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SMARt-STEReO: Preliminary Concept of Operations

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Scope and Objectives

The Scalable Traffic Management for Emergency Response Operations (STEReO) project focuses on leveraging NASA technology for emergency response. Emergency response includes earthquakes, pandemics, and wildfires, among others. The first type of emergency response considered in this project is aerial firefighting. According to the U.S. Forest Service, there are an average of 7500 wildfires every year on National Forests and Grasslands [1]. While these fires can be caused naturally by lightning strike, they can also be human caused. Wildfires are a natural part of wildland ecosystems and in many cases can have ecological benefits, including reducing fuels [1]. However, wildfires also pose a threat to humans, property, and natural and cultural resources [1]. This can result in substantial costs due to firefighting efforts as well as from damages. Wildfire response aims to manage wildfires to gain ecological benefits, while mitigating their impact on society.

Wildfire response operations rely on several interacting organizations and systems, including coordination with law enforcement, local firefighting agencies, and natural resource specialists. Within this environment, firefighting operations coordinate firefighters and ground equipment with aerial assets applied to the wildfire event. Aerial assets, in general, work to support ground crews in the construction of fire lines, which are used to contain the wildfire. Air tankers drop water or retardant to cool the fire or slow its spread. Air surveillance, including piloted and unpiloted aircraft, provides information to the incident commander about the condition and location of the fire. Helicopters move ground crews and equipment. This operation can become extremely complex in large wildfire events. Not only is the task itself multifaceted, but also the operation requires coordination of vehicles and teams operated by different organizations as well as management of the airspace around the fire.

Despite these complexities, firefighting operations remain relatively low-tech, relying on visuals and radio communications to conduct and coordinate aerial firefighting efforts. In this situation, a central coordinator communicates with the pilots and operators to assure that a safety margin is maintained so that the aircraft do not crash into each other or otherwise conflict. Presently, very little data is exchanged between pilots and operators without going through the coordinator. It is possible that higher bandwidth communications and data relay could reduce the aerial supervisor load and help operators make better decisions. Additionally, unpiloted aircraft systems (UAS) can only be used when portions of the airspace are cordoned off, reducing efficiency and opportunities to fully utilize UAS. Finally, aerial firefighting presents several risks to human operators, with aerial operations accounting for 26% of firefighter deaths between 2000 and 2013 [2]. It may be possible to transfer this risk to UAS for certain tasks. Goals and opportunities are summarized in Figure 1.

The System Modeling and Analysis of Resiliency in STEReO (SMARt-STEReO) project leverages NASA technologies to improve the operational performance and resiliency of wildfire response in a cost-effective way. Specifically, this project investigates the use of vehicle autonomy, improved communications, and software for better coordination. This report describes a concept of operations (ConOps) for wildfire response adopted by the SMARt-STEReO project. Specific implementation details are outside the scope of this ConOps; rather, this report focuses on conceptual and operational descriptions. This concept is used to identify areas in which NASA technology can be leveraged and to construct a realistic, executable model. This report provides adequate background in wildfire response as well as detailing current aerial firefighting practices and potential new technologies to be tested within STEReO.

