finally, current aerial wildland firefighting methods were analyzed quantitatively, focusing explicitly on the cost of using conventional fixed-wing aircraft versus swarm technology against the theoretical fire. Through comparative analysis and practical testing, a theoretical deployment model was built, addressing concerns of stakeholders and the potential of performing UAV swarm operations as a commercial operation.

D. RESEARCH OBJECTIVES

- Examine the feasibility of utilizing UAV swarms for wildland firefighting.
- Identify how UAV swarms may be applied to wildland firefighting.
- Identify current UAV swarm applications specific to the military that could be adapted to wildland firefighting.

E. CHAPTER OVERVIEW

This thesis is heavily influenced by the personal experience of firefighters in the urban–wildland interface. Chapter I discussed the motivation of this research and its criticality. Wildland firefighting is a highly specialized field that brings its own language and jargon, so Chapter II defines background information about wildland firefighting and introduces terms relevant to understanding this thesis. Chapter III addresses academic literature relevant to the thesis topic and the research question. In Chapter IV, methodologies for comparative analysis are described and explained. As there is limited research on swarm technology, Chapter IV delineates given assumptions and constraints within the analysis. It also relies heavily on the Innoslate 4 systems engineering software to graphically illustrate the process of fighting the fire. The results of our experimentation and modeling are presented at the end of the chapter. Chapter V discusses the results of the comparative analysis between a traditional fixed-wing air tanker and a flight of 50 UAVs in a swarm. From this comparative analysis, recommendations were devised for UAV swarm implementation in the future. Chapter VI reviews the conclusions and recommends follow-on research to further develop the topic of UAV swarm use in the wildland environment. The research should enhance the viability of using UAV swarms for direct fire attack. While the practical application of this technology and research may be years in the future, these findings should provide a place for future researchers to start.

II. BACKGROUND

Suppressing fires has changed little in the past 60 years. Suppression of wildland fires may be through one of two methods: direct and indirect attack. First, in a direct fire attack, firefighters are positioned on the fire line, either directly in front of or on the fire's flanks, using tools and hose lines to suppress the fire with water to cool and interrupt the combustion process. Alternatively, in an indirect fire attack, firefighters and machines stop the fire's progression by denying the fire fuel by setting backfires, cutting lines using hand tools or bulldozers (creating fire breaks), and placing retardant in the path of the fire to slow or stop it.[20] Perhaps the most significant innovation in wildland fire suppression came in the late 1950s and early 1960s with the advent of aerial assets to drop water (direct attack) or fire-suppressing retardant (indirect attack) on fires or in advance of fires from the air to slow their progress. These methods do not replace but rather augment and multiply the force of ground firefighters to suppress a fire entirely. Fires are aggressively suppressed using direct and indirect fire attack methods to stop the fire from progressing from a small manageable fire to a sizable destructive conflagration. As fires grow more rapidly and become more destructive each year, it is critical to modify or augment fire response to maximize all available technologies and assets. This chapter provides background information on how, where, and why fires are fought and the criticality of technological innovation specific to wildland firefighting.

A. DECISION FACTORS FOR SUPPRESSION OPERATIONS

Both direct and indirect fire-attack techniques utilize physical assets, including ground and aerial forces in the form of personnel, fire engines, hand crews, helicopters, and fixed-wing aircraft. Each of these assets represents a cost and a risk for deployment. Fire managers must weigh the risk-benefit of each decision based on the expected outcome

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[20] Elena Ausonio, Patrizia Bagnerini, and Marco Ghio, "Drone Swarms in Fire Suppression Activities" (Cornell University arXiv, 2020), 1–2, https://arxiv.org/abs/2007.00883v2.

relative to the risk to exposed assets.[21] Wildland fires are heavily impacted by weather conditions, wildland topography, the remoteness and accessibility of the fire in relation to available road systems, and the sheer size of the overall incident. Based on the complexity, size, safety considerations, and accessibility of the fire, incident commanders determine the tactics employed to suppress the fire. A direct fire attack may be chosen if the fire is of low to moderate intensity. Fire managers are often required to trade acreage to be burned for time to obtain, set up, and deploy firefighting resources to stop the fire's progression. In this case, an indirect fire attack would be indicated. While it is desirable to aggressively attack every fire, keep it small, and limit its impact on firefighters, the public, and the environment, at times, the fire is too dangerous for firefighters to attack it.

When a fire starts in the wildland or the urban–wildland interface, the on-scene fire manager evaluates multiple variables and defines decision points. The fire's location and expected fire behavior within the fire area, current and predicted weather, availability of suppression assets, historical recognition of the fire behavior, and the danger that the fire represents to nature and the public are all factors that need considering.[22] Based on the perceived threat level to the forest, infrastructure, and personnel, fire managers may attempt to suppress the fire immediately, committing personnel to a direct attack operation. If only limited personnel and equipment are available, they may decide to fortify existing fire breaks using an indirect method of fire attack. An additional tactic may be to allow the fire to burn until it goes out naturally, or the threat of the fire to assets and infrastructure becomes such that resources are dedicated to suppressing it.

While most fires eventually require firefighters on the ground to suppress and contain them, one of the first actions that fire managers may take is to request an aerial asset to collect intelligence on the fire and begin to suppress or contain it. These assets are

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[21] Jeffrey G. Borchers, "Accepting Uncertainty, Assessing Risk: Decision Quality in Managing Wildfire, Forest Resource Values, and New Technology," *Relative Risk Assessments for Decision-Making Related to Uncharacteristic Wildfire*, ed. Larry L. Irwin and T. Bently Wigley, special issue, *Forest Ecology and Management* 211, no. 1 (June 2005): 36–46, https://doi.org/10.1016/j.foreco.2005.01.025.

[22] Thomas Zimmerman, "Wildland Fire Management Decision Making," *Journal of Agricultural Science and Technology* B, no. 2 (2012): 171–72, https://www.nrfirescience.org/sites/default/files/Zimmerman_2012.pdf.

usually helicopters with water-dropping capabilities or fixed-wing aircraft with water- or retardant-dropping capabilities. Alternatively, fire managers may use UAVs to gain intelligence about the fire. However, UAVs cannot perform suppression operations. In an era of more people impacting the wildland environment by expanding homes into the urban interface and recreating in more remote locations, not to mention more severe weather events causing fires, the collection of intelligence and early suppression becomes increasingly essential.

Fires are managed first at the local level, then regionally, and finally nationally. Determining the severity of wildland fires is the responsibility of the National Interagency Coordination Center (NICC), located in Boise, Idaho. The NICC is the clearinghouse for firefighting assets in the United States, responsible for coordinating all available firefighting assets, including personnel, vehicles, aerial assets, and equipment.[23] These assets are apportioned daily by the NICC based on the importance and severity posed by each fire. Personnel and equipment are further apportioned starting at the local level until resources have been depleted, at which point requests for assistance are made both regionally and nationally. Depending on how a fire is fought, and the progress made fighting the fire, aerial assets are moved on a sometimes-daily basis to the most severe fires, where they can have a significant positive impact.

1. Direct Fire Attack

A direct fire attack is the preferred method of attacking fires if the goal is complete suppression, resulting in the smallest amount of acreage burned. In a direct attack tactic, water is placed directly on the fire using firefighters and hoses or aerial assets that drop water or retardant directly on the fire. The goal is to suppress the fire where it is, cooling the fire enough to extinguish it. For a direct attack to succeed, the fire must be of an intensity (low to moderate) conducive to getting physically close enough with personnel or aircraft to place water on the fire effectively. In general, fires with flame lengths of six feet

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[23] "About Us," National Interagency Coordination Center, accessed March 9, 2022, https://www.nifc.gov/nicc/about/about.htm.

or less are attacked directly.[24] A direct attack is the preferred method of fire attack in the initial operational period, defined as the first burning period of the fire, typically the first 12 to 24 hours. Initial attack fires are defined as those suppressed to completion, having burned fewer than 300 acres.[25] The USFS reports that approximately 97 percent of fires are suppressed at this limit. The safety of firefighters and the public is the most critical concern for the incident commanders to determine a fire attack tactic. If the fire is burning at such a high intensity as to be unsafe, a direct fire attack would not be appropriate.

The utilization of aerial assets for direct fire attacks has both positive and negative attributes that fire managers must consider. The most significant reason to use helicopters and aircraft to suppress fires is to leverage their speed of attack by quickly placing water or fire retardant on station. Theoretically, the faster a fire is attacked, the faster it can be brought under control, ultimately utilizing fewer assets, thus limiting its potential impact on the wildland environment.[26] However, there are limitations to using aerial assets, including the inability to fly in darkness, smoke, and extreme weather conditions and the inherent danger of flying aircraft low, slow, and under less-than-ideal conditions. To effectively place water or retardant on the fire, aircraft usually fly between 200 and 400 feet above the ground.[27] At these low altitudes, there is little margin for error. Aerial assets are expensive to deploy and maintain, in terms of cost of the airframe, time of flight, and the opportunity cost of not having the limited asset (aircraft) available to attack a more critical fire. Therefore, fire managers must constantly evaluate the desired and expected outcomes of using aerial assets versus the cost-benefit of deploying a scarce resource.

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[24] "Control Measure: Consider Appropriate Wildfire Suppression Tactics and Develop and Implement a Tactical Plan," National Fire Chiefs Council, accessed December 13, 2021, https://www.ukfrs.com/guidance/search/consider-appropriate-wildfire-suppression-tactics-and-develop-and-implement.

[25] Hari Katuwal et al., "Predict and Attack (or Don't): An Econometric Approach to Large Wildfire Early Detection and Suppression Effectiveness" (paper presented at the Annual Meeting of the Agricultural and Applied Economics Association, Washington, DC, August 5–7, 2018), 4.

[26] Katuwal et al., 1.

[27] "Aerial Firefighters & Fire Fighting: Dangerous but Effective?," Frontline Wildfire Defense, accessed March 9, 2022, https://www.frontlinewildfire.com/aerial-wildfire-fighting-how-effective-is-it/.

2. Availability of Aerial Assets

Surprisingly, the USFS does not own most aerial firefighting assets in the United States. For the 2021 fire season, there were only 18 large air tankers (LATs) (capacity of 3,000 gallons or more) committed for the entire United States, all operated by private contractors.[28] These aircraft are on "exclusive use" contracts and are available for immediate deployment in aerial firefighting for a contracted time during the year. The USFS ensures they are dedicated to firefighting operations and can be deployed quickly for direct attack fires. These air tankers are based all over the country but can quickly be redeployed when fires break out or weather conditions indicate a fire may be imminent. Five additional large tankers are on a "call when needed basis."[29] Call-when-needed aircraft are utilized after all the exclusive-use assets are assigned to fire duty. These aircraft must be recalled from whatever services they are performing for their owners and outfitted for firefighting operations, resulting in delayed response times. Eight military C-130 fixed-wing aircraft can be converted for firefighting using the Modular Airborne Firefighting System (MAFFS) and are considered large tankers.[30] The MAFFS units are composed of self-contained tanks, pressurization systems, and nozzles loaded onto military aircraft. The MAFFS units are owned by the USFS but are deployed by specially trained units of the U.S. military. When wildfires grow rapidly, multiple LATs are frequently assigned to a single fire. It is not uncommon for the United States to run out of LATs when multiple large fires are burning. It becomes incumbent on fire managers to deploy tanker assets effectively yet release assets not being maximally utilized.

Using helicopters rather than fixed-wing aircraft for a direct aerial attack may be more effective because more helicopters are available and generally dispersed across the country. However, helicopters are limited by the comparatively short flight time and range

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[28] Bill Gabbert, "Forest Service Has 18 Large Air Tankers This Year under Contract," Wildfire Today, March 9, 2021, https://wildfiretoday.com/2021/03/09/forest-service-has-18-large-air-tankers-this-year-under-contract/.

[29] "2021 U.S. Forest Service Airtankers: Schedule of Items," National Interagency Coordination Center, July 22, 2021, https://www.nifc.gov/nicc/logistics/aviation/Federal_Contract_Air_Tanker_List.pdf.

[30] Steven E. Dubay, "Improving Access to Military Aircraft during Civilian Wildfires" (master's thesis, Naval Postgraduate School, 2015), 94, http://hdl.handle.net/10945/47938.

compared to fixed-wing aircraft. Essentially, if the helicopter is not physically close to the fire, it is challenging to deploy in a direct attack role. In the 2020 fire season, there were 622 helicopters available to the USFS, with the vast majority of them on a call-when-needed contract—but none owned and operated by the USFS.[31] Of these 622 helicopters, only 213 were classified as Type 1 helicopters, with the ability to drop at least 700 gallons of water or retardant.[32] While this might seem like many aircraft to leverage, there were only 102 aircraft on exclusive-use contracts, meaning they were dedicated to firefighting operations and ready to respond at a moment's notice. The balance of the helicopters must be recalled from their current jobs, outfitted for firefighting, and flown to the fire or helibase. Speed of deployment is a critical factor in the early stages of a wildland fire respective to positive direct-attack outcomes. Due to their limited range, helicopters tend to be a very localized resource when utilized for direct attack operations.

The SEAT is an increasingly viable option for initial direct-attack operations. These are smaller, single-engine, single-piloted aircraft equipped with a turboprop engine, allowing for moderate loads of water or retardant to be dropped on the fire. The most common of these aircraft is the AT-802 made by Air Tractor. While purpose-built as a crop-dusting aircraft, it is easily configured for firefighting operations. This aircraft has a dumping capacity of 800 gallons of water or retardant and has a significant advantage in effective range compared to a Type 1 helicopter. Comparing the Kaman K-Max Type 1 helicopter (drop capacity of 700 gallons) with the AT-802, the K-Max has a range of 300 nautical miles compared to 700 nautical miles for the fixed-wing.[33] The AT-802 can be configured in a conventional manner utilizing a standard airport for its fixed landing gear or converted into a scooper-type floatplane that can refill its tanks by "landing" on a body

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[31] U.S. Forest Service, *Aviation Annual Report 2020*, 12.

[32] "Interagency Type Specifications for Helicopters," Interagency Helicopter Screening and Evaluation Subcommittee, April 14, 2014, 1, https://www.nwcg.gov/sites/default/files/committee-correspondence/IHSES-Interagency-Type-Specifications-for-Helicopters.pdf.

[33] Valley Air Crafts and Air Tractor, "Air Tractor Aerial Fire-Fighting Solutions: Fire Agency Briefing" (presentation, Valley Air Crafts, Tulare, CA, September 2015), https://www.dnr.wa.gov/publications/rp_fire_aviation_fireboss_agencybriefing.pdf.

of water.[34] Contractors can configure their aircraft depending on the prevailing topography. In an area with multiple bodies of water, such as Minnesota, the floatplane scooper option is the most effective. Conversely, in Texas, the standard configuration is more suitable. The contactors operating these aircraft appreciate the versatility in mission as they can quickly be configured to firefighting operations from their standard aerial spraying missions.

3. Indirect Fire Attack

An indirect fire attack is frequently utilized when a wildland fire moves at a rate or intensity that is too dangerous to attack from the head or flanks of the fire.[35] An indirect fire attack is usually necessary when the fire is influenced by wind or terrain features that encourage rapid fire growth and burning. An example is a fire starting at the base of a mountainside with the natural terrain features funneling the fire upward while the burning fire preheats the fuels above through convective air currents. Indirect fire attacks are frequently the result of fire managers' evaluating the relative risks and benefits of attacking a fire directly. Sometimes, even small fires may represent a great risk to firefighters because of outside forces such as weather or difficult topography. In these cases, the degree of risk to firefighters may be simply too great to commit resources to a direct fire attack. Fire managers must be risk-averse to ensure the safety of firefighters and employ an indirect fire attack.[36]

In an indirect fire-attack strategy, the objective is to deny the fire the needed fuel to continue burning. The general tactic is to remove the fuel in front of the fire by creating control lines using firefighters to dig or bulldoze lines in a safe area or set backfires to deny the fire a continuous fuel supply. When the fire reaches the area where the fuel has been removed, it will theoretically either go out or reduce to the point that firefighters can attack it directly due to lack of fuel. Specific to aerial operations, indirect fire attacks most

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[34] "AT-802F Fire Boss: Amphibious Scooper Air Tanker," Air Tractor, accessed March 10, 2022, https://airtractor.com/aircraft/at-802f-fire-boss/.

[35] National Fire Chiefs Council, "Consider Appropriate Wildfire Suppression Tactics."

[36] Borchers, "Accepting Uncertainty, Assessing Risk," 36–37.

commonly occur with the aerial application of fire-retardant chemicals to support man-made or natural fire breaks to stop the fire from progressing. A relatively new method of indirect aerial attack is utilizing UAVs or helicopters to start backfiring operations.[37]

Indirect fire attacks are frequently the first tactic to address new fire starts. There are many reasons that fire managers choose an indirect fire attack rather than a direct attack. The most common reason is that the fire is moving at such a rate as to be too dangerous to attack. Fire managers may simply lack ground resources to commit to fighting the fire. This situation frequently happens at the height of fire season when resources are spread thin, and additional resources may be days away. An indirect fire attack is also indicated when a fire is either especially remote or difficult to access with no known roadways. This situation may take ground forces hiking or parachuting into an area to find and suppress the fire. These remote fires are challenging as all the tools and equipment to fight the fire must be packed or flown into the area. In all these cases, the one tactic that fire managers can employ is dispatching aerial assets to hold the fire to a manageable size before other firefighters arrive.

4. Fire Retardants

The most frequently utilized aerial method of indirectly attacking fires is using fire retardant to stop or slow the fire. The ubiquitous image of the LAT dropping thousands of gallons of bright red fire retardant down a ridgeline is an example of aircraft building or reinforcing control lines. Fire retardant chemicals are composed of mostly water, ammonia or phosphate fertilizer, and other minor chemicals to provide surfactant and color.[38] Fire retardants can be used to reinforce fire lines that have been created through manual means or to reinforce natural fire breaks like rockslides or ridgelines. Fire retardants can also be used as a proactive method to pretreat valuable assets such as homes and critical

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[37] "U.S. Forest Service and Drone Amplified Partner to Drive Search for Domestic Firefighting Drones," FireRescue1, September 14, 2020, https://www.firerescue1.com/fire-products/drones/press-releases/us-forest-service-and-drone-amplified-partner-to-drive-search-for-domestic-firefighting-drones-VWuKcEuAMQaaFjWi/.

[38] "Wildland Fire Chemical Products Toxicity and Environmental Concerns: General Information," U.S. Forest Service, January 17, 2007, 1, https://www.fs.fed.us/rm/fire/documents/envissu.pdf.

infrastructure. However, applying retardants in this manner is rarely accomplished using aerial assets due to the precision necessary. It is more likely that an engine with a retardant tank performs this job.

The most widely used aerial-delivered fire retardant is Phos-Chek, made by Perimeter Solutions.[39] The retardant is shipped to air tanker bases as a powder and then mixed with water before loading onto aircraft. The infrastructure necessary to mix and load retardant is limited to very few airbases in each state and is regulated by the USFS to meet minimum requirements.[40] The lack of critical infrastructure to load fire retardant means that the drop, reload, and return cycle time for fixed-wing air tankers is much greater than for water-dropping helicopters, which simply need a convenient body of water or a dip tank. Fire retardant is mixed at a ratio of one pound of retardant to one gallon of water and costs approximately $2.50 per gallon.[41] Approximately 100 million gallons of Phos-Chek retardant are dropped each year supporting firefighting operations.[42] The chemicals that make up Phos-Chek are relatively non-toxic; however, aircraft generally do not drop retardant near waterways if possible. Fire retardant coats and protects the vegetation on which it is applied. It protects by providing a water barrier until the water evaporates (quickly) and then provides a chemical barrier inhibiting the propagation of the fire. As the fire approaches, the chemicals react with the heat produced by the fire, breaking down and forming a protective barrier on the vegetation or structure that it covers. While it does not "fireproof" vegetation, it significantly reduces the ability of vegetation to burn. As the retardant dries out, it protects until washed off the vegetation or the wind disperses it. It takes only about one-eighth of an inch of rain to wash the retardant off and render it

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[39] Samantha Masunaga, "The Fire Retardant Dropped Out of Planes? It's Sticky, Gooey and Made in the Southland," *Los Angeles Times*, October 1, 2020, https://www.latimes.com/business/story/2020-10-01/phos-chek-red-fire-retardant-dropped-from-planes.

[40] Fred Cammack, *Fire Retardant Standard Mixing System* (San Dimas, CA: San Dimas Technology and Development Center, 1999), https://www.fs.fed.us/t-d/pubs/pdf/99511204.pdf.

[41] Masunaga, "Fire Retardant Dropped Out of Planes."

[42] Anthony C. Yu et al., "Wildfire Prevention through Prophylactic Treatment of High-Risk Landscapes Using Viscoelastic Retardant Fluids," *Proceedings of the National Academy of Sciences* 116, no. 42 (2019): 2, https://doi.org/10.1073/pnas.1907855116.

ineffective.[43] Perimeter Solutions is producing a new type of fire retardant that is not susceptible to washing off by light rain. However, the retardant must be applied by truck, not by air, and costs significantly more than Phos-Chek.[44]

The effectiveness of fire retardant in suppressing fires depends on multiple variables, especially placement. Placing retardants on a target via an aerial platform primarily depends on the individual pilot's ability and the retardant delivery system; therefore, the human factor must be considered. Every aircraft that delivers retardant goes through a certification process to evaluate the effectiveness of its dropping capability. This process is known as the cup-and-grid method—in which cups, placed in a grid, capture retardant drops and are then weighed. This number is extrapolated and gives a gallon-per-hundred-square-foot measurement.[45] The aircraft is certified to perform retardant drops if the coverage is sufficient. In 2021, the Boeing 747 aircraft used for aerial firefighting, owned and operated by Global Supertanker, was decertified by the federal government and made ineligible for federal contracts due to its inability to provide adequate retardant drop coverage based on the cup-and-grid test.[46] If the retardant is not dropped in the correct area or in a manner that would inhibit the fire, its use is moot. Additionally, if the retardant is ineffective, there is no value in dropping it, and the substantial amount of money spent on the retardant and flight time has been wasted. The necessity for accuracy and placing enough retardant in a specific area drives pilots to fly at low altitudes. While low altitude flying increases the accuracy and density of retardant drops, it also subjects the pilot and airframe to dangerous flying conditions with no room for error.

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[43] "Phos-Chek Fire Retardants for Use in Preventing & Controlling Fires in Wildland Fuels: Frequently Asked Questions," ICL Performance Products, accessed October 3, 2021, 2, https://www.fs.usda.gov/Internet/FSE_DOCUMENTS/stelprd3851594.pdf.

[44] Keith Ridler, "Fire Retardant Could Be 'Game-Changer' in Fighting Wildfires," ABC News, October 5, 2021, https://abcnews.go.com/Politics/wireStory/fire-retardant-game-changer-fighting-wildfires-80424418.