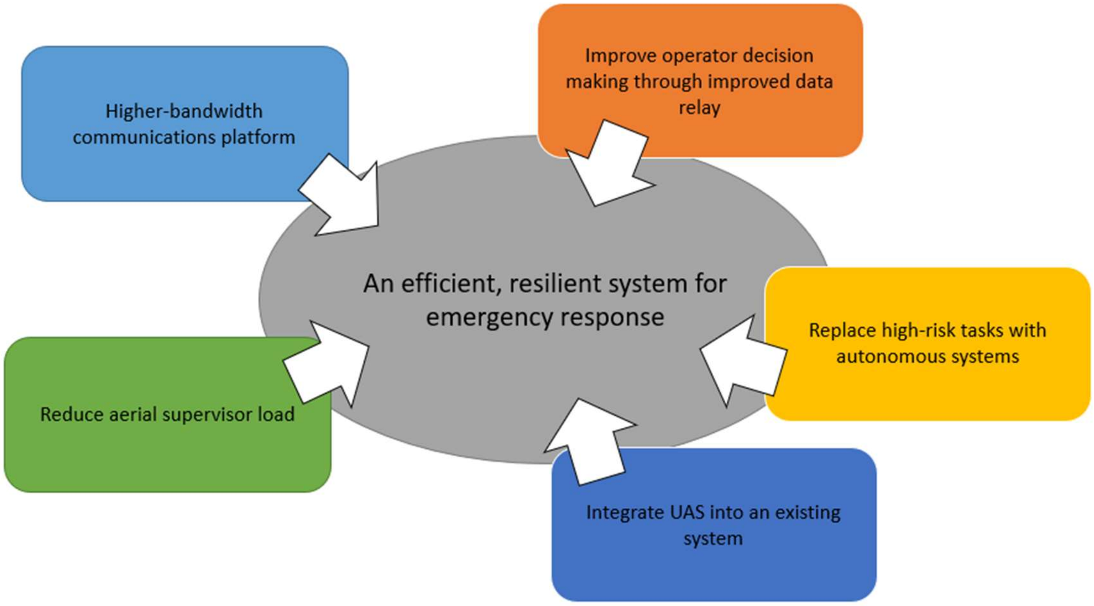

Figure 1 Goals and opportunities in SMARt-STEReO.

Operational Description

The objective of wildfire response is to contain the fire in such a way as to protect property, lives, and resources. In accomplishing this goal, aerial, ground, and communications assets work in tandem. Aerial assets typically include an airtanker, a lead plane, an aerial commander, and helicopters to move crews and equipment and for surveillance. The roles of the aerial commander, which is effectively an aerial air traffic controller, and lead plane, which leads the tanker to the drop location, are sometimes combined. There is also an incident commander on the ground. Severe fires may require increased quantities of each type of asset, and the aerial commander role may be split into multiple roles, such as helicopter coordinator and airtanker coordinator. Currently, pilots communicate and coordinate operations via radio and line-of-sight. Pilots listen to all radio frequencies and decide in which order to respond to commands. Commands may include clearing an area for a drop or picking up or dropping off crews. Operators may also communicate to obtain a better understanding of the system state. Environmental conditions are gauged using local awareness and experience rather than sensors. Decision making about the performance of individual aircraft is delegated to the pilot.

General Description of Wildfire Response

The main objective of crews is to create fire lines, which circumscribe the fire and thereby contain it [3]. This can be done by clearing flammable materials. In short grasses, typically 12-36 inches is sufficient for a fire line [3]. Other scenarios, such as dense forests, could require up to 100 ft of fire line [3]. Sometimes a burnout is conducted in which the crew starts a fire at the fire line that burns toward the fire, thereby removing all flammable materials in the fire’s path [3]. When constructing a fire line, there is a risk of a crew becoming surrounded by flames. To minimize this risk, an anchor point, such as a river or other non-flammable terrain, is often used [3]. Airtankers and helicopters assist in the construction of the fire line by dropping water or retardant [3]. These applications can cool a fire such that it is safe for ground crew operation or slow the spread of the fire, respectively [3]. Firefighting attacks can be either direct or indirect. A direct attack is when the fire line is placed at the fire’s edge [4]. An indirect attack is when the fire line is placed some distance away from the fire's edge [4]. These tactics depends on terrain, fuels, fire behavior, and resources [4].

The initial attack on the fire involves an incident commander (ground), ground crew, dozer, engine, and aircraft [4]. This phase involves gathering important information about the fire, including size, location, best access points, fuels, risks, and weather [4]. Sometimes, an initial attack is sufficient for containing a fire. When the initial attack is insufficient for containing the fire, an extended attack may be used [4]. More resources are used in the extended attack [4]. Staging areas and possibly incident bases may be established in this phase [4]. Ground crews in this phase are divided into firing squads, firefighters, and engines [4]. The number and types of resources allocated to the fire depend on its size and complexity, typically rated as Types 1-5 where Type 1 is the most severe and Type 5 is the least severe [4]. Type 5 attacks are only for very small fires, typically involving minimal complexity and able to be managed by fewer than six personnel [5]. Type 4 attacks are slightly more complex, but can still be resolved with an initial attack in a single operational period [5]. Type 3 fires require an extended attack and several resources [5]. Types 2 and 1 require significant resources and managerial functions due to high complexity [5]. Some very large incidents may also be divided into two or more separate incidents [5].

After the fire, mop up and recovery efforts begin. First, firefighters must put out all smoldering embers. The fire perimeter is cold trailed, meaning felt with bare hands, to confirm that the fire will not escape or spread [6]. Different ecosystems may benefit or be harmed by wildfires to varying degrees. For instance, burned trees can provide habitats for birds, but fires may also strip soil of important nutrients [7]. Rehabilitation and restoration efforts may follow containment of destructive fires. Soil may be raked and efforts to minimize erosion may be taken.

SMARt-STEReO Description of Operations

SMARt-STEReO augments the typical operations described above with two technologies: UAS and UTM. UAS are implemented as a flexible, inexpensive solution to relieve some strain from other aerial operations. UTM is introduced as a method of integrating UAS operations with piloted aircraft operations and for improving communications and data relay.

UAS in Wildfire Response

UAS are applied to two support missions. Typically, small UAS (sUAS) are used. Fixed wing UAS, featuring conventional engines, are used for surveillance missions. These UAS gather data by flying over the incident area. They can gather data about the fire itself as well as locations of strategic resources, such as water sources and crews, which can be relayed in near real-time. Meanwhile, multirotor UAS are used for logistics delivery missions. These UAS deliver supplies to ground crews periodically. These missions reallocate tasks from helicopters and surveillance aircraft, allowing them to be more productive. As an additional benefit, UAS can be operated at night, enabling 24/7 resupply to firefighters. Given that UAS are potentially obtainable by local fire agencies due to their small size and relatively low cost, it may be possible to deploy them rapidly, much before other aerial assets are likely to arrive on the scene. This availability could have significant benefits in terms of minimizing damages and acres burned.

Surveillance Missions – Currently, there are two methods of fire monitoring: aircraft and satellite. Aircraft are generally used for tactical decision making as they can produce higher resolution imagery. Satellites are generally used for strategic decision making and for monitoring trends since they produce lower resolution imagery. However, there are some benefits to satellite imagery, such as their ability to produce near real-time imaging and their wider coverage. SMARt-STEReO uses UAS to provide high resolution imagery closer to real time.

Fire Monitoring by Aircraft - National Infrared Operations (NIROPS) aircraft, managed by the US Forest Service, currently obtain fire mapping information at night, which is used for decision-making during the following day [8]. These aircraft fly through the night to obtain data on fires throughout the US, mapping the fire by flying over multiple times in overlapping paths. Since this is only performed once daily, maps used in decision-making can be up to 18-24 hours old [9]. The information obtained includes fire front and affected area [8]. Fire monitoring by NIROPS aircraft is based on priority, and low priority fires are often not monitored by NIROPS aircraft during peak season [8]. Fire monitoring using aircraft can also be improved through the use of advanced sensor systems, such as hyperspectral cameras, image intensifiers, and thermal cameras, which until recently have been cost prohibitive [10].

Fire Monitoring by Satellite - Currently, NASA and NOAA satellites provide higher-level views of fires around the world. Satellites have the benefit of increasing real-time or near real-time information availability [8] at the cost of lower resolution. NASA's Fire Information for Resource Management System (FIRMS) is capable of relaying fire data within three hours from satellite data – specifically NASA's Moderate Resolution Imaging Spectroradiometer (MODIS) and NASA's Visible Infrared Imaging Radiometer Suite (VIIRS). Satellite based imaging has been successful for strategic decision making; however, alternatives with higher spatial resolution are necessary for tactical decision making. Active fire detection algorithms provide a remote sensing solution that is more similar to aircraft data [8].

Fire Monitoring by UAS - UAS have the potential to improve wildfire monitoring. Various approaches for integrating UAS into wildfire monitoring have been proposed. For instance, in [11] a leader-follower coalition is formed for wildfire monitoring. In this setup, fixed wing UAS fly at higher altitudes and survey a wide area more quickly, whereas rotary UAS fly lower and get higher resolution imagery ("coalition leaders" vs. "observer UAVs") [11]. UAS equipped with thermal cameras can "see" through smoke, a significant advantage in smokey conditions and for nighttime operations. Additionally, UAS can also fly lower than helicopters, further enhancing their monitoring capabilities.

Logistics Delivery Missions – Multirotor UAS transport supplies to ground crews, relieving strain from helicopters which might otherwise be required to carry out these missions. Supplies may include hand tools, water, or foam. The multirotor UAS must be recharged after missions. In emergency resupply missions, the UAS may interrupt its current mission to perform the more critical mission first, as ascertained by the incident commander.