[45] Ann Suter, *Drop Testing Airtankers: A Discussion of the Cup-and-Grid Method*, TE92P32—Technical Services, Aerial Delivery (Missoula, MT: U.S. Forest Service, 2000), 4.

[46] Bill Gabbert, "The 747 Supertanker Shuts Down," Wildfire Today, April 23, 2021, https://wildfiretoday.com/2021/04/23/the-747-supertanker-shuts-down/.

The most critical variable in fire retardant effectiveness is the intensity of the fire it tries to suppress. Plucinski found, “Retardant drops were able to hold fires up to one hour when the fire intensity was less than 2000 kW/m.”[47] Very high-intensity fires can produce energy in the neighborhood of 7500 kW/m.[48] Essentially, retardant was effective against low- to moderate-intensity fires but had difficulty holding fires with higher intensities due to spotting—firebrands being carried by wind in front of the fire and starting additional fires—over the fire line. Therefore, it may be inferred that using fire retardant to suppress low- to moderate-intensity fires is most effective. Fires exhibit these specific traits during the early phases of fire propagation before the fire is severely impacted by weather and moves at a rate that would support frequent spotting. When fire managers place retardant early and close to the fire, there is a better chance of containing the fire. This early indirect fire attack may hold the fire in check until ground forces intervene.

B. CURRENT UAV OPERATIONS

UAVs currently operating on wildland fires are considered a strategic information adjunct rather than a tactical direct-suppression asset. At this time, UAVs do not fly direct fire-suppression missions due to technological restrictions primarily associated with flight time, payload, and cost limitations.[49] UAVs are classified as aircraft and must comply with all Federal Aviation Administration (FAA) rules and requirements, including where, when, and how they may fly.[50] UAVs are subject to multiple FAA rules regarding aircraft, specifically under 14 C.F.R. 107. For example, 14 C.F.R. 107.35 requires one pilot for every aircraft.[51] This rule becomes problematic when flying multiple UAVs with one pilot, as is necessary when flying swarms of UAVs. Additionally, UAV classification is based

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[47] Matt P. Plucinski, “Fighting Flames and Forging Firelines: Wildfire Suppression Effectiveness at the Fire Edge,” *Current Forestry Reports* 5, no. 1 (March 2019): 11, https://doi.org/10.1007/s40725-019-00084-5.

[48] Plucinski, 11.

[49] Akhloufi, Castro, and Couturier, “UAVs for Wildland Fires,” 1.

[50] David Stuckenberg and Stephen Maddox, “Drones in the U.S. National Airspace System,” *International Journal of Aviation Systems, Operations and Training* 1, no. 2 (2014): 5, https://doi.org/10.4018/IJASOT.2014070101.

[51] Operation of Multiple Small Unmanned Aircraft, 14 C.F.R. 107.35 (2021), https://www.ecfr.gov/.

on weight, with large UAVs over 55 pounds requiring special FAA Part 107 certifications for the pilots.[52] Operators of large UAVs must be certified through the FAA as UAV pilots.[53] This requirement further limits UAV flights based on piloting requirements. Although large wildland fires typically employ temporary flight restrictions around the fire, UAVs and aircraft must still adhere to FAA rules within the temporary flight restrictions. While some commercial exemptions are available with a blanket certificate of authorization (COA) or waiver, these blanket exemptions are limited to "low-risk, controlled environments" with UAVs under 55 pounds.[54] In general, it appears that the blanket COA exemption may not apply in the wildland environment; however, the standard COA exemption may.[55] With all the aircraft flying in the wildland fire areas, these aircraft must be coordinated and deconflicted to ensure safe flights.

C. COMMAND AND CONTROL OF AERIAL ASSETS

The Incident Command System (ICS) has become the predominant management system in the United States and is deployed on everything from routine local emergencies to significant multi-state incidents. ICS is a method to manage everything that happens at an emergency incident while ensuring accountability and safety. It is the default management system for all wildland fires in the United States.[56] All personnel, equipment, and assets on a wildland fire are integrated into the ICS. The system's goal is to ensure accountability, supervision, and operations coordination while retaining the ability to expand or contract dynamically, as the incident dictates.[57] On a wildland fire, every aspect of the management system focuses on suppressing the fire. Each firefighting asset reports

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[52] Federal Aviation Administration, *Unmanned Aircraft Operations in the National Airspace System (NAS)*, Air Traffic Organization Policy N JO 7210.891 (Washington, DC: Federal Aviation Administration, 2015), 2, https://www.faa.gov/documentLibrary/media/Notice/Notice_UAS_7210.891.pdf.

[53] Federal Aviation Administration, 2.

[54] Federal Aviation Administration, 2.

[55] Federal Aviation Administration, 2.

[56] D. Dague and P. Hirami, "The United States Forest Service's Incident Command System 40 Years On: From Domestic Wildfires to International Disaster Response," *Unasylva* 66, no. 243/244 (2015): 81, ProQuest.

[57] Dague and Hirami, 82.

to a manager, who ultimately reports up the chain of command to the incident commander. The Air Operations Branch director controls all aircraft employed in the wildland environment under the operations section chief within the ICS (see Figure 1).[58]

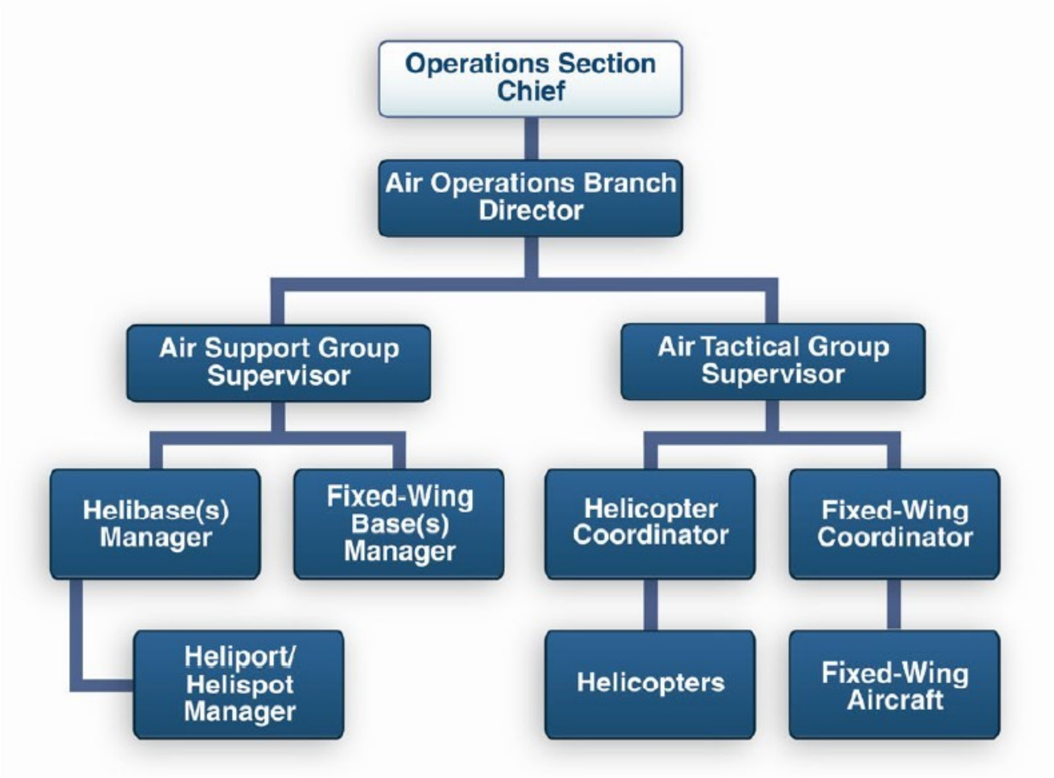

Figure 1. Typical ICS Air Operations Branch Organizational Chart[59]

The safety of the pilots, public, and firefighters is the most critical consideration when determining when and where aircraft fly on wildland fires. It is not uncommon to have multiple aircraft flying in the same air space, including large and small fixed-wing aircraft, helicopters, and UAVs. This air traffic requires strict coordination from the air tactical group supervisor, and in particularly congested air space, an airborne aerial

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[58] National Wildfire Coordinating Group, *NWCG Standards for Fire Unmanned Aircraft Systems Operations*, PMS 515 (Potomac, MD: National Wildfire Coordinating Group, 2019), 4, https://www.nwcg.gov/publications/515.

[59] Source: Department of Homeland Security, "Appendix B: Incident Command System," in *National Incident Command System* (Washington, DC: Department of Homeland Security, 2008), 102, https://www.fema.gov/pdf/emergency/nims/NIMS_core.pdf.

coordinator may be utilized. Whether traditional aerial assets or UAVs, all aircraft must be coordinated over the fire airspace to prevent inflight incidents.

UAVs always give way to piloted aircraft when deconflicting regardless of their mission.[60] Airspace managers have determined that flying UAVs and traditional aircraft in the same airspace is inherently dangerous for the piloted aircraft. One way that air tactical group supervisors can address this issue is not to allow UAVs and conventional aircraft to fly simultaneously or in the same airspace. If UAVs are flown while traditional aircraft are also flying, they typically fly at altitudes higher than those of conventional aircraft. UAV flights during the daytime usually are high-altitude, long-duration flights using a military-grade Predator or Reaper style UAV.[61] These styles of UAVs fly high enough not to conflict with traditional aircraft performing fire-suppression duties. However, most aerial operations by UAVs are typically flown at night to deconflict operations with traditional rotary and fixed-wing aircraft, as traditional suppression aircraft rarely fly at night.

UAV swarms have not been utilized in the wildland firefighting environment. There has been no discussion about how they would integrate into the ICS, nor how and when they would be utilized. Based on the current utilization of UAVs, it is likely they would be placed in the Air Operations Branch, possibly with a UAV-specific coordinator to manage swarm operations. The first iteration of a UAV swarm operation would likely be at night when crewed aircraft do not fly. Historically, the fire service has been slow to adopt new concepts in firefighting. However, should UAV swarms provide fire attack support, especially at night when fire crews are making progress against the fire, it is likely UAV swarms would be accepted. As the fire service looks to the future, it is likely that UAV swarms will have an increased role in aerial operations on wildland fires and will be integrated into the ICS under the Air Operations Branch.

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[60] National Wildfire Coordinating Group, 5.

[61] A. Ollero, J. R. Martínez-de-Dios, and L. Merino, "Unmanned Aerial Vehicles as Tools for Forest-Fire Fighting," in "The Fifth International Conference on Forest Fire Research," ed. D. X. Viegas, supplement, *Forest Ecology and Management* 234S (November 2006), https://doi.org/10.1016/j.foreco.2006.08.292.

III. AIRCRAFT AND UAVS

Wildland fires pose a direct threat to homeland security, both as a natural disaster and as a threat to the life and property of those living in their path. As fire managers explore safer, more effective methods to suppress wildland fires, one must analyze how fires may be suppressed more efficiently and effectively from the air. This literature review explores the current limitations of traditional firefighting aircraft. It explores the potential for UAVs to detect and suppress fires. Finally, it reviews current applications of UAVs in the wildland environment and commercial swarm operations.

A. LIMITATIONS OF TRADITIONAL AIRCRAFT

An undervalued limitation of traditional aircraft is their pace of operations. Ground firefighters work to suppress fires 24 hours a day. Much progress in suppression and building control lines can be made at night because weather conditions usually calm down at night with cooler temperatures and less wind. However, aircraft may fly only during daylight hours, defined by the USFS as 30 minutes before sun-up and after sun-down.[62] The operational tempo of traditional aircraft tends to start slowly in the morning, becomes more robust in the afternoon hours, and stops before dusk. These aircraft operate primarily under visual flight rules, requiring pilots to see the ground and horizon. These rules limit their ability to fly and fight fire during heavy smoke, extreme burning conditions, weather events, and darkness.

Most traditional aircraft are not equipped with night vision capabilities, although some Cal Fire helicopters work with this technology.[63] However, this technology is in its infancy, and only a few of Cal Fire's newest helicopters have it. Night vision flying in fixed-wing aircraft is also in its infancy. The first SEAT flight equipped with night vision technology was in Colorado on November 16, 2021. Unfortunately, the aircraft crashed,

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[62] James Faasau, *Large Airtanker Operations Plan* (Washington, DC: U.S. Forest Service, 2017), 18, https://www.fs.fed.us/fire/aviation/av_library/index.html.

[63] Guy Kovner, "Cal Fire Debuts Helicopter with Night Firefighting Ability," Firehouse, July 6, 2021, https://www.firehouse.com/operations-training/wildland/news/21229386/cal-fire-debuts-24m-helicopter-with-night-firefighting-ability.

and the pilot was killed attempting the first night drop of retardant using night vision goggles.[64] This incident will likely set night retardant drops back while both the National Transportation Safety Board (NTSB) and the firefighting industry study the reasons for this plane crash.

Piloting wildland firefighting aircraft takes a highly specialized set of skills, many of which can only be learned by flying firefighting missions. Pilots with these skills are scarce and in high demand during the wildland fire seasons. The pilot killed when his SEAT crashed in Colorado was a veteran pilot with over 8,000 hours of flight time.[65] Flying heavy aircraft at low altitudes over varied terrain requires a precise skill set. Coulson Aviation, for example, prefers its wildland pilots have at least 2,500 hours of flight time along with 250 hours in the specific firefighting aircraft before hire.[66] Many of the skills necessary to pilot firefighting aircraft are hard to obtain, including cargo hauling, agricultural flying, and low-level flying missions over varied terrain. Ultimately, much of this type of flying is by stick and rudder or having a "feel" for the aircraft. New pilots who have learned to fly aircraft using automation are not suited for this type of flying.[67] As the current generation of pilots age out of fighting fires, it will become increasingly challenging to find pilots who can do this work.

In addition to the scarcity of airframes and pilots, the way aircraft are contracted has not adapted to the more frequent and early deployment of aerial assets on wildland fires. Glickstein contends that the method of contracting aerial firefighting in the United States is flawed and inefficient based on the current practice of exclusive-use and call-when-needed contracts used by fire managers. He further asserts that these contracts disincentivize operators from investing in better avionics and night-flying packages because the contracts are based not on when and where the aircraft can fly but rather on

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[64] Marc Sallinger and Angela Case, "Pilot Dies in Air Tanker Crash Near Kruger Rock Fire in Colorado," NBC 9 News, November 17, 2021, https://www.9news.com/article/news/local/wildfire/air-tanker-crashes-kruger-rock-fire/73-77e124e6-804d-424f-8405-0634ec9f2b73.

[65] Sallinger and Case.

[66] "How to Become an Aerial Firefighter," Coulson Aviation, April 14, 2020, https://www.coulsonaviationusa.com/newsmedia/how-to-become-an-aerial-firefighter.

[67] Coulson Aviation.

the volume of water or retardant they can drop.[68] He explores the options of expanding the role of the active-duty military into providing all-aerial firefighting, having the National Guard provide all-aerial firefighting, or creating a new aerial firefighting arm under the Department of Homeland Security (DHS).[69] Glickstein argues that active-duty military cannot take on the additional mission, and the new aerial firefighting arm under DHS would be cost-prohibitive. In his opinion, the National Guard would be the most appropriate entity to complete this mission. It currently flies firefighting missions with C-130s (fixed-wing) equipped with USFS-owned MAFFS units and H-60 Blackhawk helicopters, which are snorkel and water-dropping equipped.[70] The specially trained National Guard units with aircraft equipped for firefighting missions also have professional pilots who are comfortable flying firefighting missions under challenging conditions and at night. Leveraging this capability could substantially increase the operational pace of aerial operations on fires and potentially increase the ability to suppress fires quickly. However, should the National Guard take on this expanded duty for the entire country, the time needed to train and operate for firefighting duty would increase, potentially lengthening deployments for personnel. National Guard forces would also be unavailable to surge to assist regular forces during times of conflict.

B. LIMITATIONS OF CURRENT UAVS

Current UAV systems are limited by many factors: the necessity to have reliable data links in areas that may not have good communications coverage; FAA requirements for UAVs, especially pertaining to having one pilot for each individual aircraft; a weight restriction placed on UAVs by the FAA for which special waivers are required; the overall limited duration of flight time for small quad-copter style UAVs; and the overall limited payload capacity of UAVs, subject to weight-versus-power issues. UAVs are viewed as a valuable tactical adjunct within the wildland environment despite these limitations.

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[68] Geoffrey L. Glickstein, “Improving Air Support for Wildfire Management in the United States” (master’s thesis, Naval Postgraduate School, 2014), 24, http://hdl.handle.net/10945/43917.

[69] Glickstein, v.

[70] Glickstein, 95–100.

When UAVs fly over the horizon, pilots control the UAVs using data links to direct their location and flight mission. At lower altitudes and over varied terrain, UAVs can lose the data link with their home base due to signal degradation when they are not in the line of sight of their operator. Chung et al. experienced these phenomena when experimenting with flying large numbers of UAVs.[71] High-altitude, long-duration UAVs such as Predators and Reapers are not susceptible to this constraint. These UAVs fly high enough to be controlled by satellite and are not subject to communication degradation. With varied terrain and altitudes, the wildland environment can produce difficulties related to loss of communication, which must be accounted for prior to launching. UAVs flown close to the fire must be controlled within the line of sight to ensure accurate flights. As 5G cellular service infrastructure becomes robust and cellular data coverage increases through satellite communications, UAVs will likely have less difficulty keeping positive uplinks with their base stations.

The National Wildfire Coordinating Group (NWCG) has published the *NWCG Standards for Fire Unmanned Aircraft Systems Operation* to standardize and ensure minimum operational requirements for UAV operations.[72] The FAA has multiple classifications for UAVs and flight characteristics, including when, where, and how UAVs may be flown, and further classifies UAVs based on their weight. These rules can be found in the *Code of Federal Regulations*, Title 14, Chapter I, Subchapter F, Part 107.[73] It is relatively simple to obtain a license to fly UAVs less than 55 pounds under the Part 107 rules. However, special authorization on a case-by-case basis is required under FAA code Section 333 for operators to fly UAVs greater than 55 pounds.[74] The ability to fly heavy-lift, long-duration UAVs includes those that classify into the over 55-pound category. As

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[71] Timothy H. Chung et al., "Live-Fly, Large-Scale Field Experimentation for Large Numbers of Fixed-Wing UAVs," in *2016 IEEE International Conference on Robotics and Automation* (Piscataway, NJ: IEEE, 2016), 1261–62, https://doi.org/10.1109/ICRA.2016.7487257.

[72] National Wildfire Coordinating Group, *Standards for Fire Unmanned Aircraft Systems*, 2.

[73] Small Unmanned Aircraft Systems, 14 C.F.R. 107 (2021), https://www.ecfr.gov/current/title-14/chapter-I/subchapter-F/part-107.

[74] "Flying Large Drones over 55 Pounds Using Section 333 Exemption," Drone U, July 23, 2019, https://www.thedroneu.com/blog/large-drones-55-pounds-section-333-exemption/.

UAVs are used for more commercial applications in the future, current FAA policies will likely need review and revision.

According to NWCG standards, four types of UAVs are currently flown in the wildland environment. The first type is classified as either Type 1 or Type 2 fixed- or rotor-wing UAVs used for high-altitude information gathering primarily using infrared sensors for fire-edge mapping. The typing is relevant to how long the UAV can fly, the altitude at which it flies, and the range it may fly from its base. Type 1 UAVs fly up to 14 hours at up to 8,000 feet with a range of 50 miles, while Type 2 UAVs can fly up to 6 hours at up to 6,000 feet with a range of 25 miles.[75] Type 1 and 2 UAVs are generally contracted to fires through private companies on a call-when-needed basis. They provide their own pilots and support personnel. Both Type 1 and 2 UAVs are expected to fly in day and night missions.

The second type consists primarily of small quad-copter UAVs, powered by lithium-ion batteries, with relatively small payload packages used for intelligence gathering specific to the local firefighting mission. Under NWCG typing, these aircraft are Types 3 and 4.[76] One of the significant limitations of these UAVs is their short flight time due to the high electrical consumption for flight, loiter, and return. However, these UAVs are easy to launch, are man-portable, and provide real-time intelligence to firefighters on the ground. These UAVs are extremely valuable for real-time intelligence about the location of the fire and the terrain in the area, as well as situational awareness about other ground forces in the area. This type of UAV requires minimal training for piloting and certification.

All UAV systems are subject to weight-versus-power limitations as it takes more power to lift a heavier weight. Additionally, more power frequently means heavier batteries to supply that power, creating more weight. As UAVs become heavier, their flight time decreases, limiting their operational window. The weight-to-power conundrum is currently being addressed by multiple private vendors in the UAV building industry. Parallel Flight Technologies is beta testing a heavy-lift UAV that uses a hybrid gasoline–electric

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[75] National Wildfire Coordinating Group, *Standards for Fire Unmanned Aircraft Systems*, 2.

[76] National Wildfire Coordinating Group, 2.

propulsion system. The company claims that with this system, it achieves a 1:1 weight-to-power ratio, allowing its UAV to carry a payload equal to the weight of the UAV. The technology would allow the Parallel Flight Technologies' Firefly to carry a 100-pound capacity for a flight time of two hours.[77] Should this concept become viable, it would open the door to suppression operations by UAV.

Historically, UAV operators have focused on longer flight times by minimizing payload packages. Developing a UAV to complete a fire suppression mission requires the UAV developer to factor in the comparatively much larger weight of the suppressing agent compared to traditional sensor packages. Water weighs 8.34 pounds per gallon. While this may seem like a small weight, this becomes a significant payload of 83.40 pounds when a UAV carries 10 gallons of water or 89.70 pounds when carrying 10 gallons of mixed retardant.[78] The larger the payload, the shorter the flight time because of the energy necessary to move the heavy payload. Due to these limitations, having a UAV system that can lift a significant payload, fly to the fire line, deploy the payload, and return on one battery charge has been a challenge multiple companies have sought to solve. In their research, Sarghini and DeVivo illustrate that it is possible to lift heavy weights with a purely electrically powered UAV; however, the flight time is such that it is impractical to implement.[79] Many companies are now working with internal combustion engines to gain a power-to-weight advantage. However, internal combustion engines add additional weight to the UAV, decreasing the potential payload. As with all aircraft, weight and balance issues must be addressed on every flight.

1. Privacy Concerns regarding UAVs

Once swarm technology is robust and scalable, the applications are limited only by imagination. UAV swarms have potentially unlimited applications, from commercial

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[77] "Firefly Heavy-Lift UAS," Parallel Flight Technologies, accessed January 17, 2022, https://www.parallelflight.com/product.

[78] "Product Information: Phos-Chek LC-95A-R," U.S. Forest Service, Wildland Fire Chemical Systems, accessed December 13, 2021, https://www.fs.fed.us/rm/fire/wfcs/products/pc_lc-95a.htm.

[79] Fabrizio Sarghini and Angela De Vivo, "Analysis of Preliminary Design Requirements of a Heavy Lift Multirotor Drone for Agricultural Use," *Chemical Engineering Transactions* 58 (July 2017): 628–30, https://doi.org/10.3303/CET1758105.

delivery systems, to emergency response and management, to movement of people and goods, to offensive and defensive military operations. However, the concept of multiple or even hundreds of UAVs flying independently to complete missions in the surrounding airspace will assuredly lead to questions about privacy and security.

The concept of swarms or multiple UAV systems that use collaborative, decentralized control (while under the supervision of a human operator) in flying and gathering intelligence opens some discussion regarding privacy concerns and the supposition of privacy by citizens. At the very least, UAVs are equipped with a global positioning system (GPS) and sensor technology such as cameras.[80] When swarms fly, they gather information for their mission and share it with the others in the swarm and a base station. The idea that a swarm could build a profile of a person or group by picking up small bits of information and aggregating them among the swarm—systematically building a clearer picture of the surveillance subject—does not sit well with some privacy advocates. Arkam et al. define how swarms could be weaponized as offensive to gather information through open wireless internet connections. As the swarm siphons off information, it could be transmitted to the end-user. He additionally offers potential solutions and hardening practices to ensure that swarms of UAVs are not susceptible to attack.[81] This concern of Arkam et al. may be best understood with multiple swarms of UAVs in an urban environment. Based on the location that firefighting swarms would be utilized, typically in the remote forest and the urban–wildland interface, there would be little opportunity for swarms to gather personal information due to the low population density of these areas. Regardless of where UAVs are flying, there will always be people who are leery of allowing any increased surveillance into their lives.

An unexpected privacy issue in the UAV community was realizing that most UAVs available for commercial use are made in China or with Chinese parts. The manufacture of

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[80] Maisa Albalawi and Houbing Song, "Data Security and Privacy Issues in Swarms of Drones," in *Proceedings of the 2019 Integrated Communications, Navigation and Surveillance Conference* (Piscataway, NJ: IEEE, 2019), 4, https://doi.org/10.1109/ICNSURV.2019.8735133.

[81] Raja Naeem Akram et al., "Security, Privacy and Safety Evaluation of Dynamic and Static Fleets of Drones," in *Proceedings of the 36th Digital Avionics Systems Conference* (Piscataway, NJ: IEEE, 2017), 6, https://doi.org/10.1109/DASC.2017.8101984.

UAVs by foreign adversaries is such a homeland security concern that former President Trump signed Executive Order 13981, "Protecting the United States from Certain Unmanned Aircraft Systems," on January 18, 2021. The executive order prohibited the procurement of UAVs produced by or assembled with components made in adversary countries for use by the U.S. government.[82] The Chinese company DJI produced the most common governmentally deployed UAV, the Mavic II Enterprise.[83] There is a worry that many of these Chinese-produced UAV systems could be compromised through a cyberattack or are actively spying and sending information back to China. Because of this concern, in January 2020, the Department of the Interior suspended all government flights by UAVs made in China.[84] While there had been many privacy concerns by people worried about UAVs collecting personal information, the idea that many of the UAVs being flown for government applications could be susceptible to Chinese attacks was unanticipated. In September 2020, the USFS contracted with Drone Amplified to ensure that UAVs used to fight fires are made in the United States and are less susceptible to Chinese attacks.[85]

As UAV swarms become more ubiquitous in application, the UAVs themselves could be considered security risks. UAVs could be hacked, as could the control systems sending them messages. Interestingly, a single UAV with a single operator may be more secure than a swarm of UAVs. An enemy UAV could join the swarm and siphon off information in the swarm configuration.[86] However, as Hutchinson notes, the weakest security link is the communication system in a non-autonomous UAV system (piloted

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[82] Exec. Order No. 13981, 86 Fed. Reg. 6821 (January 18, 2021), https://www.federalregister.gov/documents/2021/01/22/2021-01646/protecting-the-united-states-from-certain-unmanned-aircraft-systems.

[83] "Government: Secure and Reliable Solutions for Government," DJI Enterprise, accessed December 23, 2021, https://www.dji.com/enterprise/government.

[84] Bill Chappell, "Interior Department Grounds Chinese-Made Drones, Months after It Approved Them," NPR, January 29, 2020, https://www.npr.org/2020/01/29/800890201/interior-department-grounds-all-of-its-drones-citing-cybersecurity-other-concern.

[85] "U.S. Forest Service and Drone Amplified Partner to Drive Search for Domestic Fire-Fighting Drones," Fire Ignition Management: IGNIS by Drone Amplified, September 9, 2020, https://droneamplified.com/u-s-forest-service-and-drone-amplified-partner-to-drive-search-for-domestic-fire-fighting-drones/.

[86] Albalawi and Song, "Data Security and Privacy Issues in Swarms of Drones," 4.

UAV).[87] One of the solutions to UAV hacking is utilizing the SeL4 microkernel operating system. With this operating system, the UAV's functionality is separated, and invasive attempts to hack the UAV's systems are stopped before the hack migrates from one place to another. For example, if a hack occurs in the sensor package, it will not migrate to the flight controls or other systems. The SeL4 technology essentially isolates each system and keeps any invasive incursions isolated. A Defense Advanced Research Projects Agency–funded test ensured that an uncrewed helicopter could not be taken over via cyberattack using the SeL4 technology.[88] When using UAV swarms for wildland firefighting, it appears that the benefits outweigh the risk of information loss, hacking, and privacy concerns.

2. Accuracy of Information Collected

The question of sensor accuracy on UAV swarms must be evaluated. As UAV swarms could potentially take independent action on a fire, there is an argument that human interpretation should be built into the positive action process. In the wildland fire setting, UAV swarms will be required first to detect the fire, identify if the fire is hostile or not (inside or outside the geofence), and then decide to take action to suppress it or not. Artificial intelligence (AI) algorithms should complete all these actions without human interaction or intervention. Additionally, if the UAV acts on something that it should not have—suppressing the wrong fire, for example—the "cost" is minimal. Utilizing AI and UAVs in the wildland firefighting space can make fire detection, identification, and suppression more accurate and reliable.

The first step in fire suppression is accurately detecting and identifying a fire. Akhloufi, Couturier, and Castro explored multiple sensing applications for UAVs and their effectiveness in identifying fires.[89] If UAV swarms and AI can accurately detect and

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[87] William Hutchinson, "Deceiving Autonomous Drones," *International Journal of Cyber Warfare and Terrorism* 10, no. 3 (2020): 7, https://doi.org/10.4018/IJCWT.2020070101.

[88] Albalawi and Song, "Data Security and Privacy Issues in Swarms of Drones," 9.

[89] Moulay A. Akhloufi, Andy Couturier, and Nicolás A. Castro, "Unmanned Aerial Vehicles for Wildland Fires: Sensing, Perception, Cooperation and Assistance," *Drones* 5, no. 1 (March 2021): 7–12, https://doi.org/10.3390/drones5010015.

identify fire starts early through infrared, flicker, or video comparison, resources can be dispatched to suppress the fire before it advances to a large fire. If the swarm has suppression capabilities, it can take early offensive action against the fire. The Douglas Forest Protective District employs cameras that use an AI algorithm to detect smoke plumes.[90] Previous detection methods used human interpretation, which could misinterpret things like dust plumes from machinery or localized fog banks that look like smoke. The new AI-assisted camera system can detect and identify fires earlier with a higher degree of accuracy than conventional citizen reporting or humans in fire watchtowers. The camera system allows the firefighters to respond quickly and suppress the fire at a manageable stage.

Multiple studies have been undertaken regarding AI's ability to identify fires. The goal is to identify the fire accurately and early in the fire propagation. The National Oceanic and Atmospheric Administration provides access to all lightning strikes that ground to the earth.[91] If a lightning storm comes through a designated geographic area, it would be advantageous to launch UAVs to scan the area for possible fire starts. AI algorithms could use multiple sensors across many spectrums, including visible light, infrared light, color segmentation, and movement, to develop a clear picture of a possible fire.[92] Sungheetha and Rajendran go so far as to argue that fire detection will become ubiquitous through the internet of things, utilizing the cloud, wireless systems, UAVs, and other smart-city innovations to aggregate fire information.[93] As AI computing becomes more prevalent and accessible, UAV intelligence gathering will likely incorporate it more frequently as a standard package of sensing equipment.

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[90] Drew Reeves, "AI Technology Helps Fire Prevention Specialists Spot Fires in the Early Stages," FOX 12 Oregon, July 28, 2021, https://www.kptv.com/news/ai-technology-helps-fire-prevention-specialists-spot-fires-in-the-early-stages/article_3e71fcf2-f000-11eb-92c3-7bea7fdc1048.html.

[91] "Lightning Products and Services," National Oceanic and Atmospheric Administration, accessed July 18, 2021, https://www.ncdc.noaa.gov/data-access/severe-weather/lightning-products-and-services.

[92] Akhloufi, Couturier, and Castro, "Unmanned Aerial Vehicles for Wildland Fires," 8–10.

[93] Akey Sungheetha and Rajesh Sharma Rajendran, "Real Time Monitoring and Fire Detection Using Internet of Things and Cloud Based Drones," *Journal of Soft Computing Paradigm* 2, no. 3 (2020): 173, https://doi.org/10.36548/jscp.2020.3.004.

C. BENEFITS OF USING UAVS IN THE WILDLAND ENVIRONMENT

The primary benefit of using UAVs for fire suppression operations, in place of piloted conventional aircraft, is that it leaves the piloted aircraft available for more critical missions. Additionally, pilots and airframes are not exposed to as many potentially dangerous missions. Flying conventional aircraft in the wildland environment is inherently dangerous because of the terrain features, updrafts from heat, obscured vision from smoke, and loaded aircraft having a minimal margin for error. As noted previously, there are very few firefighting aircraft, and the loss of even one of them represents a significant opportunity cost for loss of use on subsequent fires. The utilization of UAVs within this inherently dangerous workspace may prevent further loss of life for aircrews and firefighters.

UAVs may have fewer limitations regarding when they can be flown compared to conventional piloted aircraft in the wildland space. While there are several restrictions about when and where UAVs can fly, variances can often be obtained through the FAA. An example of such a variance would be for the FAA's condition of one pilot per aircraft under Part 107.35.[94] While flying swarms of UAVs would be prohibited under the 107.35 requirement, swarms may be flown if the pilot has the appropriate waiver or COA. Additionally, it may be possible to obtain expedited waivers through the Special Governmental Interest process in emergencies.[95] It appears that the FAA recognizes the need for an agile process to ensure UAV operations are safe and efficient.

UAVs' primary missions in the wildland environment are mapping and hot spot detection. These missions may be better suited at night than in daytime as infrared heat signatures are more distinct with a cooler nighttime background. One example of the FAA's rule flexibility is the new Part 107.29 requirement that UAVs not be flown at night. However, this rule is easily circumvented provided the pilot has the proper training and the

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[94] "Part 107 Waiver," Federal Aviation Administration, April 19, 2021, https://www.faa.gov/uas/commercial_operators/part_107_waivers/.

[95] "Emergency Situations," Federal Aviation Administration, August 27, 2020, https://www.faa.gov/uas/advanced_operations/emergency_situations/.

UAVs are equipped with the correct lights.[96] Because UAVs excel at night flying, it is vital to have a process by which they can complete their mission. For future suppression missions, the ability for UAVs to fly in both smoke and the darkness of night would significantly increase the operational tempo of aerial firefighting operations, effectively doubling the time that suppression missions could be flown.

In general, UAVs cost significantly less than piloted aircraft. When aircraft are deployed to a fire, they are contracted on a per-day basis and an hourly flight cost. Not only is the aircraft contracted, but the pilot and, if necessary, the crew are contracted as well. These contracts are based on actual hours flown and contracted days on the fire. Therefore, fire finance managers must frequently pay the daily cost for aircraft they cannot use due to conditions that ground the aircraft, such as weather, smoke, or flight hour restrictions. It is not uncommon for aircraft to be assigned to a fire and not fly missions due to smoke conditions or unfavorable weather. UAVs are also contracted on a per-day basis under a call-when-needed contract; however, every UAV is required to operate both day and night and under conditions that would ground piloted aircraft.[97] The ability to fly both day and night missions provides a more robust return on investment when ordering UAV aerial assets. Finally, the fire service must not discount the relative expendability of UAVs compared to crewed aircraft. While it is not ideal to lose any aircraft during operations, the cost is significantly less to lose a UAV compared to a crewed aircraft in terms of the actual cost as well as the emotional trauma of experiencing an aircraft crash and the necessity of an NTSB investigation.

1. Current Utilization of UAV Systems for Fire Suppression

UAVs are currently utilized in the wildland fire setting for multiple missions on almost all large-scale fires. They are used primarily to map the fire edge, detect and identify

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[96] Small Unmanned Aircraft Systems.

[97] "Interior Awards First Contract for Small Unmanned Aircraft Systems Services," Department of the Interior, May 15, 2018, https://www.doi.gov/pressreleases/interior-awards-first-contract-small-unmanned-aircraft-systems-services.

hot spots (fire), and take high-level weather readings.[98] With destructive wildland fires on the rise, fire managers, legislators, and government entities are increasingly interested in using UAVs to gather intelligence, increasing safety factors for firefighters, and developing systems to integrate UAVs into suppression operations. UAVs have proven so effective at collecting intelligence that Washington Senator Maria Cantwell introduced a bill in the U.S. Senate in 2018 that would require the utilization of UAVs to provide real-time intelligence on all large fires.[99] Unfortunately, that bill died in committee.

The application of UAV systems in the firefighting profession is developing rapidly, with multiple stakeholders attempting to determine where UAVs can assist in making firefighting operations safer for firefighters. Many large municipal fire departments now have UAV programs that use off-the-shelf quad-copters for real-time intelligence gathering on fires or emergencies. The Fire Department of New York has a UAV unit that responds to all multi-alarm fires to provide the incident commanders real-time intelligence about the fire and the surrounding buildings.[100] The Los Angeles Fire Department has been particularly proactive in utilizing UAVs, having deployed its first quad-copter in 2017 on the Skirball Fire.[101] Los Angeles has also taken possession of the first tracked firefighting robot, which is attached to hose lines and can enter burning structures to fight the fire when it is too dangerous for firefighters to do so.[102] While not a UAV, this tracked robot (resembling a tank) is remotely piloted by a firefighter. It has the

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[98] Luis Merino et al., "An Unmanned Aircraft System for Automatic Forest Fire Monitoring and Measurement," *Journal of Intelligent & Robotic Systems* 65, no. 1–4 (January 2012): 534, https://doi.org/10.1007/s10846-011-9560-x.

[99] Lisa Murkowski, *Wildfire Management Technology Advancement Act of 2018*, Senate Report No. 115–441 (Washington, DC: Senate Energy and Natural Resources Committee), https://www.congress.gov/congressional-report/115th-congress/senate-report/441.

[100] Michael Leo, "Drones in the Big City," Firehouse, April 1, 2019, https://www.firehouse.com/tech-comm/drones/article/21069479/fdny-drone-program.

[101] Hailey Branson-Potts, "L.A. Fire Department Used Drones for the First Time during Skirball Fire," *Los Angeles Times*, December 15, 2017, https://www.latimes.com/local/lanow/la-me-ln-lafd-drone-skirball-fire-20171214-story.html.

[102] Francesca Giuliani-Hoffman, "The First Firefighting Robot in America Is Here—and It Has Already Helped Fight a Major Fire in Los Angeles," CNN, October 21, 2020, https://www.cnn.com/2020/10/21/business/first-firefighting-robot-in-america-lafd-trnd/index.html.

same objective—to increase the safety of firefighters by keeping them out of hazard zones where they could be burned or entrapped by structure fires.

2. Current UAV Research and Experimentation

Internationally, fire services are integrating UAV applications into their daily operations. In January 2020, the Chinese fire department in Dazu, Chongqing, demonstrated a tethered UAV system for high-rise firefighting. In this demonstration, the department set the exterior of a building on fire and then attacked the fire with UAVs tethered to fire engines using hoses for water.[103] It extinguished a significant volume of fire with just three UAVs. This type of fire represents a residential or commercial high-rise with the fire having breached an exterior window and extended to floors above. The Grenfell Tower Fire in London in 2017, in which 72 people died, is a good representation of this type of fire extension.[104] Every city in the world with high-rise buildings could experience this problem at some point.

It is essential to understand that traditional fire trucks in the United States have a mounted ladder length of 100 feet. Due to setbacks of streets and overhead obstructions, firefighters can expect to deploy their ladders at a maximum height to reach the sixth floor of most buildings. Most of these ladders have waterways that can deliver elevated master streams (over 500 gallons per minute) at the tip of the aerial. They might lob water to the seventh floor, but ground-based water delivery is virtually impossible beyond that height. Therefore, for any firefighting above the sixth floor, firefighters must walk up the stairs, bringing their hoses and related equipment with them to connect to a building standpipe system. Interior high-rise firefighting is physically draining and time-consuming for the firefighters as they carry upwards of 100 pounds of protective and firefighting equipment. Once they get to the fire floor, they must engage in a dangerous firefight. Thus, the concept

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[103] Jieyu Wang and Martini Tan Kailong, “The First Fire Drill for High-Rise Fire Fighting Drones Was Held in Dazu, Chongqing,” *IChongqing* (blog), January 22, 2020, https://www.ichongqing.info/2020/01/22/the-first-fire-drill-for-high-rise-fire-fighting-drones-was-held-in-dazu-chongqing/.

[104] “Grenfell Tower: What Happened,” BBC News, October 29, 2019, https://www.bbc.com/news/uk-40301289.

that UAVs could fly vertically, above the reach of traditional ladder trucks, to place water on the fire from the exterior is an exciting idea. While they will not fully extinguish a fire from the exterior, the fire may be held in check for the firefighters to go aloft and attack it. The fire would theoretically be less intense, providing a safer environment for firefighters and any citizens who could be trapped above the fire.

In a related experiment, Alshbatat has suggested using untethered UAVs for firefighting in high-rise buildings and rugged and remote locations. In his research, he proposed using UAVs equipped with explosive firefighting extinguishing balls that could be launched into the fire, much like deploying fire extinguishers.[105] He and his team have developed a small-scale model that provides a proof of concept yet does not solve the scalability of a long-duration, heavy-lift UAV system. Alshbatat's research comes from the need to provide firefighting services to areas that may have no firefighters, or the firefighters may be stationed a long distance away. Dr. Alshbatat is from Jordan, which has fewer building regulations and far fewer firefighters compared to the United States. Utilizing UAVs as a firefighting tool is an innovative way to provide firefighting services for citizens.

Drone Amplified, which is now providing UAVs to the USFS, is also the maker of the IGNIS system.[106] The IGNIS system is an aerial ignition solution using a United States–produced UAV coupled with the IGNIS deployment module to drop chemical fireballs to start backfires. These UAVs can fly into areas that are inaccessible to firefighters, in virtually zero visibility and at night. The UAV flies along a prescribed route dropping chemical fireballs, which start the backfire operation. Detweiler reports that the Drone Amplified UAV can perform the same aerial ignition function for $1,800 per day compared to a crewed helicopter for $16,000 per day.[107] The Department of the Interior

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[105] Abdel Ilah N. Alshbatat, "Fire Extinguishing System for High-Rise Buildings and Rugged Mountainous Terrains Utilizing Quadrotor Unmanned Aerial Vehicle," *International Journal of Image, Graphics and Signal Processing* 11, no. 1 (January 2019): 25, https://doi.org/10.5815/ijigsp.2018.01.03.

[106] FireRescue1, "U.S. Forest Service and Drone Amplified Partner."

[107] Carrick Detweiler, "Opinion: Congress Needs to Be Careful about Banning All Parts for Drones Made outside the U.S.," Fire Aviation, October 21, 2020, https://fireaviation.com/2020/10/21/opinion-congress-needs-to-be-careful-about-banning-all-parts-for-drones-made-outside-the-u-s/.

tested the IGNIS application on prescribed burns in 2019 and authorized the IGNIS system for both prescribed burns and firefighting operations.[108] The IGNIS system is the first application of an indirect fire attack by a UAV in the United States. While the IGNIS system is currently a stand-alone system using the single-piloted UAV concept, using multiple IGNIS UAVs in a swarm could increase the effectiveness of backfiring operations through better saturation of chemical fireballs and the ability to perform more extensive burns in a single mission.

3. Current Applications of Swarm Technology

While UAV swarms may seem like theoretical technology, several swarm applications are happening now. Most people in the United States have probably viewed what they believe to be swarm operations through small, coordinated UAV light shows. However, while these light shows are advertised as swarms, they may be better defined as pre-programmed, pre-positioned, multi-vehicle operations. These light shows use multiple UAVs that fly a pre-programmed route and perform a specific function. To be considered a swarm, the UAVs would have to perform a collective action, deconflicting among themselves, and adapt to the loss of members of the swarm to complete the mission.[109] While it is tempting to call a group of UAVs being controlled by a single controller a swarm, a true swarm must be able to take independent action. The company Rantizo has a commercial application for agricultural spraying and seeding in Iowa that uses an off-the-shelf DJI UAV that it has modified. Rantizo operators can fly a three-UAV swarm to increase the overall application rate.[110] These seeding and aerial spraying applications may be better classified as multi-UAV operations. However, the flights by Rantizo become swarm operations when the UAVs are patrolling a plot of land and identify weeds, at which

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[108] FireRescue1, “U.S. Forest Service and Drone Amplified Partner.”

[109] Gustavo A. Cardona and Juan M. Calderon, “Robot Swarm Navigation and Victim Detection Using Rendezvous Consensus in Search and Rescue Operations,” *Applied Sciences* 9, no. 8 (January 2019): 3–6, https://doi.org/10.3390/app9081702.

[110] Matthew Wilde, “Three Drones Work Together to Spray and Seed Fields,” DTN Progressive Farmer, June 2, 2021, https://www.dtnpf.com/agriculture/web/ag/crops/article/2021/06/02/three-drones-work-together-spray.

point they take a spraying action against them.[111] Internationally, Korea Air uses UAV swarms for aircraft inspections, completing a 10-hour process in less than four hours. Its UAVs can detect flaws as small as a millimeter.[112] Korea Air's use qualifies as a swarm because if one UAV fails in its operation, another takes its place.

The first commercial application of heavy-lift (UAVs over 55 pounds) UAV swarms may have come from the company DroneSeed in Washington state. DroneSeed uses three to five UAVs in a swarm to do aerial seeding on locations that have been subjected to wildfires or have been previously logged. DroneSeed has been granted the only FAA waiver to use heavy-lift UAV swarms.[113] This FAA waiver allows heavy-lift UAVs to fly beyond the visual line of sight (BVLOS) and in a swarm.[114] This means that one operator can control up to five UAVs, each performing a specific planned seeding mission without keeping the UAV in sight or using spotters to watch the UAV. The system has a 57-pound payload of seedlings in seed vessels that DroneSeed claims can plant three-quarters of an acre on every flight with each UAV. DroneSeed can replant 3.75 acres during every flight with a five aircraft swarm. Not only does this complete seeding in a much faster manner, but it does not expose personnel to walking through uneven and sometimes dangerous terrain. Forest reseeding is an extremely labor-intensive operation requiring personnel to carry 40 pounds of one- to two-year-old seedlings with them and plant each one by hand. The process is slow and can be dangerous. Aerial seeding by helicopter is another option, simply dropping seeds onto bare ground. However, aerial seeding has a low uptake rate and is costly to perform. Seeding from UAVs may be the best and most economically viable way to perform reforestation work.

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[111] Joel Reichenberger, "Iowa Startup Hopes to Provide Efficiencies and Options with Amped-Up Drone Sprayers," DTN Progressive Farmer, November 30, 2019, https://www.dtnpf.com/agriculture/web/ag/news/article/2019/11/20/iowa-startup-hopes-provide-options.

[112] Eric Kulisch, "Korean Air Develops Drone Swarm Technology to Inspect Aircraft," *Flying Magazine*, December 20, 2021, https://www.flyingmag.com/korean-air-develops-drone-swarm-technology-to-inspect-aircraft/.

[113] "Home Page," DroneSeed, accessed October 11, 2021, https://droneseed.com/.

[114] Evan G., "DroneSeed Granted First Ever FAA Heavy-Lift Drone Swarm BVLOS Waiver for Reforestation," U.S. Civilian Intelligence Agency, December 10, 2020, https://www.us-cia.com/post/droneseed-granted-first-ever-faa-heavy-lift-drone-swarm-bvlos-waiver-for-reforestation.

The DroneSeed system consists of a heavy-lift UAV and a delivery module, much like the IGNIS system. It drops capsules, including sprouted seedlings, dirt, and nutrients. In the future, it may be possible for DroneSeed to adapt the IGNIS system to its aircraft as a contractor for aerial backfiring or Drone Amplified to partner with DroneSeed for indirect fire attacks using its swarm technology.

The threat of wildland fires and fires in the urban interface will continue to grow as the population expands into the interface area. This impact, coupled with increasing global warming factors, indicates a trend in more severe and more dangerous fire seasons in the coming decades. It will be necessary for fire managers to leverage technology and other innovative ideas to provide the safest, most effective workplace possible. The concept of utilizing UAVs to assist in fighting fires through information gathering has been proven effective. Exploring the idea of using swarms of UAVs for direct fire suppression is a logical next step in advancing and integrating technological solutions to combat the increasing fire problem.

IV. METHODOLOGY AND RESULTS

To evaluate the validity of UAV swarms performing firefighting operations, it is necessary to perform a comprehensive analysis of their abilities compared to current aerial firefighting aircraft. As swarm technology is in its infancy, it is not easy to accurately compare swarms of firefighting UAVs to aircraft in a meaningful way. There have been no instances of swarms of UAVs performing direct fire-suppression operations. However, it is possible to develop a model of a theoretical UAV swarm and compare it to a known firefighting asset in relation to fighting a specific fire. This chapter shows the comparative value of each asset based on how much suppression product can be delivered on the fire within a given time. Additionally, the cost per gallon of suppressing agent can be compared between the UAV swarm and aircraft.

A. FIELD EXPERIMENTATION: FLYING SWARMS OF UAVS

The practical research for this thesis started by assisting the ARSENL group at the Naval Postgraduate School (NPS) with UAV swarm test flights. During this field research, we evaluated the effectiveness of flying swarms of aircraft in the fixed-wing and quad-rotor-wing configuration while integrating ground-based rover-type unmanned ground vehicles (UGVs) into the swarm group. The concept of flying swarms of UAVs is theoretical for most people. However, within NPS, the ARSENL group has been performing this research for several years. ARSENL has an ongoing commitment to testing swarm technology with the mandate to explore the ability of UAV swarms to make a positive impact in the military battlespace. As ARSENL expanded its testing protocols, it identified multiple civilian roles for which UAV swarm technology could be applicable. In exploring the research question of how UAV swarms could be integrated into wildland firefighting, the value of hands-on knowledge specific to swarm operation is critical. To gain that practical knowledge, in May 2021, we performed swarm test flights at McMillian Airfield at Camp Roberts, California. On the days we were testing, the weather was good, there were very few terrain obstructions, most UAV flights were performed in the line of sight with controllers and data links, and there were no other radio signals to conflict with the UAVs due to the controlled airspace at Camp Roberts.

The objective of these flights was to test the viability of developed tactics composed of multiple plays that ARSENL had developed. Tactics are best understood in the context of an overall mission objective, while the plays are the component parts of that mission. For example, a direct fire attack is a tactic, and specific plays to achieve that tactic include putting water on the fire, digging the fire line, and supporting the operation with logistics.

While the primary nexus of this testing has military implications, many of the plays can be adapted to wildland firefighting. An example is the so-called direct-drop play in which something on the ground is identified as hostile and the UAV "attacks" it.[115] The direct-drop play can be adapted to wildland firefighting as the direct fire-attack tactic in which the UAV identifies the fire as hostile and then attacks it. Another military-based play that we tested required UAVs to deploy smoke in front of oncoming ground forces during an amphibious landing. The UAVs fly to a designated point in this play and evaluate the prevailing wind direction. Once the UAV swarm defines the wind direction, it flies to the upwind side of the geofence, a pre-designated area of operations where the UAVs are allowed to operate, and then "drops smoke" down the geofence line. The play is designed to hide the oncoming ground forces as they advance to the landing beach. The smoke-drop play can be adapted to wildland firefighting using UAVs for aerial ignition. When igniting backfires, it is crucial to start the fire on the upwind side of the geofence, so the fire will burn in the desired direction. These examples indicate the value of building tactics and plays that can be adapted to multiple civilian and military applications.

An early observation during our flight testing was the speed of launch of quad-rotor UAVs compared to fixed-wing UAVs. The quad-rotor UAVs launch as they attain lift much like standard helicopters as they are powered up. For launching purposes, the quad-rotor UAVs simply needed to be "pre-flighted" (have the batteries installed and checked for flight dynamics), armed, and checked for connectivity with the launching station.

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[115] Kathleen B. Giles et al., "Expanding Domains for Multi-Vehicle Unmanned Systems," in *2021 International Conference on Unmanned Aircraft Systems* (Piscataway, NJ: IEEE, 2021), 1407, https://doi.org/10.1109/ICUAS51884.2021.9476788.

Conversely, the fixed-wing aircraft needed to be individually launched using a purpose-built fixed-wing UAV launcher to gain the necessary speed to provide lift for flight. Each fixed-wing UAV had to be individually pre-flighted, placed on the launcher (see Figure 2), armed, checked for connectivity with the base station, and launched. This process required at least three people, one to place and launch the UAV, one to manage the control of the launch, and one to establish the data link.

Figure 2. Fixed-Wing UAV Launcher[116]

When launching large swarms of UAVs (especially involving fixed-wing UAVs), it became apparent that the extended launch time per UAV cut into the actual flight time for the entire swarm. During our test flights, we launched a total of about 12 UAVs. The total launch time was approximately 12 minutes. We were not attempting to launch quickly during the launching process but instead focused on ensuring that each UAV was ready to join swarm operations post-launch. Our UAV swarm might have been launched in a slightly quicker time. The practical hands-on experimentation of flying designated plays illustrates the relative ease or difficulty of putting UAV swarm operations into practical application.

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[116] Photograph taken by Robert Hutchens.

The information collected during just a few test flights of UAV swarms indicated both the relative value of UAV swarms and the pressure points that could be encountered during implementation. One such pressure point was the relatively large number of ground personnel necessary to prepare and fly UAV swarms. As with any cutting-edge technology, concepts that look flawless on paper can end up being impractical or impossible in practice. The hands-on flying of UAV swarms was imperative to our understanding of both the limits and the potential for firefighting UAV swarms.

B. MODELING AND SIMULATION ANALYSIS

In addition to field experimentation, it was necessary to develop a theoretical wildland fire for both the UAV and the conventional aircraft to attack. By comparing the UAV swarm to a conventional air attack, conclusions could be made about the validity and relative value of UAV swarms fighting wildland fires. Additionally, simulations were built and performed using Innoslate systems engineering software to understand the relations and potential issues when managing aircraft operations. The quad-copter Firefly made by Parallel Flight Technologies was chosen as a representative UAV for firefighting operations, and the AT-802 aircraft was chosen as it could attack the fire in our designated location. The following information defines the parameters under which we made our calculations, assumptions, and the visual representation of aircraft operations.

1. Preflight Assumptions

The preflight process for UAVs is extensive and essential to ensuring a safe and successful flight. As the UAVs will be operating in a swarm and sharing position and orientation (POSE) information, all flight systems, data links, GPS, and sensor systems must be tested before flight. Each of these systems takes time to test and verify. The preflight for fixed-wing aircraft is much more extensive compared to the quad-rotor UAVs. For the fixed-wing aircraft, batteries must be installed and the aircraft checked for flight connectivity, the pitot tube must operate correctly, flight surfaces must be checked, and finally, the attitude (what the aircraft is doing in space, i.e., moving left, right, up, or down) of the aircraft must be consistent. Our theoretical fire assumed enough Oregon Department of Forestry (ODF) personnel to complete the preflight checks, fuel the aircraft, add water for suppression, and prepare for deployment to complete all tasks in one hour. For the UAV swarm evaluated in this analysis, it was assumed that a full preflight was completed on each UAV. Additional prefights were unnecessary during the return, reload, and redeploy phases. A natural time for additional flight system checks would be at the end of the overall mission (post-flight) or the operational period.

The preflight operations for fixed-wing conventional aircraft are well established in the aerial firefighting industry.[117] The process includes checking the aircraft, checking the weather, and ensuring proper radio communications and flight procedures. One of the most time-consuming portions of fixed-wing preflight for actual firefighting missions is mixing the retardant, as it is generally mixed when needed and not kept mixed on hand. This simulation assumed that all necessary preflight operations would be completed within a one-hour window. Because we assumed that all preflight operations for both types of aircraft (quad-rotor UAV and conventional fixed-wing) would be completed in one hour and neither system had a time advantage, the preflight time was omitted from the mission timing.

2. Simulation Components

In dynamic situations such as wildland fires it is critical to remember there is a high likelihood that the situation will change at some point and the actions taken must adapt with the changes. In the simulations we identified actors including the UAV, the aircraft, and the fire. However, weather, current fire conditions, planned operations, and unanticipated logistical issues might change the means of attack. As such, our simulations were based on best-case scenarios with no significant changes in the fire.

a. The UAV

For all our simulations, we use Parallel Flight Technologies’ Firefly (see Figure 3), a hybrid electric and two-cycle gasoline-powered, heavy-lift UAV system for this

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[117] Faasau, *Large Airtanker Operations Plan*, 10–12.

analysis.[118] This UAV can lift 100 pounds and fly for up to two hours with a 100-pound payload. The Firefly UAV is not a small unit at almost five feet in length, four feet in width, and three feet in height.[119] The payload capacity allows each UAV to deliver 10 gallons of water weighing 84.30 pounds. We assumed that the delivery system, avionics, and sensor package comprise the remaining payload. The UAV swarm has 50 UAVs in total. Therefore, the whole swarm delivers 500 gallons of water for fire suppression during each flight cycle. The swarm continues to suppress the fire until the swarm has flown for four hours, representing the one fuel cycle of the conventional aircraft. The four-hour period was chosen because it is a realistic time frame for aircraft to attempt to suppress the fire. From past experiences, we know fires typically show marked improvement in four hours of aerial suppression. If they do not, aerial tactics will likely be revisited and potentially changed. While it is unlikely that all UAVs in a swarm will operate correctly every time in actual fire scenarios, for this scenario, we assumed a 100 percent success rate in flying, identifying the fire, and suppressing it through proper deployment.

Figure 3. Parallel Flight Technologies' Firefly UAV[120]

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[118] Sara Isenberg, "Fly Longer, Lift More, and Fight Wildfires," Santa Cruz Tech Beat, October 25, 2019, https://www.santacruztechbeat.com/2019/10/24/fly-longer-lift-more-and-fight-wildfires/.

[119] Parallel Flight Technologies, "Firefly Heavy-Lift UAS."

[120] Source: Parallel Flight Technologies, "Firefly Heavy-Lift UAS."

The Firefly UAV has a range of 25 nautical miles based on flight time and type, according to NWCG typing guidelines.[121] The Firefly falls into the NWCG Type 2 (6,000-foot ceiling and a range of 25 miles) category based on its performance.[122] The UAVs are assumed to be based at the ODF's district headquarters (HQ) at 801 Gales Creek Road, Forest Grove, Oregon, 97116. All UAVs are launched, serviced, and recovered from this location.

b. The Aircraft

The aircraft modeled in this scenario (Figure 4) is the Air Tractor AT-802 SEAT.

The SEAT is the type of aircraft most likely dispatched to a fire in western Oregon. The AT-802 has a primary payload of 800 gallons of fire retardant. The Salem, Oregon, airport is the closest air base to service the AT-802, which has a range of 800 nautical miles. For this scenario, the aircraft suppressed the fire for one standard fuel cycle with necessary reserve fuel to return to base safely. The AT-802 can fly for up to four hours on one tank of fuel but ceases operations with 30 minutes of fuel left to return to the airport safely. The aircraft can make four retardant drops in our scenario before performing an extended service for fuel and retardant. The Salem airport is located at 2990 SE 25th Street SE, Salem, Oregon, 97302.[123]

c. The Fire

The fire for our comparative analysis scenario is in the Tillamook State Forest in western Oregon. The fire is located at Southwest Scoggins Valley Road and Dodson Road (GPS 45.5323 W, 123.2702 N), 5.79 nautical miles from the Forest Grove ODF district HQ (GPS 45.5323 N, 123.1327 W). The AT-802 is based at the Salem, Oregon, airport (44.9120 N, 123.0033 W), the closest airport to service the aircraft with mix tanks for retardant. The Salem, Oregon, airport is located 39.09 nautical miles from the fire. The fire

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[121] National Wildfire Coordinating Group, *Standards for Fire Unmanned Aircraft Systems*, 2.

[122] National Wildfire Coordinating Group, 2.

[123] Air Tractor, "AT-802F Fire Boss."

is assumed to move at a rate and intensity that could be attacked with UAVs or conventional aircraft. The weather is assumed to be negligible.

Figure 4. AT-802 in Standard Configuration[124]

3. Graphical Representation of UAV Swarm Flight Profile

The UAV swarm flight profile is represented in Figure 5. The graph highlights the flight operations of the UAV swarm attacking the fire over four hours, represented in local time. For graphical purposes, the flight time is rounded to 10 minutes from 9 minutes, 56 seconds, from launch to the fire (see Table 1). We assumed that flight times are slower when the UAVs are loaded with water but faster on return to base as they are unloaded. These two legs of the flight averaged 20 minutes of flight time for the roundtrip. We assumed that the UAVs travel horizontally and vertically when climbing and descending. The cruise altitude is 350 feet above ground level (AGL), descending to 20 feet AGL for the water drop. The graph indicates that the UAV swarm can make two drops on the fire before refueling with two-cycle gasoline. Blue arrows indicate the water drops while green lightning bolts indicate water reloading. The red diamonds on the graph represent the extended service time for refueling and reloading. Even with UAVs that can fly for two

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[124] Source: Alejandro Hernández León, “Air Tractor AT-802,” Airliners, June 5, 2010, https://www.airliners.net/photo/FAASA-Chile/Air-Tractor-AT-802/1722755.

hours, such as the Firefly, this 50 aircraft swarm will be labor-intensive to service to maximize flight time. Ensuring adequate ground support personnel is critical to having a successful outcome. Eight ground personnel are dedicated to completing the ground service for the UAV swarm for our simulation. During the four-hour flight cycle, the UAV swarm can make five round trips, for a total of 2,500 gallons of water delivered.

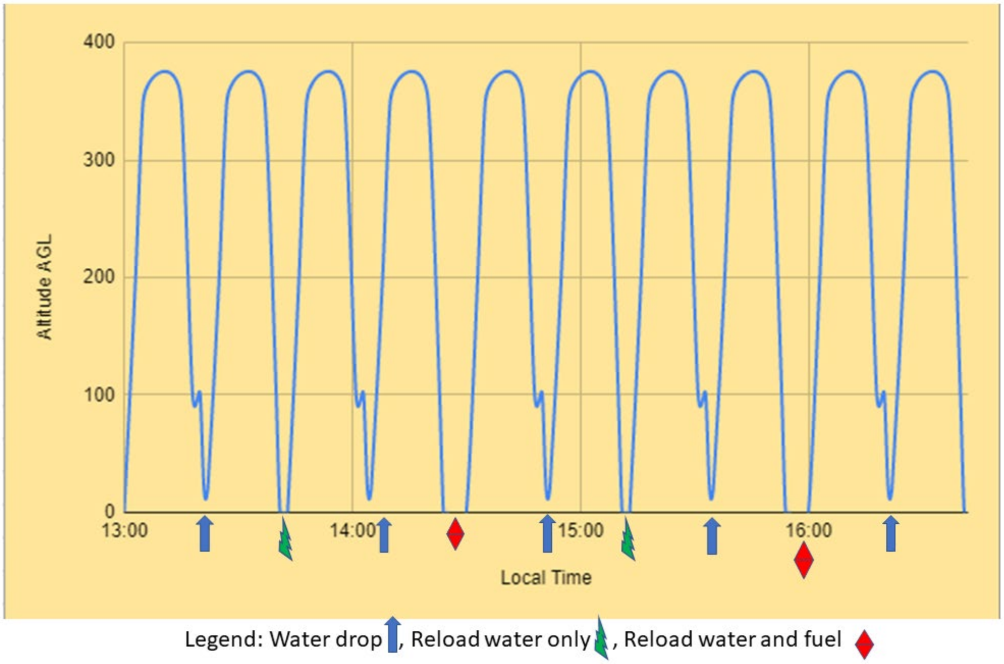

Figure 5. Graphical Representation of UAV Swarm Firefighting Flights over Four Hours

Table 1. Flight Information for the Firefly UAV

Flight Speed	Distance from ODF HQ to Fire	Flight Time to Fire
35 mph	5.79 miles	(60 minutes * 5.79 miles)/ 35 mph = 9 minutes, 56 seconds

4. Graphical Representation of AT-802 Flight Profile

The fire suppression operations of the SEAT are represented in Figure 6. The graph highlights the direct attack flight operations against the fire using a single AT-802 over four hours of flight time, graphically represented in local time. For graphical purposes, the flight time is rounded to 15 minutes from 14 minutes, 40 seconds, from launch to the fire (see Table 2). We assumed that flight times are slower when the aircraft is loaded with retardant but faster on return to base. The two legs of the flight average 30 minutes of flight time for the roundtrip. We assumed that the aircraft travels horizontally and vertically when climbing and descending. The graph in Figure 6 represents a general flight path during drop and reload cycles. As such, the AT-802 may move more horizontally or vertically during its climb and decent. The cruise altitude is 1,500 feet AGL, descending to 80 feet AGL for the retardant drop.[125] The graph indicates that the AT-802 makes four drops on the fire (represented by the blue arrows) during the single fuel cycle. Notably, the AT-802 is certified for "hot reloading," meaning that it can be refilled with retardant without having to shut down its engines.[126] Hot reloading minimizes the reload time for each trip as the aircraft must only land, taxi, reload, and take off again. Retardant reloading is represented by the green lightning bolts. Throughout the four-hour flight cycle, the aircraft can make four round trips for a total of 3,200 gallons of retardant delivered. The red diamond represents an extended service time to refuel and reload with retardant.

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[125] Jesse Weaver (chief pilot of Dauntless Aviation), personal communication, January 23, 2022.

[126] National Wildfire Coordinating Group, *Interagency Single Engine Air Tanker Operations Guide*, PMS 506 (Boise, ID: National Interagency Coordination Center, 2014), 36, https://gacc.nifc.gov/swcc/dc/nmsdc/documents/Dispatch/Reference/INTER_SEAT_Op_Guide_4-14.pdf.

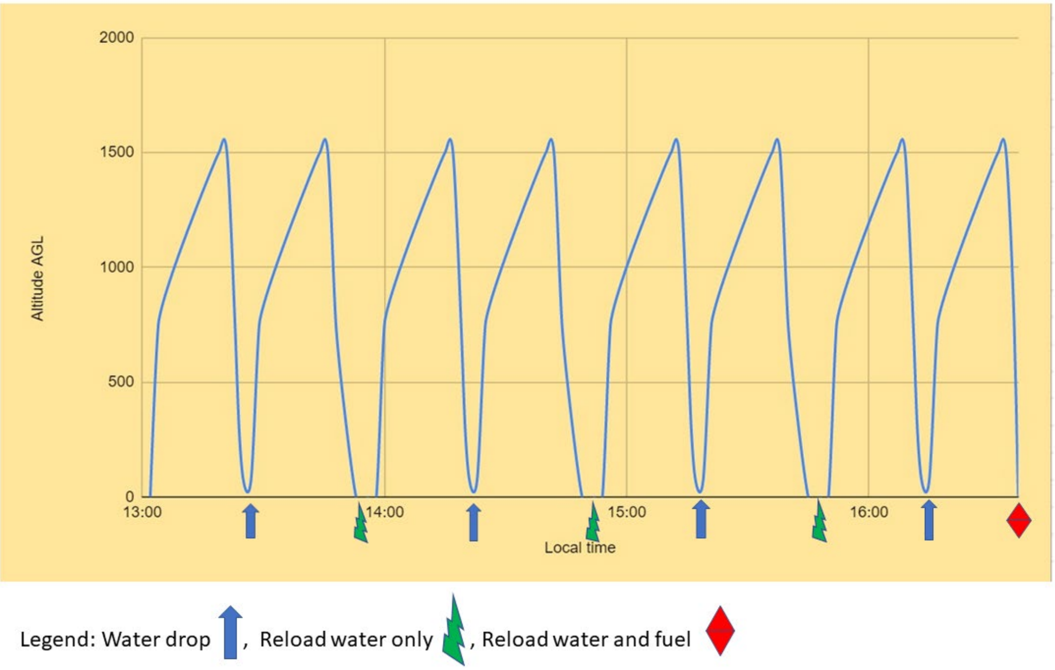

Figure 6. Graphical Representation of the AT-802 Firefighting Flights over Four Hours

Table 2. Flight Information for the AT-802

Flight Speed	Distance from the Salem Airport to the Fire	Flight Time to Fire
160 mph	39.09 miles	(60 minutes * 39.09 miles)/ 160 mph =14 minutes, 40 seconds

5. Action Diagrams to Represent Firefighting Operations

The concept of swarms of UAVs performing complex actions like firefighting requires a method to evaluate and visualize the flight process. As the research questions were investigated, it became clear that a process was needed to model complex systems. Innoslate 4, version 4.5.1.0, model-based systems engineering (MBSE) software was chosen for this function. Innoslate allows users to graphically represent complex actions and relationships using Life cycle Modeling Language. This open standard modeling language provides clarity for all stakeholders viewing the models, from dedicated system engineers, to project managers, to workers who are implementing the project.[127] Choosing a language whereby all persons can understand what is happening reduces the chance of incomprehension or mismanagement.

In the case of the fire scenarios, action diagrams were chosen to represent specific flight operations. These diagrams allow users to define specific actions and the relations of those actions to the next logical progression. The diagrams are generally read from left to right but may not be in sequential order from top to bottom as simultaneous actions may relate to others. The software allows for "looping," "or," and "triggering" gates to visually represent specific actions and their relations to others. The software further allows users to test their action diagrams using executable models with realistic timelines. If a model does not make sense logically in the executable model mode, it will deadlock and indicate a fault in the system. The presented tactics and plays have been tested to ensure they fully complete their required actions within the reasonable time frames of the given flight pattern graphs, as shown in Figure 5 (UAV swarm operation) and Figure 6 (AT-802 operation). Each tactic or play has a unique numbering system to define what action is happening. It starts with a tactic or play designation, for example, "AT" for the aircraft tactic, followed by a number starting with number one. The tactic or play moves logically from number one to the end. If actions happen simultaneously, they are designated by a number and an alpha and bravo designator to illustrate their co-occurrence. Utilizing a systems methodology with a common language for this comparison ensured that the hypothesis parameters were feasible and accurate.

The following diagrams represent theoretical operations completed by either the UAVs or AT-802 aircraft in the fire scenarios. These diagrams are referred to as tactics or plays loaded into the UAV's performance algorithm or the standard operating procedures for the piloted aircraft. By graphically representing the actual steps in completing the designated tasks, faults in the system could be identified.

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[127] Steven Dam, *Life cycle Modeling Language (LML) Specification* (Life cycle Modeling Language, 2015), 3–5, https://lifecyclemodeling.org/wp-content/uploads/2021/01/LML_Specification_1_1.pdf.

a. Reload and Return Play

The reloading and return play illustrated in Figure 7 is a standard play that has been deconstructed for the follow-on diagrams in the interest of space and readability. In the following figures, the reloading and return play is embedded in the figure and represented as "R&R Reload and Return Decomposed." Regardless of which aircraft (UAV or AT-802) performs the suppression task, they must move through the reload and return play. The play determines whether the fire is still burning after one suppression drop. If it is not, the entire scenario is complete, and the aircraft returns to base for the next mission. If the fire is still burning, the aircraft returns to its base, reloads with a suppressant, and re-enters the firefighting play. The "return for suppressing agent" trigger point is indicated in gray to show that it is not required to complete the play. The reload and return play continues until the fire is suppressed or the air boss calls off the flights.

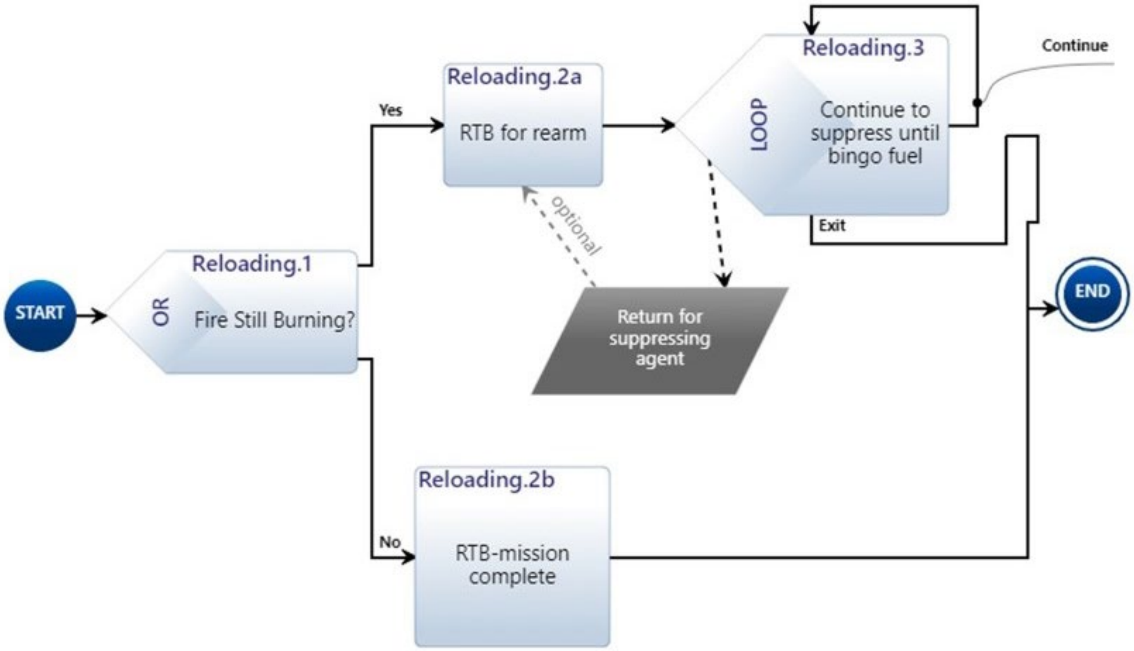

Figure 7. Reload and Return Play[128]

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[128] Reload and return is a standard play to visualize the necessity for UAVs and fixed-wing aircraft to return to base, reload with suppression agent, and return to the fire.

b. AT-802 Piloted Aircraft Firefighting Tactic

The steps for utilizing air tankers to fight fires are represented in Figure 8. The tactic starts with a notification of the fire and a request for tanker support from the ODF. As air tankers are a scarce resource, all tanker requests must be approved at the state level to ensure the proper utilization of resources. The green parallelogram blocks are trigger points that must be completed to advance the sequence or deadlock the scenario. The gray parallelogram blocks are optional triggers. For example, if the ODF has no air tankers to assign, the “assign mission” returns a negative response, and the mission cannot continue. In the case of this scenario, the aircraft may or may not return for suppressing agent. The fire may be out, and additional retardant drops are not necessary. As with all suppressing assets, the AT-802 must move through the deconstructed Reload and Return play (Figure 7). Notably, fixed-wing air tankers also need ground support personnel. However, the aircraft’s overall preparation and the necessary ground support to load and mix the retardant are less labor-intensive than the UAV swarm.

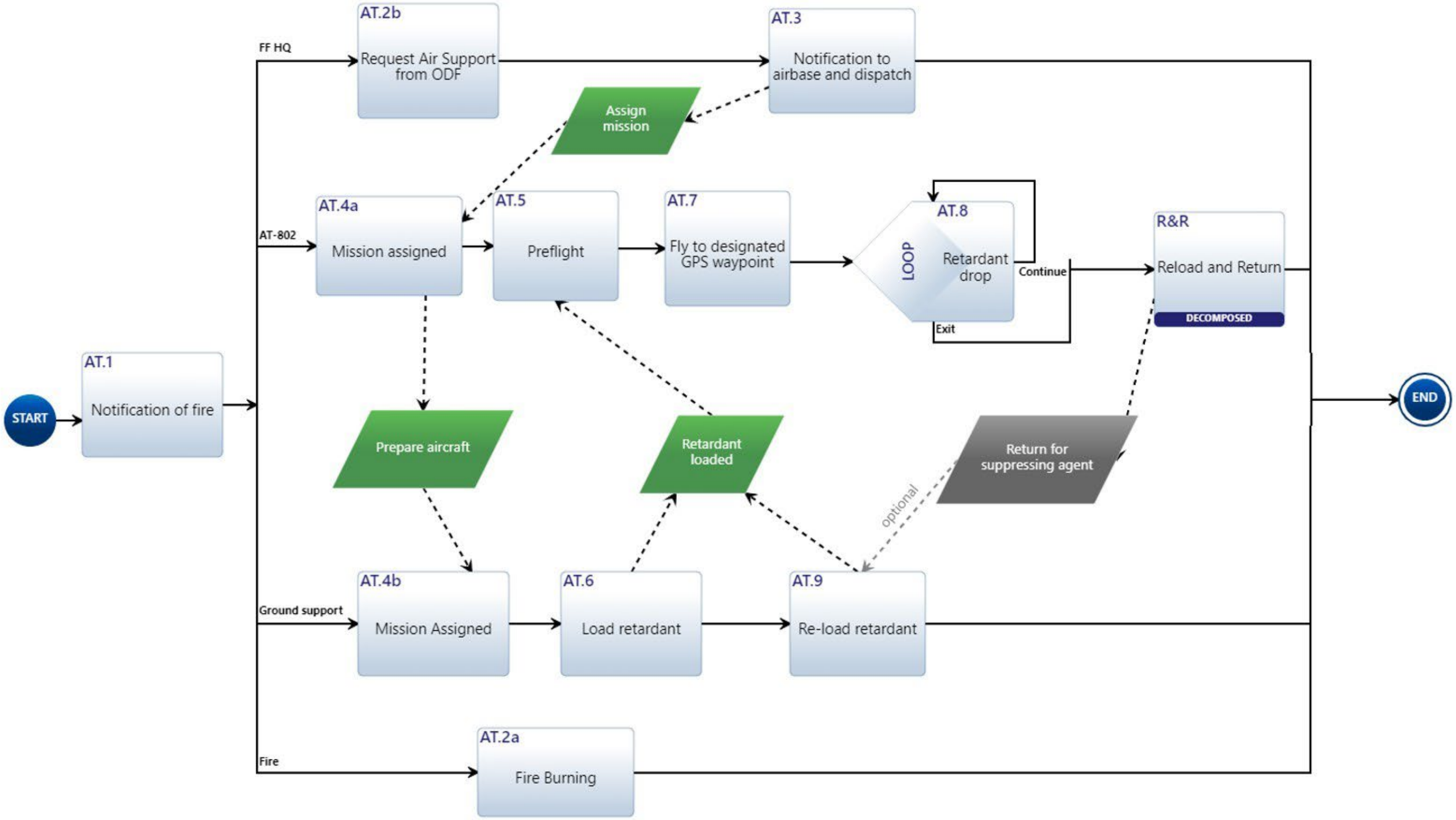

Figure 8. Fire Attack by Fixed-Wing Aircraft from the Airport to the Fire

c. Firefighting Operation Performed by UAV Swarm Tactic

The firefighting operation of the UAV swarm is represented in Figure 9. The tactic starts when firefighting HQ is notified of a potential fire in a specific location. It is assumed that the fire is burning for this tactic and firefighting HQ has an actual location with which they can load geofence coordinates for the UAV swarm. The UAV swarm launches, identifies, and begins to suppress the fire and continues in a return and reload loop until the tactic is called off or the onboard sensors of the UAV no longer perceive the fire. Embedded in this tactic is the play to define that UAVs can carry either water or fire retardant as a suppressing agent. The weight difference between 10 gallons of water and 10 gallons of retardant is within the parameters for the Firefly UAV to lift effectively.[129] We chose water each time the UAV reloaded due to its accessibility in our scenario. However, it is important to note that using fire retardant is feasible.

It is necessary to have enough personnel to prepare, recover, and reload the swarm of UAVs to complete this play effectively. In the scenario, with the swarm flying for four hours, the swarm needs to be loaded with water five times and needs to be refueled with mixed gasoline twice. A 50 UAV swarm will take a significant number of support personnel to complete these tasks promptly. The minimum ground support crew consists of at least eight persons and two water pumping vehicles. The ground support crew needs one person to operate the water pumps, two people to load water into the UAVs, three people to refuel the UAVs, one person to manage the area's staging and act as a floating helper, and one person to supervise the servicing operation. This designated ground support crew does not perform the functions of launching or recovering the UAVs, so additional personnel are needed to complete those tasks.

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[129] Cammack, *Fire Retardant Standard Mixing System*, 2.

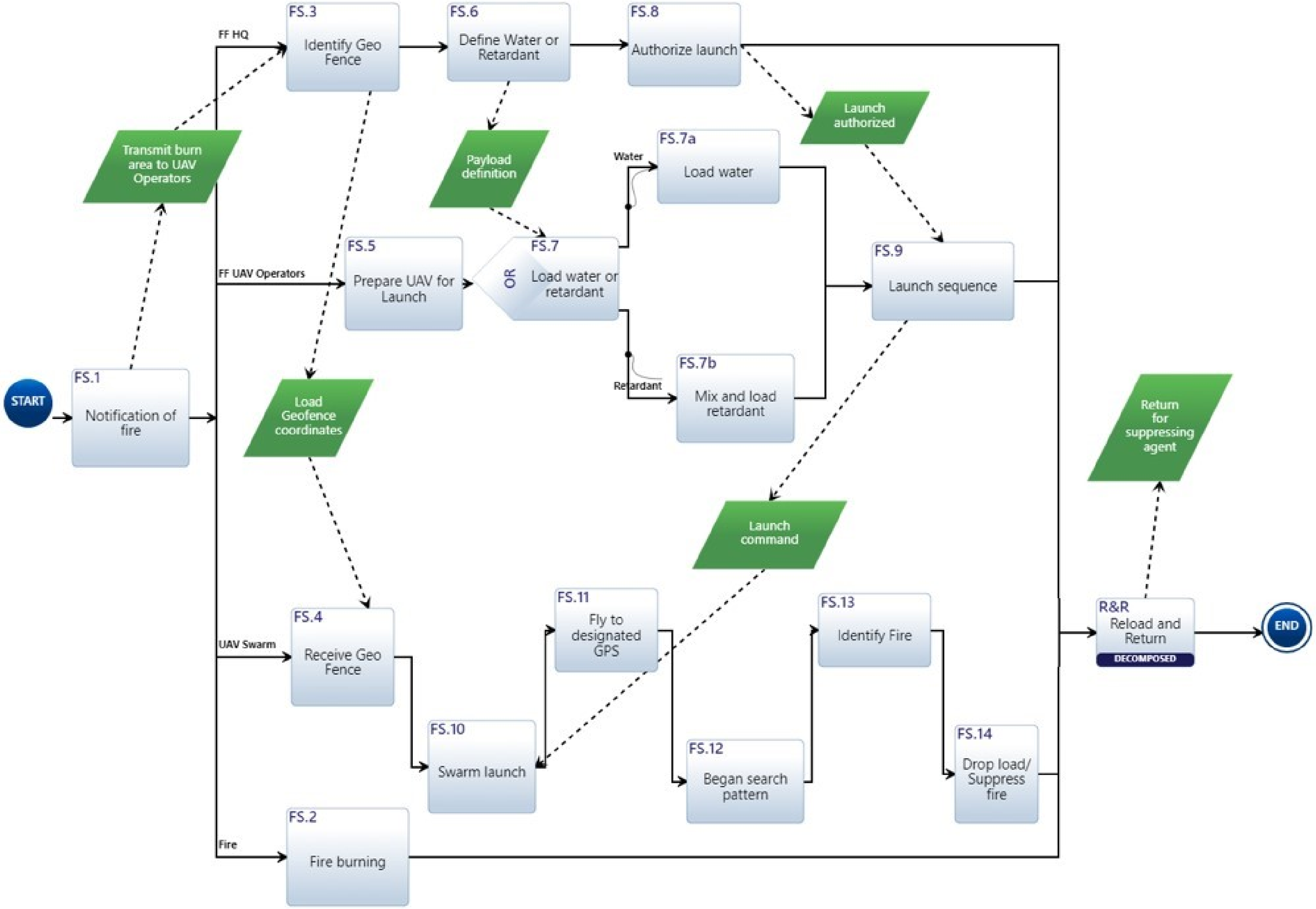

Figure 9. UAV Swarm Taking Fire Suppression Action against a Fire

d. Indirect Fire Attack through UAV-Ignited Backburn with a UAV Firefighting Support Tactic

The indirect fire-attack tactic represents the most complex firefighting operations modeled in the firefighting scenarios, as shown in Figure 10. In this tactic, incendiary UAVs are dispatched to perform a backburn within a designated geographic area. Backburning is a complex mission that must factor in current and anticipated weather, topography, and the ability of firefighters to control the burn should it move out of control. Backburning is a highly orchestrated event that seeks to burn away specific fuel to deny the progression of the primary fire. Ground forces are required to define the burning area, watch the weather, and monitor the fire's progression. These forces may be physically in the local area or monitoring from a safe area.

In this scenario, coordination must be achieved between two different swarms of UAVs performing complementary missions and the ground forces that must monitor the fire. The firefighting operation commences with the incendiary UAVs being dispatched to a specific area to start the burn while an additional firefighting UAV swarm is directed to monitor and control any fire that escapes the geofenced area. While the incendiary UAVs start the fire, the firefighting UAVs are loitering and monitoring any identified fire outside the geofenced coordinates. This contrasts with our firefighting tactic in which the UAV swarm is looking for fire within a geofenced area. If they find a fire that has moved outside of the backburn's expected path, they take action to suppress the fire. As the firefighting ground crew monitors the progression of the burning operation, they determine whether the fire is meeting the expected goals and moving in the anticipated direction. If it is, they may continue the burning operation; if it is not, the mission is aborted, and all UAVs return to base. Should the fire burn in an unanticipated area, it is likely that the firefighting UAV swarm will be retasked to general firefighting operations (see Figure 9) and expected to suppress the fire until the tactic is canceled.

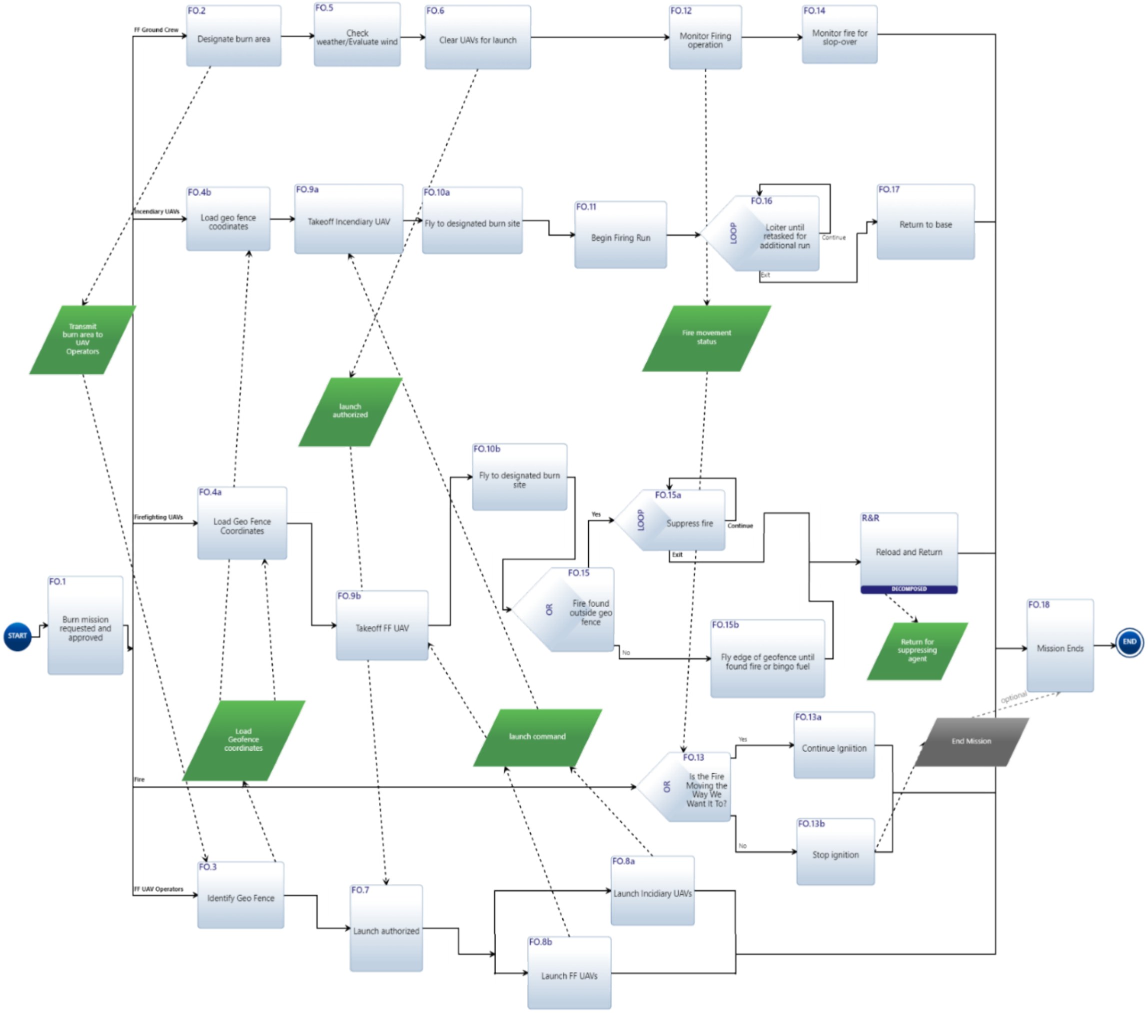

Figure 10. Indirect Fire Attack Using Incendiary and Firefighting UAVs

C. COST COMPARISON: A UAV SWARM VERSUS THE AT-802

To evaluate the effectiveness of the firefighting scenarios involving both the UAV swarm and the conventional air tanker, standard metrics were defined so they could be evaluated across both platforms. The amount of suppressing agents delivered in the given time (water for the UAVs and fire retardant for the SEAT) and the cost per gallon to deliver the suppression agent with each aircraft system were compared.

Parallel Flight Technologies expects to have the Firefly in commercial production in 2023. Currently, there is no public costing information available. Therefore, the cost of each UAV is assumed to be $15,000 per aircraft for comparison purposes.[130] The price point of $15,000 was chosen as a mid-point of two comparable UAVs being used in wildland and agricultural applications. The two UAVs are the DJI Matrice 600, which was used by Drone Amplified for its IGNIS system before the Chinese technology embargo, and the DJI Agras, a largely agricultural-based UAV. DJI's Matrice costs about $7,000 and the DJI Agras about $21,500.[131] It is expected that Parallel Flight Technologies will offer the Firefly at a relatively low price point to make headway into the UAV market. The price is theoretical and subject to change as production becomes more scalable and available. The first generation of UAVs will likely cost significantly more than $15,000 per vehicle. However, the cost should decrease rapidly as the UAV becomes more scalable and modular. Should the costs increase or decrease significantly, they will simply need to be placed into the calculations table to compare aerial systems.

The cost calculations for the swarm operation appear in Table 3. The Firefly UAV uses a mixed gasoline–electric hybrid system, which requires fueling twice during our flight scenario. For our scenario, water has been assigned a zero cost as it is readily available and easily transported. As noted previously, this is a labor-intensive process and requires a comparatively large ground crew. We estimate that the ground support crew will be eight persons with a cost of $50 per hour per person. Factoring all costs, the estimated cost per gallon of water delivered by the UAV swarm is $2.00 per gallon.

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[130] Christian Balderas, "'Game Changing,' Central Coast Company Unveils Firefighting Drone," KSBW Monterey, February 2, 2022, https://www.ksbw.com/article/game-changing-central-coast-company-unveils-firefighting-drone/38956762.

[131] "DJI Matrice 600 Series," Advexure, accessed February 28, 2022, https://advexure.com/collections/dji-matrice-600-series; "DJI Agras T16 Agriculture Drone—Ready to Fly Kit," DroneNerds, accessed February 28, 2022, https://www.dronenerds.com/products/drones/enterprise-drones/dji-agras-series/agrast16/dji-agras-t16-agrast16-dji.html.

Table 3. Cost Comparison for UAV Swarm and AT-802

Cost/Expense	UAV Swarm	AT-802
Cost of a single aircraft	$15,000	$1,700,000
Number of aircraft working	50	1
Total acquisition cost of aircraft	$15,000 * 50 = $750,000	$1,700,000
Gallons of suppressant dropped per flight	50 aircraft * 10 gallons = 500 gallons	800 gallons
Gallons of suppressant dropped in 4 hours	500 gallons * 5 drops = 2,500 gallons	800 gallons * 4 drops = 3,200 gallons
Personnel costs	8 dedicated personnel at $50 per hour for 4 hours = (8 * $50) * 4= $1,600	Built into hourly and daily costs
Cost of suppression agent	Negligible	$2.50 per gallon
Average daily cost	N/A	$4,500
Average cost per flight hour	N/A	$4,500 per hour
Fuel cost	17 gallons per UAV at $4 per gallon = $68 per UAV	Built into the hourly cost
Fuel cost for swarm	$68 per UAV * 50 UAVs = $3,400	N/A
Cost of suppressant per drop	Negligible	800 gallons * $2.50 per gallon = $2,000
Total cost of flight operations for 4 hours	$3,400 fuel + $1,600 personnel = $5,000	$4,500 + ($4,500 * 4 hours) + ($2,000 * 4 drops) = $30,500
Total cost of suppressant delivered	$5,000/2,500 gallons = $2 per gallon	$30,500/3,200 gallons = $9.53 per gallon

The standard version of the AT-802 with standard landing gear and belly tank retails for $1.7 million.[132] The air tankers utilized in Oregon are contracted on either an exclusive-use or call-when-needed contract through private air tanker operators. Air tankers are contracted based on a fixed cost plus an hourly rate for flight time. The costs for the AT-802 operations appear in Table 3. According to Jesse Weaver, the chief pilot for Dauntless Air (private air tanker contractor), the average cost for the AT-802 is a fixed $4,500 per day plus $4,500 per hour of flight time.[133] All associated fuel and personnel costs are integrated into these daily costs. However, the cost of the retardant is generally borne by the fire and is $2.50 per gallon.[134] Therefore, the cost for the operation of the AT-802 is the daily cost, plus the cost of flight time and the cost of the retardant. The scenario defines that the aircraft drops 3,200 gallons of retardant during the four-hour operation. The overall cost per gallon of retardant delivered is $9.53 per gallon. In this formula, the cost per gallon of retardant delivered decreases as the length of flight time per day increases, as the fixed cost of the daily rate is spread over more gallons of retardant dropped. However, if the aircraft works a full 14-hour day, the cost per gallon of retardant dropped decreases only to $8.53 per gallon.

In evaluating the costs for suppression in our fire scenario and with the stated assumptions, the UAV swarm provides a more economical solution than the AT-802. Should we replace the retardant on the air tanker with water in the scenario; the cost decreases to $7.03 per gallon of water delivered. This still represents a significantly higher cost than the $2.00 per gallon of water delivered by the UAV. However, in the scenario, it is assumed that the UAV swarm is owned and operated by the forest protection entity, in this case, the ODF. As an owned asset used for wildland firefighting, the daily cost of the swarm is not a factor as the swarm is being used as a tool, much like a fire engine or chainsaw. The first swarms used in wildland firefighting will likely be owned and operated by private entities and contracted for use when a wildland fire happens, much like how air tankers are contracted. In this case, there would likely be a daily rate and a cost of flight

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[132] Valley Air Crafts, “Fire Agency Briefing,” 9.

[133] Weaver, personal communication.

[134] Masunaga, “Fire Retardant Dropped Out of Planes.”

time, which would increase the cost per gallon of water delivered. Unfortunately, there is no experience with UAV swarm contracting, so educated guesses about how these assets would be procured and integrated into existing fire operations must be made.

The primary advantage of the UAV swarm system is that it can operate in conditions that crewed aircraft cannot. To compare two vastly different systems, the flight operation was constrained to one fuel cycle of the aircraft. However, the AT-802 can conceivably fly up to 14 hours per day, flying from 30 minutes before sunrise to 30 minutes after sunset.[135] The aircraft is additionally constrained by the 14-hour crew day rule and the inability to fly in darkness and smoke.[136] The likelihood of achieving 14 hours of productive firefighting time from a conventional aircraft is unlikely. Conversely, the UAV swarm could theoretically fly up to 24 hours per day, assuming it had enough ground support personnel. Based on our estimate of eight personnel to support flight operations, the total needed ground support personnel swell to 16 or more when performing operations over 24 hours. If we extrapolate the time and gallons delivered, the UAV swarm could theoretically drop 30,000 gallons of water in 24 hours. The AT-802 could theoretically deliver 11,200 gallons of retardant in the maximum 14 hours of flight time in one day. Based on this finding alone, the exploration of UAV swarms as firefighting tools appears to be justified.

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[135] National Wildfire Coordinating Group, *Single Engine Air Tanker Operations Guide*, 16.

[136] National Wildfire Coordinating Group, 3.

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V. DISCUSSION AND RECOMMENDATIONS

The process of operating UAV swarms requires the integration of many component parts to ensure a successful outcome. In this chapter, the research is analyzed relative to UAV swarm operation, identified opportunities, and defined pressure points that should be overcome before full implementation of UAV swarm fire suppression. Practical field experimentation coupled with systems engineering modeling was used to identify and understand the relationships of actions within systems and the potential hurdles to full implementation of UAV swarm operations. The potential logistical challenges identified include lost-communications protocols, extended launching times, and management of UAV swarms while in flight.

By using a systems engineering approach to the defined problem, recommendations about best practices could be made regarding aerial asset choice for fire suppression operations. Further, for both systems, it was necessary to minimize transit time to increase the volume of suppressant on the target. The recommendations informed the development of a decision tree for incident commanders to use to determine the most appropriate aerial asset. Finally, a cost comparison was completed illustrating the value of utilizing UAV swarms for fire suppression. The ability to scale UAV swarms for firefighting operations can potentially change the landscape of how fire suppression is delivered in the wildland environment. The opportunity to fight fires earlier in their propagation, more safely without putting aircraft crews in harm's way, and potentially 24 hours per day, even in remote areas, represents a momentous change in how wildland fires could be attacked.

A. FIELD EXPERIMENTATION

The test missions flown in May 2021 illustrated the value for swarm management of a common programming language and the concept of a hierarchical method of plays supporting tactics and tactics supporting the overall mission. By developing general plays and tactics, specific missions could be completed by the most appropriate asset using decentralized multi-vehicle control methods such an auction algorithm. The auction algorithm allows the swarm to use collaborative autonomy to complete the tasks rather than assign specific tasks to each UAV. The swarm completed the plays and tactics while sharing POSE information and deconflicting task assignments within the swarm. The use of ARSENL's concept of plays and tactics, providing a common language across UAV platforms, was necessary to integrate multi-system UAV swarms or swarms performing multiple tasks.[137] The commonality ensures functional performance across platforms regardless of the type of vehicle when implementing plays and tactics. The ability to write one type of code shows the benefit of a common language in the practical operations of swarms.

Having completed the test flights, it was clear that mission building was as important as—if not more important than—the actual UAV performance or ability to perform a specific task. While the building and development of mission-specific UAVs receive much publicity and could be considered the "sexy" part of UAV development, the computer scientists who program the actual flights and ensure that UAVs do what they are supposed to do are the unrecognized backbone of UAV swarm programs.

1. Logistical Challenges of Flying UAV Swarms

One of the most critical and often overlooked items for UAV swarm operations is the logistical support required for flying multiple UAVs. It is easy to believe that UAVs do not require extensive logistical support because the term "unmanned" is in the name. The cost comparison shown in Table 3 illustrated the logistical need to dedicate eight personnel to ground support servicing of the UAV swarm. Additionally, those eight people were defined as the ground support team only. Personnel will be required to upload the mission parameters and maintain the data link throughout the flight, and other personnel will be required to manage the control of the UAV swarm. A 50 UAV swarm may require as many as 12 to 14 personnel to fly and support it effectively. During the test flights and modeling, it was clear that not only do UAV swarms need logistical support, but those who support need to be more technologically specialized and more highly trained than personnel servicing conventional aircraft.

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[137] Giles et al., "Expanding Domains for Multi-Vehicle Unmanned Systems," 1403.

The need for specialized personnel thus becomes an additional constraint that must be overcome. As mentioned previously, the Firefly is not a small UAV. Each UAV takes up about 20 square feet of floor space. The rotors themselves are three feet long. As such, these UAVs cannot easily be transported in a standard pickup truck. Likely, multiple box trucks or even several standard 53-foot heavy-haul trucks and trailers with racks would be required to transport 50 Firefly UAVs. The estimate of eight personnel to service the 50 UAV swarm may be underweighted. As stated, should fire managers attempt to perform 24-hour flights, the personnel needed at least doubles. Further, it is likely not feasible to expect basic firefighters to complete these job requirements.

Gasoline could become a limiting factor in flying UAV swarms. The Firefly UAV is designed to use mixed gasoline in its fuel-powered engines. The wildland fire service tends to use equipment that requires 50:1 mixed gasoline. The gasoline has oil mixed into it, and the motors do not have an oil reservoir. These motors are typically referred to as two-stroke engines. Conventional automobile motors that use unleaded gas and have a separate oil reservoir are considered four-stroke engines. Wildland fire applications for two-stroke motors include chainsaws and pressure and volume pumps. Because every wildland fire uses saws and pumps, the concept of using mixed gasoline for the Firefly UAV makes sense. However, most small engine applications require fuel to be mixed in five-gallon batches, yet the fuel requirement for a 50 UAV swarm operating for four hours is 850 gallons. Extrapolating this to 24-hour operations means that the UAV swarm consumes 5,100 gallons of fuel in 24 hours! The fuel requirement will likely necessitate a dedicated fuel truck with mixed fuel and additional personnel. Mixing and offloading fuel becomes a labor-intensive process that can extend logistical support time.

Finally, although a 100 percent success rate for the UAV swarm was assumed in the scenarios, the swarm will likely experience some failures. These failures may be found during the preflight process, thus rendering the UAV inoperable, or in flight, potentially manifesting as communication and uplink disruptions. During the field testing, we experienced all these issues. Swarm operators must expect some failures of the UAVs, which means they need to prepare more UAVs than they intend to fly to ensure a positive flight from their required number.[138] These failures will necessitate personnel who can troubleshoot the issues and fix the problems so the UAV can be put back in service. The additional workload of preparing extra UAVs increases the personnel and time needed to prepare UAVs. Additionally, should a contractor or a forest protection agency seek to own and operate a flight of 50 UAVs, it must purchase additional UAVs to ensure a full flight operation. The extra purchase represents an additional sunk cost.

The logistical requirements of flying UAV swarms, including personnel, cannot be underestimated. While it is easy to assume that when switching from crewed to an uncrewed option for aerial applications the personnel requirements will decrease, it is likely that initially, the personnel requirements will increase. As UAV swarms are deployed and practical knowledge is gained, specific personnel requirements and costs will likely be refined to an optimal level. However, before that optimal level is found, logistical constraints may require flexibility in UAV operators to solve logistical problems as they arise.

2. Lost Communication

Field testing illustrated how difficult it is to ensure stable data links with UAV swarms. On the days that we tested, the conditions were extremely favorable to having positive uplinks from the controllers and stable data links throughout the flight. Even so, multiple UAVs lost communications with their controllers during the flight. During the test flights, every type of UAV (quad-rotor, fixed-wing, and ground rover) experienced lost communication for different reasons. These reasons included loss of data link, loss of control link, and in the case of the ground UGVs, loss of link due to terrain obstruction. Many of the systems could reestablish communications and return to the swarm, but some had to follow the internal return-to-base protocol for a communication failure. The NWCG requires the loss-of-communications protocol for all UAVs flying in the wildland environment.[139] Fortunately, each of the UAVs that lost communications followed a lost-communications protocol and took a failsafe action to land immediately (quad-copters) or

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[138] Chung et al., "Live-Fly, Large-Scale Field Experimentation," 1258.

[139] National Wildfire Coordinating Group, *Standards for Fire Unmanned Aircraft Systems*, 11.

perform a return-to-base action for the fixed-wing and rover style UGVs. Admittedly, ARSENL UAVs are not optimized for communications reliability; however, some communication failures can be expected unless communications infrastructure is maximized using mesh networks or satellite communications.

One of the critical factors that UAV swarms must account for is maintaining positive control and data links when flying BVLOS missions. In almost all wildland applications, especially firefighting, the UAV swarm will be flying in conditions where the operator does not have direct visual contact with the swam. Obviously, when the controller cannot observe the UAV in a BVLOS situation, the UAV cannot "see" the controller and could have degraded ability to receive controlling input and data links. The ability to fly past the vision of the controller is currently only granted under an FAA Part 107 waiver and usually for controlled airspaces.[140] While operations on wildland fires are governed by temporary flight restriction rules controlling the airspace, the ability to fly BVLOS missions still requires a waiver. It has previously been established that the pilots operating the firefighting UAV swarms must be FAA certified. They will likely need to have appropriate waivers or certificates for BVLOS flying. The evolution of UAV swarm flying may require a more robust communication platform to ensure that positive communication links are maintained. Moving forward, the continued roll-out of 5G technology with increased bandwidth and the associated infrastructure should positively impact the ability to ensure positive uplinks and effectively fly swarms of aircraft.[141]

3. Launch Times

The process of launching UAVs, including the preflight time, is a pressure point that could be leveraged to maximize UAV flight time. Decreasing launch times could manifest by launching multiple UAVs simultaneously or by developing a system whereby launch times are minimized by ground support personnel. There is potential to model

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[140] Federal Aviation Administration, "Part 107 Waiver."

[141] Muhammad Yeasir Arafat, Md Arafat Habib, and Sangman Moh, "Routing Protocols for UAV-Aided Wireless Sensor Networks," *Applied Sciences* 10, no. 12 (January 2020), https://doi.org/10.3390/app10124077.

mission launch times using a systems engineering approach to identify incremental improvements that could be integrated into the UAV launch cycle.

For UAVs with a limited total flight time, the objective should be to launch quickly so the UAV or UAV swarm can start its mission. Should that mission involve multiple cycles, as firefighting missions do, maximizing the time that the UAV swarm is directly completing the mission is critical. When launching large swarms of 50 UAVs, the time from launch to swarm formation could significantly reduce flight times. Chung et al., also testing with the ARSENL group, experienced this phenomenon when launching a 50 fixed-wing aircraft swarm.[142] However, maximizing mission time is critical even with moderate flight duration UAVs such as the Firefly.

4. Scalability: Management of UAVs in the Air

A critical function of UAV launching and swarm assembly is the human controller's management and control of the UAVs. UAV swarms are not yet at the point of being fully autonomous, self-dispatching, determining threats, attacking, reloading, and returning until the threat is mitigated. Human interaction is still necessary to ensure proper swarm operation. Managing a 50 UAV swarm is not practical for one human controller. According to Chung et al., their team found that one operator could maximally control five to six UAVs using conventional approaches and interfaces during their experimentation.[143] The requirement of one pilot flying one aircraft is addressed through the FAA's Part 107 waiver process.[144] However, even with a waiver to fly multiple aircraft, the conceptual construct of pilots flying each aircraft must shift to a mission manager rather than a single entity controller. One way to facilitate this idea is to allow the UAV many flight decisions within the programmed plays and tactics. In their experimentation, Chung et al. used a human swarm monitor and a human swarm operator, managing by function rather than by aircraft.[145] During our test flights, the small swarm

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[142] Chung et al., "Live-Fly, Large-Scale Field Experimentation," 1259.

[143] Chung et al., 1258.

[144] Federal Aviation Administration, "Part 107 Waiver."

[145] Chung et al., "Live-Fly, Large-Scale Field Experimentation," 1258.

we launched was managed by two people easily. However, those people were intimately familiar with UAV swarm operations and have worked with the ARSNEL team for many years. The criticality of having personnel who are familiar and comfortable operating swarm systems cannot be understated.

As UAV swarm technology becomes more scalable, it will be critical for the UAV swarm itself to complete many of its own self-checks and diagnostics and report back to the controller if there is a problem. The flight of each UAV in the swarm becomes a management-by-exception issue rather than active, positive management of each aircraft for the human controller. The controller would only intervene when there was an issue identified by the UAV that required assistance from the human controller. While the UAV cannot place its own batteries in the battery slot or refuel or reload itself, it should be able to complete mission diagnostics, communications, and data link checks and "ready to launch" determinations. In reporting its own systems checks and potential faults, the UAV could allow for both a faster lift-off time and potentially lower in-mission failure rate. As the UAV swarm becomes more sentient about its health, it becomes more efficient as it should lose fewer members to faults and failures in flight operations.

B. SYSTEMS MODELING

Using Innoslate system engineering software allowed for visually illustrating the simultaneous relationships between entities during aerial firefighting operations. By ensuring that all entities were "speaking the same language," the relationships considered problematic could be identified and those that might result in a failed mission could be mitigated. By understanding the actors' relationships, areas of potential improvement for UAV swarm operations become the focus. The executable simulation mode within the Innoslate software allows users to add realistic time values to each action. These simulations illustrated where flight operations could become time constrained. The time constraints became a critical focus of the flight scenarios as they are some of the primary limitations to achieving maximal suppression agents on the fire.

1. Location of the Fire Relative to Location of the Aerial Asset

The modeling confirms the relative value of correctly positioning aerial assets, regardless of type, close to the fire to maximize the number of suppressing drops that each system can make. When the UAV swarm and the fixed-wing air tanker systems are compared specifically for placing suppressing agents on a target, the advantageous nature of having the delivery system close to the fire location is clear. The need to minimize transit time is clearly illustrated in Figure 5 and Figure 6 (graphs for cycle times). The faster the transit time, the more suppressing drops can be made within a given time. When aerial assets are committed to a fire, because of the scarcity of the resource, every incident commander seeks to get the most work (suppressant on the fire) out of each asset that he or she can. Not only does maximizing aerial asset utilization assist in controlling the fire, but it also maximizes the impact of the aerial suppression asset in relation to the financial cost of ordering the asset.

In the fire scenario, the swarm was located less than six miles from the fire and still had a 20-minute roundtrip transit time. The swarm could only make two water drops before it needed an extended service to refuel and reload with water. Because of the UAV swarm's relative portability and the relative ease of finding a place to service the UAVs (only requiring an open area and water source), moving the UAV swarm as close to the fire location as possible maximizes the effectiveness of the resource.

As the analysis indicates that UAV swarms are constrained by transit time, one can also observe in Figure 6 (AT-802 cycle time) that much of the fixed-wing aircraft's cycle time is spent in transit from the airbase to the fire location. While unrelated to the research question about UAV swarms, interestingly, conventional aerial assets are constrained by transit time and service location, much like the UAV swarm. The aircraft is limited by the need for a paved runway and a place to mix and load fire retardant. In the fire scenario, the aircraft base was located about 35 miles farther from the fire than the UAV base, but those extra miles added only five minutes per leg of transit time. The aircraft's speed could overcome the relative distance compared to the UAV swarm.

The air tanker cycle time could be further decreased if loaded with simple water rather than fire retardant. The aircraft would not need a designated airstrip that could batch-mix retardant. Any paved runway located closer to the fire becomes a viable option for reloading. The aircraft would need a simple pumping engine and a water source to reload. The most likely base for water reloading is the Hillsboro airport located 15.38 miles from the fire for the designated fire location. As shown in Table 2, by loading with water at the Hillsboro airport, the flight time from Hillsboro to the fire would be approximately five minutes, 45 seconds, decreasing the transit cycle time from 30 minutes to approximately 12 minutes. The findings illustrate the relative value of scooper-type aircraft that "land" on bodies of water, reload their water tanks, and then take off again. According to Jesse Weaver, most fires attacked by scooper aircraft are within 10 miles of a suitable water landing area to maximize drop cycles. The scooper rarely flies more than 100 feet above the ground, further limiting climb and decent transit time.[146]

2. Choice of Asset for Fire Suppression

UAV swarms are not the answer for every fire. An interesting observation by Jesse Weaver, the AT-802 pilot, was that the UAV swarm could be subject to difficult thermal turbulence located near the fire front. He recounted that it is sometimes difficult to handle a 16,000-pound aircraft in the turbulence created by the fire front and doubted that the UAVs would be stable enough to drop effectively.[147] To maximize the efficiency of the aerial asset, incident commanders must evaluate the expected cycle time of aircraft, the necessity for precision-point suppression drops (of which helicopters are best suited), availability of aerial assets, and the direct or indirect fire-attack tactics to be employed. A visual decision tree (see Figure 11) was developed to assist fire managers in choosing the appropriate aerial suppression asset to deploy. Incident commanders are constrained by which assets they have access to for fire suppression. However, given unlimited access, this decision tree represents the best use of assets based on the fire conditions. The location of the fire in relation to the base area of the aerial suppression system should be a significant

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[146] Weaver, personal communication.

[147] Weaver.

consideration when deciding which type of aircraft to order to combat wildland fires. Should a fire be close to a suitable body of water, scooper aircraft (those that land on the water to refill) may be the most appropriate asset to employ. There may be times when the most appropriate aerial asset is geographically located far away from the fire. One example may be when the fire is advancing fast and an indirect fire attack is needed. The incident commander may request a very large airtanker (VLAT), such as a DC-10 aircraft, to place upwards of 9,000 gallons of retardant in one drop to stop the fire. However, after its first drop, the VLAT will refill at the closest appropriate airbase to the fire for follow-on missions.

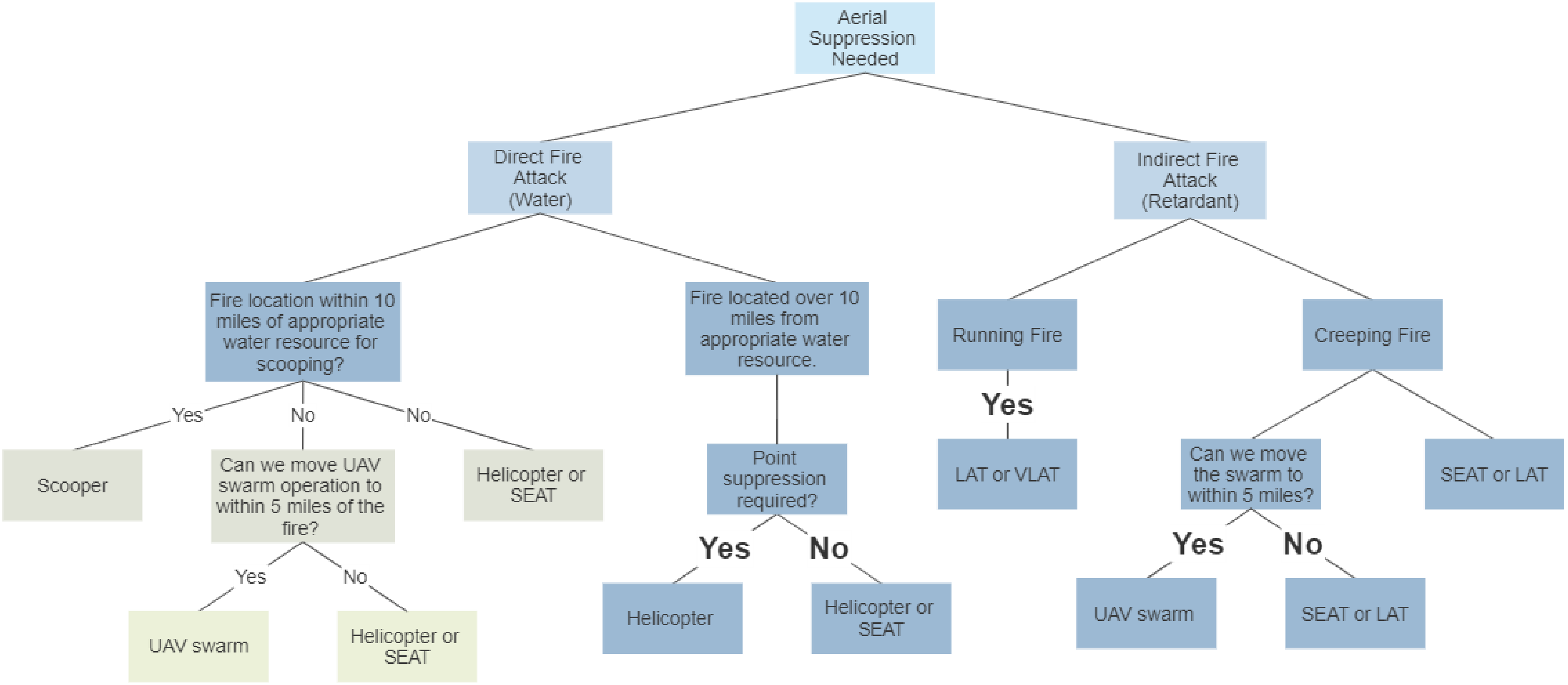

Figure 11. Decision Tree for Aerial Suppression Asset

C. COST COMPARISON

The cost comparison illustrated the relative value in deploying UAV swarms for fire attacks (see Table 3). Traditional aerial assets are extremely expensive to procure and operate, not solely because of the skill necessary to pilot them. The pilot's expertise and the relative danger of piloting aircraft during firefighting operations equate to both a high daily and hourly cost rate. As UAVs swarms are remotely piloted, they represent significantly less cost for both procurement and replacement should an airframe be lost. Their daily and hourly cost of operation will likely be far less than conventional aircraft. However, there is little empirical data to study as firefighting UAV swarms have not been contracted yet. Certainly, the first generation of UAV swarms will have a high upfront procurement cost, but that cost should come down as innovations and best practices are established through flying actual missions.

The cost per gallon of suppressant dropped was significantly higher using a conventional aircraft as compared to the UAV swarm. Even when comparing UAV water drops to conventional air tankers dropping water, the UAV cost per gallon was significantly lower. However, it would be interesting to compare UAV costs per gallon to a scooper aircraft as scoopers inherently have a much higher drop-cycle rate than conventional aircraft.

D. RECOMMENDATIONS

Based on the research, UAV swarms appear to be best suited for direct fire attacks on smaller, less volatile fires located close to their base of operations to minimize flight time and maximize drop cycles. This research indicates that several pressure points could be addressed to make a UAV swarm program more viable and scalable in the future.

1. Logistics Upgrades

Placing the UAVs as close to the fire as possible for servicing makes the UAV swarm more effective and economical. To accomplish this goal, the UAV swarm should be as portable as possible, conceivably in a truck and trailer configuration that can easily be moved to suitable launching points. As mentioned previously, the Firefly UAV is not a small unit. Transporting 50-plus UAVs will likely require multiple truck and trailer combinations to get all the UAVs and associated communications gear to the launching point. The UAV swarm may need to travel with dedicated tender and engine assets to fill the UAVs with water and complete the required UAV servicing between missions. Building a self-sufficient logistics package should allow the UAV swarm to stand alone and not require additional firefighter support. It is important to note that the operation will be labor-intensive and, if scaled to complete missions 24 hours per day, will require multiple personnel working in shifts to complete these tasks.

For swarm technology to be viable as a firefighting tool, it will be critical to ensure robust communications infrastructure prior to launching UAV swarms. The failure of communication uplinks during test flights illustrates how fragile communication between controllers and UAVs can be. Ensuring positive communications may necessitate launching a communications UAV or a UAV swarm to act as a repeater. While not ideal, placing physical repeaters on prominent geographic points before swarm launch would be possible. Based on the action diagrams, it may be necessary to commit ground forces to the fire location to assess communication links prior to swarm launch. Once again, what could be classified as a logistical issue must be solved to ensure successful UAV swarm flights.

As UAVs become more scalable, it will be necessary to ensure that multiple aircraft can be launched simultaneously to quickly assemble the swarm in the air. Utilization of the quad-copter style UAV exclusively will significantly decrease the overall swarm launch time. The quad-copter style UAV allows for an unassisted launch and simply needs a clear area to launch from. It may be necessary to develop systems in which the UAV itself can establish connectivity with the data link, run connectivity and flight control checks, and launch without positive control of a human controller other than a “go” or “no go” command. As UAVs develop to have longer flight times overall, their launch speed becomes less important. However, at this time, any time saved in launching is time gained for fire suppression.

2. Policy Development

As UAV swarm flying matures, it is imperative to ensure that local and federal policies and procedures evolve with the technology. Decreasing the barriers for UAV swarm flying, especially relating to policy development—such as changing BVLOS rules, Part 107 one-pilot/one-aircraft rules, and the weight restrictions for flying UAVs—will allow operators to provide services that could transform the application of swarms. Changing these policies could open the concept of commercial UAV swarm flying to more companies, potentially increasing the pace of innovation for UAV swarm flying.

It may be necessary to develop a national standardization for component specifications as UAVs and UAV swarms become more modular and interchangeable. There are elements of this standardization in the North Atlantic Treaty Organization (NATO)'s Standardization Agreement 4586, a rule for UAV interoperability.[148] This agreement ensures that UAVs from NATO partner countries can support each other through multiple interface methods. However, this standardization applies only to military applications within NATO countries. While some private companies will seek to keep components proprietary, it is necessary to support the idea of interchangeable components and mission-specific modifications. An excellent example of this collaboration comes from Drone Amplified, which acquired IGNIS (the incendiary delivery system) to be paired with multiple UAVs. Should the idea of shared components and standard specifications take hold, it will allow the domestic UAV manufacturing industry to support each other in times of supply chain disruptions. At the very least, logistical support for managing the power system, command and control, flight operations, and personnel operations should be defined by policy and protocol to maximize standardization and minimize the potential for failure.

One simple finding from the analysis is that each state or region must evaluate the relative effectiveness of each aerial asset and make decisions based on what type of aircraft works the best for that specific area. Air Tractor makes a scooper-type aircraft with floats

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[148] Terry Bandzul, "STANAG 4586—Enabling Interoperability" (presentation, CDL Systems, Calgary, Canada, 2007), 7, http://www.avcs-au.com/library/files/stanag/4586-presentation.pdf.

over wheels called the AT-802F FireBoss. The aircraft is a variation on the AT-802, specifically purpose-built for firefighting. Scooper-type aircraft have been so successful that Minnesota has committed to a majority fleet of scooper-style aircraft because of the ability to access waterborne landing and refilling.[149] In western Oregon, there are multiple areas to perform waterborne refilling. However, there is little or no opportunity for waterborne refilling in central and eastern Oregon, where most significant wildland fires occur. Therefore, most of the AT-802s located in Oregon are in a standard configuration so that they can be deployed to any location in the state. This comparison illustrates the necessity to match regional aerial firefighting assets with a realistic comprehension of maximizing the output from specific aerial assets.

3. Pre-positioning

The analysis indicates the value of having UAV swarms located near wildland fires. Having multiple UAVs swarms pre-positioned throughout the state in strategic locations could potentially solve a worsening wildfire problem. While most fire protection districts cannot afford their own aircraft or helicopter, they may be able to afford a small swarm of firefighting UAVs, especially if assisted by the DHS federal grant process. Bringing the cost of UAV swarms down may allow fire districts and fire protection agencies to invest in technology to attack fires at the incipient stage and hold them to a size that traditional ground forces can control. Additionally, should the UAV swarm system be sufficiently portable, when situations of extreme fire danger are recognized, such as red flag warning days, the UAV system could be pre-positioned to those areas to provide immediate air support if a fire starts. In Oregon, this proactive pre-positioning mimics the Office of the State Fire Marshal (OSFM)'s policies to mobilize ground forces for up to 72 hours during extreme weather events. The goal is to pre-position assets to areas that could experience multiple wildland fire starts. In 2021, the OSFM pre-positioned firefighting assets seven different times.[150] Adding UAV swarms into pre-positioning standard operating

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[149] Valley Air Crafts, "Fire Agency Briefing," 12.

[150] "Response Ready Oregon," Oregon Office of the State Fire Marshal, accessed February 19, 2022, https://www.oregon.gov/osp/programs/sfm/pages/response-ready-oregon.aspx.

procedures could enhance the ability to attack new fire starts quickly and aggressively. In short, having assets in the area (aerial and ground) and available to respond immediately makes a critical difference in the ability to stop a fire before it grows to the point of a conflagration.

VI. CONCLUSION AND FUTURE RESEARCH

The theoretical concept of UAV swarms flying firefighting suppression missions was confirmed as possible but needed additional study. Firefighting by UAV swarm shows great promise especially in areas that do not have ready access to traditional aerial assets. The ability for even small swarms of UAVs to be dispatched early in the fire's propagation allows for early aerial suppression to hold the fire to a size that is manageable for ground forces to attack.

A. FINDINGS

This thesis started with the initial question "How could UAV swarm technology be implemented as a method of fire attack in the wildland setting?" Over the course of the research for this thesis, multiple methods were used to answer that question. It was critical to define the type of fire attacks that happen in the wildland environment and how those types of direct and indirect fire attack are performed. Additionally, the current rules and regulations were explored that govern both conventional and UAV aircraft specific to who can fly, what they can fly, and when and where these aircraft can be flown especially in the wildland environment.

An extensive literature review was performed to understand current swarming operations and current applications for UAV-based firefighting. The concept of using UAVs to assist in firefighting is being evaluated by many entities to attempt to solve specific local problems. In China, a fire department is testing tethered UAVs for high-rise firefighting while, in Jordan, practitioners are exploring the idea of untethered UAVs fighting fires with fire extinguishing "bombs," much like large fire extinguishers. In the wildland environment, there are many applications of single UAVs developing intelligence and situational awareness on the fire but not being used for direct fire-suppression operations. No applications of UAV swarms are being used in the wildland space. However, there are a few small swarms of three to five UAVs working primarily in agriculture that could be directly repurposed into wildland firefighting operations.

The field testing with the ARSNEL group confirmed the feasibility of flying UAV swarms as well as the integration of UGVs into the swarm. The application of UGVs in the swarm was an unexpected finding and may be a method to address the logistical challenges of flying UAV swarms in the future. The practical field-testing performed further illustrated the pressure points identified as barriers for implementation. The field testing confirmed the idea that military-based applications of swarm systems could be repurposed into civilian wildland firefighting applications. Using a common set of plays and tactics for multiple mission types, both military and civilian, illustrates the ability for UAV swarms to fly different missions with few changes to mission modeling and language. The benefits of common plays and tactics were fully confirmed.

The next phase of the analysis used both a graphical representation of flight dynamics for the UAV swarm and the AT-802 flights and the MBSE Innoslate systems engineering software to produce visual charts of specific firefighting operations. These visual representations indicate the relationships between various actors within the firefighting operation. By placing realistic time constraints into each action, discrete event simulations identified critical operations that could limit the overall goal of placing the maximum amount of suppression agent in a given time. The visual representations allow for a jumping-off point for future research to minimize pressure points in UAV swarm operations.

A cost comparison, shown in Table 3, was developed to detail the relative costs associated with the operation of a UAV swarm and the conventional aircraft. The cost comparison weighs the cost and relative ability of each aerial system. The results of the cost comparison informed the creation of the aerial asset decision tree (see Figure 11). The aerial asset decision tree is a method for incident commanders to decide which aerial asset is most appropriate depending on fire tactics, fire conditions, and the relative location of the fire to the aerial base.

Through the field testing, systems modeling, and cost comparison, conclusions were made about UAV swarm feasibility and the appropriateness of using UAV swarms in the wildland setting. The test flights and systems modeling simulations identified limitations and opportunities that should be explored further as UAV swarm technology becomes more robust. The cost comparison indicates that fire suppression by UAV swarm is most effective and efficient when the swarm is located close to the fire and uses water to suppress the fire. While UAV swarms performing direct fire suppression are not feasible at this time primarily due to not having a UAV system that can swarm and lift the required payload for the requisite flight time (the Firefly system is still not in production), it appears that it may be feasible soon, as the Firefly is expected to go into commercial production in 2023.

B. FUTURE RESEARCH

Throughout this thesis, multiple areas have been identified that warrant more research to optimize the ability to use UAV swarms for fire suppression operations. UAV swarms will most likely be applied in direct fire-suppression operations in the future, and incremental changes focusing on solving logistics, communications, and UAV and UGV integration will allow UAV swarm development to continue in upward trajectory.

1. Logistical Implications of UAV Swarms

As illustrated in this thesis, the need for logistical support when flying UAV swarms cannot be understated. Moving forward, research should focus on addressing logistical challenges to increase functional flight time and flight cycles and decrease the necessary support personnel to manage the swarms. The logistical needs of swarm flights should be well defined depending on the type of mission that the swarm will be flying. By developing clear expectations for logistical support, UAV swarm flight operations would be subject to fewer unexpected logistical issues, supply chain interruptions, and scarcity of resources needed for continuous mission success.

As UAVs and UAV swarms become more ubiquitous in application, it is important to recognize the homeland security implications of using foreign-produced UAVs for these applications. The supply chain that supports UAV swarm operations was briefly touched on during this thesis regarding the difficulty of ensuring foreign-produced UAVs' security. It will be essential to build and support a robust domestic program of UAV innovation. This may encompass UAV production and support programs such as coding and programming for UAV flights. It will be critical to support UAV building, performance, mission specificity, and computer science applications focusing on swarm technology to advance the scope of UAV use.

Two of the main components of any UAV are the propulsion system and the control system. As seen through the current microchip shortage impacting the ability of major car manufacturers to produce new vehicles, so too could there be a shortage in microchips, electronics technology, batteries, and battery production, including critical elements to build batteries and propulsion systems. The supply chain failure of any of these elements could derail the domestic production of critical UAVs and UAV programs. It is necessary to ensure that domestic UAV manufacturers have access to these critical components. It would be interesting to identify the scarcest products used to build UAVs and establish a strategy to ensure that UAV builders have access to those resources.

2. Repeating Communications Applications

One of the issues that has been repeatedly identified in flying UAV swarms is the concept of keeping positive data and communication links between the ground controllers and the UAVs. Until UAV swarms can access mesh networks or satellite-based communications, they will continue to experience potential degradation or loss of communications during flights. A potential solution is a concept of launching a long-duration communications UAV to act as a repeater for the firefighting swarm. The communications UAV could be a long-duration fixed-wing or an unloaded Firefly, which has a flight duration of about seven hours.[151] It may be possible to use swarming technology to place multiple UAVs to create a communications network with the UAVs moving to optimize the relay strength. Regardless of the platform, the communications swarm could potentially solve loss-of-communications issues by providing a stable throughput between the UAV firefighting swarm and the ground controller.

As this thesis was developed, additional areas were identified whereby UAV swarms could positively affect wildland fire–suppression operations. The first is using

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[151] Bill Gabbert, "Parallel Flight Technology's Next Drone Model Will Be Able to Carry 100 Pounds for Hours," Fire Aviation, May 17, 2020, https://fireaviation.com/2020/05/17/parallel-flight-technologys-next-drone-model-will-be-able-to-carry-100-pounds-for-hours/.

swarms of UAVs for reliable person-to-person communications repeaters across all divisions of the wildland fire. Fire managers currently improve communication reliability by placing portable repeater units in geographically advantageous locations, usually on the tops of mountains. The process to place these repeaters is time-consuming and frequently difficult due to terrain features. Fire managers almost always experience loss of communication with ground forces due to terrain obstructions to some degree. Firefighters working on the fire line must stay in contact with both their direct supervisors and the overall incident management team to increase their safety by being aware of changing fire conditions.

The current radio system used on wildland fires must not only be repeatable but also have common communications with multiple radio systems such as the USFS, local fire service operators, air to ground, air to air, and dedicated command channels. The ability of firefighters to stay in close contact with supervisors and incident command increases their safety by allowing for early warnings of extreme fire behavior events and calling for help if they experience a catastrophic event. Using UAV-borne repeaters may ensure that stable communications are achieved. The concept of using long-flight duration UAVs or UAV swarms to perform repeating operations seems to be one of the first potential applications for UAV swarms.

As fire managers seek to increase the safety of firefighters working on the fire line, the concept of UAV swarms acting as a “shepherd” for the firefighting ground forces could increase the safety of firefighters. These UAV swarms could monitor the health and well-being of the ground forces via personal telemetry. The UAVs could offer real-time location and monitoring of personal vital signs for each member that they are tracking to supervisors. Additionally, they could offer real-time situational awareness about the fire conditions through onboard sensor packages. UAV swarms will likely be deployed for multiple missions in the wildland environment when the issues identified are addressed.

3. Self-Fueling and Reloading

UGVs were integrated into the swarm in the practical testing, creating both an aerial and ground component. From a military perspective, this was exciting. It allowed the swarm to progress to its objective in two domains requiring potential adversaries to account for threat dynamics in two different battle spaces. Not only were the UAVs and UGVs able to communicate, but they were able to do it with off-the-shelf hardware that was adapted to both types of swarms.

From the firefighting perspective, the idea of integrating UGVs with quad-copters potentially allows us to solve some of the defined logistical issues of flying UAV swarms for fire suppression. If the UAVs could be refueled and reloaded with suppressant via a ground rover, potentially landing on top of the rover and automatically plugging into fuel and suppressant tanks for refueling, the time and personnel needed to perform service could be significantly reduced. It is likely that electrical charging could efficiently be completed in this manner, much like wireless recharging for a cell phone. This technology was tested by NPS Joint Interagency Field Experimentation as recently as February 2022.[152]

The UAV swarm could begin fire suppression operations, and rather than having to fly back to the base, the UAVs could simply find a close ground rover and have remote service performed there. Multiple aerial UAVs could be serviced by a single UGV, again minimizing the service needed for UAVs and UGVs. Integrating these two systems could potentially decrease drop-cycle time and allow ground personnel to service the ground rovers rather than the UAVs. By servicing rovers with fuel and suppression tanks rather than UAVs, there would be a corresponding decrease in the personnel needed to control the swarm during landing and takeoff operations as there would be fewer trips to and from the UAV base. Servicing large tender-style UGVs would likely be easier than servicing an aircraft.

C. CONCLUSION

While there are hurdles to overcome, it appears that the future of wildland firefighting will involve UAV swarms. The concept of using UAV swarms in the wildland environment has definite value by increasing the safety and productivity of firefighting

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[152] "Joint Interagency Field Experimentation 22–2 Quad Chart," Naval Postgraduate School, February 14, 2022, 5, https://nps.edu/documents/104517539/133858610/JIFX+22-2+Quad+Charts+%28Approved+%231%29.pdf/f874df01-9e73-b571-dccb-7d3bb227c5bd?t=1638903326766.

operations. The increased utilization and prioritization of UAV swarms in the wildland setting will need champions in the political arena, paving the way for increased funding for research, training of computer scientists specifically for UAV swarm operations, and increased testing of UAV swarms. It is expected that multiple operators will seek to move to the forefront of UAV swarm building and operations both as a business opportunity and an opportunity to assist in combating an increasing wildland fire problem. While it is unlikely to see UAV fire suppression supplanting conventional aerial firefighting soon, the ability to use UAV swarms as another aerial firefighting tool, especially during the night when conventional aircraft do not fly, should offer fire managers another tool to mitigate fires quickly and more safely.

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LIST OF REFERENCES

Advexure. "DJI Matrice 600 Series." Accessed February 28, 2022. https://advexure.com/collections/dji-matrice-600-series.

Air Tractor. "AT-802F Fire Boss: Amphibious Scooper Air Tanker." Accessed March 10, 2022. https://airtractor.com/aircraft/at-802f-fire-boss/.

Akhloufi, Moulay A., Nicolás A. Castro, and Andy Couturier. "UAVs for Wildland Fires." In *Proceedings of SPIE Defense and Security*, edited by Michael C. Dudzik and Jennifer C. Ricklin. Vol. 10643 of *Autonomous Systems: Sensors, Vehicles, Security, and the Internet of Everything*, M1–M14. Bellingham, WA: International Society for Optics and Photonics, 2018. https://doi.org/10.1117/12.2304834.

Akhloufi, Moulay A., Andy Couturier, and Nicolás A. Castro. "Unmanned Aerial Vehicles for Wildland Fires: Sensing, Perception, Cooperation and Assistance." *Drones* 5, no. 1 (March 2021): 1–25. https://doi.org/10.3390/drones5010015.

Akram, Raja Naeem, Konstantinos Markantonakis, Keith Mayes, Oussama Habachi, Damien Sauveron, Andreas Steyven, and Serge Chaumette. "Security, Privacy and Safety Evaluation of Dynamic and Static Fleets of Drones." In *Proceedings of the 36th Digital Avionics Systems Conference*, 1–12. Piscataway, NJ: IEEE, 2017. https://doi.org/10.1109/DASC.2017.8101984.

Albalawi, Maisa, and Houbing Song. "Data Security and Privacy Issues in Swarms of Drones." In *Proceedings of the 2019 Integrated Communications, Navigation and Surveillance Conference*, 1–11. Piscataway, NJ: IEEE, 2019. https://doi.org/10.1109/ICNSURV.2019.8735133.

Alshbatat, Abdel Ilah N. "Fire Extinguishing System for High-Rise Buildings and Rugged Mountainous Terrains Utilizing Quadrotor Unmanned Aerial Vehicle." *International Journal of Image, Graphics and Signal Processing* 11, no. 1 (January 2019): 23–29. https://doi.org/10.5815/ijigsp.2018.01.03.

Arafat, Muhammad Yeasir, Md Arafat Habib, and Sangman Moh. "Routing Protocols for UAV-Aided Wireless Sensor Networks." *Applied Sciences* 10, no. 12 (January 2020): 1–23. https://doi.org/10.3390/app10124077.

Ausonio, Elena, Patrizia Bagnerini, and Marco Ghio. "Drone Swarms in Fire Suppression Activities." Cornell University arXiv, 2020. https://arxiv.org/abs/2007.00883v2.

Balderas, Christian. "'Game Changing,' Central Coast Company Unveils Firefighting Drone." KSBW Monterey, February 2, 2022. https://www.ksbw.com/article/game-changing-central-coast-company-unveils-firefighting-drone/38956762.

Bandzul, Terry. “STANAG 4586—Enabling Interoperability.” Presentation at CDL Systems, Calgary, Canada, 2007. http://www.avcs-au.com/library/files/stanag/4586-presentation.pdf.

BBC News. “Grenfell Tower: What Happened.” October 29, 2019. https://www.bbc.com/news/uk-40301289.

Borchers, Jeffrey G. “Accepting Uncertainty, Assessing Risk: Decision Quality in Managing Wildfire, Forest Resource Values, and New Technology.” *Relative Risk Assessments for Decision-Making Related to Uncharacteristic Wildfire*, edited by Larry L. Irwin and T. Bently Wigley. Special issue, *Forest Ecology and Management* 211, no. 1 (June 2005): 36–46. https://doi.org/10.1016/j.foreco.2005.01.025.

Branson-Potts, Hailey. “L.A. Fire Department Used Drones for the First Time during Skirball Fire.” *Los Angeles Times*, December 15, 2017. https://www.latimes.com/local/lanow/la-me-ln-lafd-drone-skirball-fire-20171214-story.html.

Butler, Corey R., Mary B. O’Connor, and Jennifer M. Lincoln. “Aviation-Related Wildland Firefighter Fatalities—United States, 2000–2013.” *Morbidity & Mortality Weekly Report* 64, no. 29 (2015): 793–96. https://doi.org/10.15585/mmwr.mm6429a4.

Cal Fire. “2021 Incident Archive.” Accessed January 14, 2022. https://www.fire.ca.gov/incidents/2021/.

———. “Facts + Statistics: Wildfires.” Insurance Information Institute. Accessed October 26, 2021. https://www.iii.org/fact-statistic/facts-statistics-wildfires.

Cammack, Fred. *Fire Retardant Standard Mixing System*. San Dimas, CA: San Dimas Technology and Development Center, 1999. https://www.fs.fed.us/t-d/pubs/pdf/99511204.pdf.

Cardona, Gustavo A., and Juan M. Calderon. “Robot Swarm Navigation and Victim Detection Using Rendezvous Consensus in Search and Rescue Operations.” *Applied Sciences* 9, no. 8 (January 2019): 1–23. https://doi.org/10.3390/app9081702.

Chappell, Bill. “Interior Department Grounds Chinese-Made Drones, Months after It Approved Them.” NPR, January 29, 2020. https://www.npr.org/2020/01/29/800890201/interior-department-grounds-all-of-its-drones-citing-cybersecurity-other-concern.

Chung, Timothy H., Michael R. Clement, Michael A. Day, Kevin D. Jones, Duane Davis, and Marianna Jones. "Live-Fly, Large-Scale Field Experimentation for Large Numbers of Fixed-Wing UAVs." In *2016 IEEE International Conference on Robotics and Automation*, 1255–1262. Piscataway, NJ: IEEE, 2016. https://doi.org/10.1109/ICRA.2016.7487257.

Cooke, Kyle. "'A Horrific Event': 991 Structures Destroyed, Three Missing in Marshall Fire." Rocky Mountain PBS, December 30, 2021. https://www.rmpbs.org/blogs/news/superior-louisville-grass-fire-colorado-evacuations/.

Coulson Aviation. "How to Become an Aerial Firefighter." April 14, 2020. https://www.coulsonaviationusa.com/newsmedia/how-to-become-an-aerial-firefighter.

Dague, D., and P. Hirami. "The United States Forest Service's Incident Command System 40 Years On: From Domestic Wildfires to International Disaster Response." *Unasylva* 66, no. 243/244 (2015): 79–85. ProQuest.

Dam, Steven. *Life cycle Modeling Language (LML) Specification*. Life cycle Modeling Language, 2015. https://lifecyclemodeling.org/wp-content/uploads/2021/01/LML_Specification_1_1.pdf.

Department of Homeland Security. "Appendix B: Incident Command System." In *National Incident Command System*, 89–134. Washington, DC: Department of Homeland Security, 2008. https://www.fema.gov/pdf/emergency/nims/NIMS_core.pdf.

Department of Homeland Security, Federal Emergency Management Agency, U.S. Fire Administration, National Fire Data Center, and National Fallen Firefighters Foundation. *Firefighter Fatalities in the United States in 2019*. Emmitsburg, MD: U.S. Fire Administration, 2020.

Department of the Interior. "Interior Awards First Contract for Small Unmanned Aircraft Systems Services." May 15, 2018. https://www.doi.gov/pressreleases/interior-awards-first-contract-small-unmanned-aircraft-systems-services.

Detweiler, Carrick. "Opinion: Congress Needs to Be Careful about Banning All Parts for Drones Made outside the U.S." Fire Aviation, October 21, 2020. https://fireaviation.com/2020/10/21/opinion-congress-needs-to-be-careful-about-banning-all-parts-for-drones-made-outside-the-u-s/.

DJI Enterprise. "Government: Secure and Reliable Solutions for Government." Accessed December 23, 2021. https://www.dji.com/enterprise/government.

DroneNerds. "DJI Agras T16 Agriculture Drone—Ready to Fly Kit." February 28, 2022. https://www.dronenerds.com/products/drones/enterprise-drones/dji-agras-series/agrast16/dji-agras-t16-agrast16-dji.html.

DroneSeed. "Home Page." Accessed October 11, 2021. https://droneseed.com/.

Drone U. "Flying Large Drones over 55 Pounds Using Section 333 Exemption." July 23, 2019. https://www.thedroneu.com/blog/large-drones-55-pounds-section-333-exemption/.

Dubay, Steven E. "Improving Access to Military Aircraft during Civilian Wildfires." Master's thesis, Naval Postgraduate School, 2015. http://hdl.handle.net/10945/47938.

Environmental Protection Agency. "Climate Change Indicators: Wildfires." Accessed March 9, 2022. https://www.epa.gov/climate-indicators/climate-change-indicators-wildfires.

Faasau, James. *Large Airtanker Operations Plan*. Washington, DC: U.S. Forest Service, 2017. https://www.fs.fed.us/fire/aviation/av_library/index.html.

Federal Aviation Administration. "Emergency Situations." August 27, 2020. https://www.faa.gov/uas/advanced_operations/emergency_situations/.

———. "Part 107 Waiver." April 19, 2021. https://www.faa.gov/uas/commercial_operators/part_107_waivers/.

———. *Unmanned Aircraft Operations in the National Airspace System (NAS)*. Air Traffic Organization Policy N JO 7210.891. Washington, DC: Federal Aviation Administration, 2015. https://www.faa.gov/documentLibrary/media/Notice/Notice_UAS_7210.891.pdf.

Fire Ignition Management: IGNIS by Drone Amplified. "U.S. Forest Service and Drone Amplified Partner to Drive Search for Domestic Fire-Fighting Drones." September 9, 2020. https://droneamplified.com/u-s-forest-service-and-drone-amplified-partner-to-drive-search-for-domestic-fire-fighting-drones/.

FireRescue1. "U.S. Forest Service and Drone Amplified Partner to Drive Search for Domestic Firefighting Drones." September 14, 2020. https://www.firerescue1.com/fire-products/drones/press-releases/us-forest-service-and-drone-amplified-partner-to-drive-search-for-domestic-firefighting-drones-VWuKcEuAMQaaFjWi/.

Frelich, Lee E., and Peter B. Reich. "Will Environmental Changes Reinforce the Impact of Global Warming on the Prairie–Forest Border of Central North America?" *Frontiers in Ecology and the Environment* 8, no. 7 (September 2010): 371–78. https://doi.org/10.1890/080191.

Frontline Wildfire Defense. "Aerial Firefighters & Fire Fighting: Dangerous but Effective?" Accessed March 9, 2022. https://www.frontlinewildfire.com/aerial-wildfire-fighting-how-effective-is-it/.

G., Evan. "DroneSeed Granted First Ever FAA Heavy-Lift Drone Swarm BVLOS Waiver for Reforestation." U.S. Civilian Intelligence Agency, December 10, 2020. https://www.us-cia.com/post/droneseed-granted-first-ever-faa-heavy-lift-drone-swarm-bvlos-waiver-for-reforestation.

Gabbert, Bill. "The 747 Supertanker Shuts Down." Wildfire Today, April 23, 2021. https://wildfiretoday.com/2021/04/23/the-747-supertanker-shuts-down/.

———. "Forest Service Has 18 Large Air Tankers This Year under Contract." Wildfire Today, March 9, 2021. https://wildfiretoday.com/2021/03/09/forest-service-has-18-large-air-tankers-this-year-under-contract/.

———. "Parallel Flight Technology's Next Drone Model Will Be Able to Carry 100 Pounds for Hours." Fire Aviation, May 17, 2020. https://fireaviation.com/2020/05/17/parallel-flight-technologys-next-drone-model-will-be-able-to-carry-100-pounds-for-hours/.

Giles, Kathleen B., Duane T. Davis, Kevin D. Jones, and Marianna J. Jones. "Expanding Domains for Multi-Vehicle Unmanned Systems." In *2021 International Conference on Unmanned Aircraft Systems*, 1400–1409. Piscataway, NJ: IEEE, 2021. https://doi.org/10.1109/ICUAS51884.2021.9476788.

Giuliani-Hoffman, Francesca. "The First Firefighting Robot in America Is Here—and It Has Already Helped Fight a Major Fire in Los Angeles." CNN, October 21, 2020. https://www.cnn.com/2020/10/21/business/first-firefighting-robot-in-america-lafd-trnd/index.html.

Glickstein, Geoffrey L. "Improving Air Support for Wildfire Management in the United States." Master's thesis, Naval Postgraduate School, 2014. http://hdl.handle.net/10945/43917.

Hernández León, Alejandro. "Air Tractor AT-802." Airliners, June 5, 2010. https://www.airliners.net/photo/FAASA-Chile/Air-Tractor-AT-802/1722755.

Hoover, Katie, and Laura A. Hanson. *Wildfire Statistics*. CRS Report No. IF10244. Version 49. Washington, DC: Congressional Research Service, January 2021. https://crsreports.congress.gov/product/pdf/IF/IF10244/49.

Hutchinson, William. "Deceiving Autonomous Drones." *International Journal of Cyber Warfare and Terrorism* 10, no. 3 (2020): 1–14. https://doi.org/10.4018/IJCWT.2020070101.

ICL Performance Products. "Phos-Chek Fire Retardants for Use in Preventing & Controlling Fires in Wildland Fuels: Frequently Asked Questions." Accessed October 3, 2021. https://www.fs.usda.gov/Internet/FSE_DOCUMENTS/stelprd3851594.pdf.

Interagency Helicopter Screening and Evaluation Subcommittee. “Interagency Type Specifications for Helicopters.” April 14, 2014. https://www.nwcg.gov/sites/default/files/committee-correspondence/IHSES-Interagency-Type-Specifications-for-Helicopters.pdf.

Isenberg, Sara. “Fly Longer, Lift More, and Fight Wildfires.” Santa Cruz Tech Beat, October 25, 2019. https://www.santacruztechbeat.com/2019/10/24/fly-longer-lift-more-and-fight-wildfires/.

Katuwal, Hari, Michael Hand, Matthew Thompson, Crystal Stonesifer, and David E. Calkin. “Predict and Attack (or Don’t): An Econometric Approach to Large Wildfire Early Detection and Suppression Effectiveness.” Paper presented at the Annual Meeting of the Agricultural and Applied Economics Association, Washington, DC, August 5–7, 2018.

Kovner, Guy. “Cal Fire Debuts Helicopter with Night Firefighting Ability.” Firehouse, July 6, 2021. https://www.firehouse.com/operations-training/wildland/news/21229386/cal-fire-debuts-24m-helicopter-with-night-firefighting-ability.

Kulisch, Eric. “Korean Air Develops Drone Swarm Technology to Inspect Aircraft.” *Flying Magazine*, December 20, 2021. https://www.flyingmag.com/korean-air-develops-drone-swarm-technology-to-inspect-aircraft/.

Leo, Michael. “Drones in the Big City.” Firehouse, April 1, 2019. https://www.firehouse.com/tech-comm/drones/article/21069479/fdny-drone-program.

Maranghides, Alexander, Eric Link, William “Ruddy” Mell, Steven Hawks, Mike Wilson, Will Brewer, Chris Brown, Bob Vihnaneck, and William D. Walton. *A Case Study of the Camp Fire—Fire Progression Timeline*. NIST Technical Note 2135. Gaithersburg, MD: National Institute of Standards and Technology, 2021. https://doi.org/10.6028/NIST.TN.2135.

Masunaga, Samantha. “The Fire Retardant Dropped Out of Planes? It’s Sticky, Gooey and Made in the Southland.” *Los Angeles Times*, October 1, 2020. https://www.latimes.com/business/story/2020-10-01/phos-chek-red-fire-retardant-dropped-from-planes.

Merino, Luis, Fernando Caballero, J. Ramiro Martínez-de-Dios, Iván Maza, and Aníbal Ollero. “An Unmanned Aircraft System for Automatic Forest Fire Monitoring and Measurement.” *Journal of Intelligent & Robotic Systems* 65, no. 1–4 (January 2012): 533–48. https://doi.org/10.1007/s10846-011-9560-x.

Meyer, Robinson. “The Most Important Number for the West’s Hideous Fire Season.” *Atlantic*, September 15, 2020. https://www.theatlantic.com/science/archive/2020/09/most-important-number-for-the-wests-wildfires-california/616359/.

Moritz, Max A. “Wildfires Ignite Debate on Global Warming.” *Nature* 487, no. 7407 (2012): 273. https://doi.org/10.1038/487273a.

Murkowski, Lisa. *Wildfire Management Technology Advancement Act of 2018*. Senate Report No. 115–441. Washington, DC: Senate Energy and Natural Resources Committee. https://www.congress.gov/congressional-report/115th-congress/senate-report/441.

National Fire Chiefs Council. “Control Measure: Consider Appropriate Wildfire Suppression Tactics and Develop and Implement a Tactical Plan.” Accessed December 13, 2021. https://www.ukfrs.com/guidance/search/consider-appropriate-wildfire-suppression-tactics-and-develop-and-implement.

National Interagency Coordination Center. “2021 U.S. Forest Service Airtankers: Schedule of Items.” July 22, 2021. https://www.nifc.gov/nicc/logistics/aviation/Federal_Contract_Air_Tanker_List.pdf.

————. “About Us.” Accessed March 9, 2022. https://www.nifc.gov/nicc/about/about.htm.

National Oceanic and Atmospheric Administration. “Lightning Products and Services.” Accessed July 18, 2021. https://www.ncdc.noaa.gov/data-access/severe-weather/lightning-products-and-services.

National Wildfire Coordinating Group. *Interagency Single Engine Air Tanker Operations Guide*. PMS 506. Boise, ID: National Interagency Coordination Center, 2014. https://gacc.nifc.gov/swcc/dc/nmsdc/documents/Dispatch/Reference/INTER_SEAT_Op_Guide_4-14.pdf.

———. *NWCG Standards for Fire Unmanned Aircraft Systems Operations*. PMS 515. Potomac, MD: National Wildfire Coordinating Group, 2019. https://www.nwcg.gov/publications/515.

Naval Postgraduate School. “Joint Interagency Field Experimentation 22–2 Quad Chart.” February 14, 2022. https://nps.edu/documents/104517539/133858610/JIFX+22-2+Quad+Charts+%28Approved+%231%29.pdf/f874df01-9e73-b571-dccb-7d3bb227c5bd?t=1638903326766.

Ollero, A., J. R. Martínez-de-Dios, and L. Merino. “Unmanned Aerial Vehicles as Tools for Forest-Fire Fighting.” In “The Fifth International Conference on Forest Fire Research,” edited by D. X. Viegas. Supplement, *Forest Ecology and Management* 234S (November 2006). https://doi.org/10.1016/j.foreco.2006.08.292.

Oregon Office of the State Fire Marshal. “Response Ready Oregon.” Accessed February 19, 2022. https://www.oregon.gov/osp/programs/sfm/pages/response-ready-oregon.aspx.

Parallel Flight Technologies. "Firefly Heavy-Lift UAS." Accessed January 17, 2022. https://www.parallelflight.com/product.

Plucinski, Matt P. "Fighting Flames and Forging Firelines: Wildfire Suppression Effectiveness at the Fire Edge." *Current Forestry Reports* 5, no. 1 (March 2019): 1–19. https://doi.org/10.1007/s40725-019-00084-5.

Reeves, Drew. "AI Technology Helps Fire Prevention Specialists Spot Fires in the Early Stages." FOX 12 Oregon, July 28, 2021. https://www.kptv.com/news/ai-technology-helps-fire-prevention-specialists-spot-fires-in-the-early-stages/article_3e71fcf2-f000-11eb-92c3-7bea7fdc1048.html.

Reichenberger, Joel. "Iowa Startup Hopes to Provide Efficiencies and Options with Amped-Up Drone Sprayers." DTN Progressive Farmer, November 30, 2019. https://www.dtnpf.com/agriculture/web/ag/news/article/2019/11/20/iowa-startup-hopes-provide-options.

Ridler, Keith. "Fire Retardant Could Be 'Game-Changer' in Fighting Wildfires." ABC News, October 5, 2021. https://abcnews.go.com/Politics/wireStory/fire-retardant-game-changer-fighting-wildfires-80424418.

Roman, Jesse, Angelo Verzoni, and Scott Sutherland. "The Wildfire Crisis: Greetings from the 2020 Wildfire Season." *NFPA Journal*, November/December 2020. http://www.nfpa.org/News-and-Research/Publications-and-media/NFPA-Journal/2020/November-December-2020/Features/Wildfire.

Sallinger, Marc, and Angela Case. "Pilot Dies in Air Tanker Crash Near Kruger Rock Fire in Colorado." NBC 9 News, November 17, 2021. https://www.9news.com/article/news/local/wildfire/air-tanker-crashes-kruger-rock-fire/73-77e124e6-804d-424f-8405-0634ec9f2b73.

Sarghini, Fabrizio, and Angela De Vivo. "Analysis of Preliminary Design Requirements of a Heavy Lift Multirotor Drone for Agricultural Use." *Chemical Engineering Transactions* 58 (July 2017): 625–30. https://doi.org/10.3303/CET1758105.

Schultz, Courtney A., Matthew P. Thompson, and Sarah M. McCaffrey. "Forest Service Fire Management and the Elusiveness of Change." *Fire Ecology* 15, no. 1 (2019): 13. https://doi.org/10.1186/s42408-019-0028-x.

Stuckenberg, David, and Stephen Maddox. "Drones in the U.S. National Airspace System." *International Journal of Aviation Systems, Operations and Training* 1, no. 2 (2014): 1–22. https://doi.org/10.4018/IJASOT.2014070101.

Sungheetha, Akey, and Rajesh Sharma Rajendran. "Real Time Monitoring and Fire Detection Using Internet of Things and Cloud Based Drones." *Journal of Soft Computing Paradigm* 2, no. 3 (2020): 168–74. https://doi.org/10.36548/jscp.2020.3.004.

Suter, Ann. *Drop Testing Airtankers: A Discussion of the Cup-and-Grid Method*. TE92P32—Technical Services, Aerial Delivery. Missoula, MT: U.S. Forest Service, 2000.

Texas A&M Forest Service. "FAQs–Austin Airtanker Base." Accessed January 13, 2022. https://tfsweb.tamu.edu/uploadedFiles/TFSMain/Preparing_for_Wildfires/Contact_Us(4)/FAQs-updated%20July%2019.pdf.

U.S. Forest Service. *Aviation Annual Report 2020*. Washington, DC: U.S. Forest Service, 2021. https://www.fs.usda.gov/sites/default/files/2021-06/CY2020_USFS AviationReport_Final_1.pdf.

———. "Helicopter Services Hourly Flight Rates, Fuel Consumption, and Weight Reduction Chart." February 16, 2019. https://www.fs.usda.gov/sites/default/files/media_wysiwyg/flt_chrt_awarded_2018-2021.pdf.

———. "Wildland Fire Chemical Products Toxicity and Environmental Concerns: General Information." January 17, 2007. https://www.fs.fed.us/rm/fire/documents/envissu.pdf.

U.S. Forest Service, Wildland Fire Chemical Systems. "Product Information: Phos-Chek LC-95A-R." Accessed December 13, 2021. https://www.fs.fed.us/rm/fire/wfcs/products/pc_lc-95a.htm.

Valley Air Crafts and Air Tractor. "Air Tractor Aerial Fire-Fighting Solutions: Fire Agency Briefing." Presentation at Valley Air Crafts, Tulare, CA, September 2015. https://www.dnr.wa.gov/publications/rp_fire_aviation_fireboss_agency briefing.pdf.

Wang, Jieyu, and Martini Tan Kailong. "The First Fire Drill for High-Rise Fire Fighting Drones Was Held in Dazu, Chongqing." *IChongqing* (blog), January 22, 2020. https://www.ichongqing.info/2020/01/22/the-first-fire-drill-for-high-rise-fire-fighting-drones-was-held-in-dazu-chongqing/.

Wilde, Matthew. "Three Drones Work Together to Spray and Seed Fields." DTN Progressive Farmer, June 2, 2021. https://www.dtnpf.com/agriculture/web/ag/crops/article/2021/06/02/three-drones-work-together-spray.

Williams, A. Park, John T. Abatzoglou, Alexander Gershunov, Janin Guzman-Morales, Daniel A. Bishop, Jennifer K. Balch, and Dennis P. Lettenmaier. "Observed Impacts of Anthropogenic Climate Change on Wildfire in California." *Earth's Future* 7, no. 8 (2019): 892–910. https://doi.org/10.1029/2019EF001210.

Yu, Anthony C., Hector Lopez Hernandez, Andrew H. Kim, Lyndsay M. Stapleton, Reuben J. Brand, Eric T. Mellor, Cameron P. Bauer et al. "Wildfire Prevention through Prophylactic Treatment of High-Risk Landscapes Using Viscoelastic Retardant Fluids." *Proceedings of the National Academy of Sciences* 116, no. 42 (2019): 20820–27. https://doi.org/10.1073/pnas.1907855116.

Zimmerman, Thomas. "Wildland Fire Management Decision Making." *Journal of Agricultural Science and Technology* B, no. 2 (2012): 169–78. https://www.nrfirescience.org/sites/default/files/Zimmerman_2012.pdf.

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