UTM for Wildfire Response

UTM is used for air traffic management, especially for its geofencing, weather and wind advisories, route planning, sequencing, spacing, contingency management, and separation management capabilities. Piloted and unpiloted aircraft send data to each other to ensure separation. Weather and wind advisories are sent to pilots directly. In other words, operators receive constraint information from UTM and can use this information to ensure safety in their operations. This degree of independence afforded to pilots and UAS operators reduces some strain from aerial supervisors. UTM enables operations management to be coordinated among operators, boosting flexibility and scalability of operations. This benefit is particularly useful in SMARt-STEReO due to challenges associated with aerial supervision and coordination of operations in an airspace that is not organized according to conventional practices.

Stakeholders

Key stakeholders within the context of the SMARt-STEReO project are listed as follows:

- Department of the Interior (DOI). This includes the Office of Aviation Services, Bureau of Land Management, Fish and Wildlife Services, Bureau of Indian Affairs, and National Park Service.
- Federal Aviation Administration (FAA). The FAA regulates aviation, including aerial firefighting.
- Federal Emergency Management Agency (FEMA). FEMA provides assistance programs for areas affected by wildfire.
- Fire protection agencies. This includes local, state, federal, and tribal agencies.
- National Interagency Fire Center (NIFC). The NIFC coordinates response to wildfires.
- Resource managers. This includes organizations related to wildlife and wilderness.
- U.S. Forest Service (USFS). The USFS manages wildfires on National Forest System lands.

Organizational Structure

The organizational structure of wildfire response scales according to the size of the incident, rated as Types 1-5 [4]. The response size may also increase over time as initial efforts fail to adequately contain a wildfire event. This decision-making may be guided by formal assessments such as the Wildfire Risk and Complexity Assessment [4]. While there are many important aspects of the organizational structure of the response, SMARt-STEReO emphasizes aerial operations and associated roles. Other important roles, though not the focus of SMARt-STEReO, include ground operations and logistics. Support systems for aerial operations including helibases and airbases are necessary in addition to the tactical air support. In large fire events, a helicopter coordinator and air tanker/fixed wing coordinator may be appointed. In smaller fire events, these roles may be centralized with an aerial supervisor.

Note that if evacuations are necessary, law enforcement has legal responsibility for evacuations [4]. The logistics branch of the fire response will coordinate with law enforcement and emergency services to organize and implement an evacuation plan [4]. If evacuation is not possible, a safe refuge is identified as an alternative [4]. Cleanup and recovery operations may require separate functions and are not considered in the organizational structure.

Initial Attack

When a fire is first reported, an initial attack is deployed. The initial attack may involve the deployment of a simplified organizational structure before fully organizing the response. Typically, this includes a ground crew, dozer, tanker, and helicopter working under an incident commander [4]. The initial attack gathers data necessary for planning the next stage of operations (if applicable), including fire conditions and various strategic locations [4]. Initial attack personnel may collect information from individuals leaving the area. Smaller fires (Types 4 and 5) that can be managed with only an initial attack normally do not require an Incident Action Plan (IAP) [4]. If the initial attack is insufficient to control the fire, a larger response, called the extended attack, is organized. Escalating the response may require transferring command to a more highly qualified incident commander.

Extended Attack

Extended attacks are typically used for fires less than 100 acres in size, although there are exceptions [4]. Whereas an initial attack is expected to be controlled within one operational period, the extended attack may span a longer period of time and may be associated with a Type 3 fire. An operational period is specified in the IAP but is normally no longer than 24 hours. An incident base may be required at this point, and an IAP will be drafted for each operational period [4]. A Type 3 fire may require up to 200 total personnel [4].

Type 1 and Type 2 Attacks

If the extended attack fails to control the fire, the response will scale accordingly to a more complex effort, generally to a Type 2 organization. This condition may also occur with a prolonged effort requiring support for food, sleep, and supply needs of crews [4]. Escalating to a Type 1 organization may be required for diverse aerial operations and/or large numbers of personnel (over 500 operations personnel or over 1000 total personnel) [4]. At this stage, the full range of planning, operations, logistics, and finance/admin functions are necessary, working under the incident commander. Extended operational periods spanning several weeks may be required. The most complex aerial operations will be seen in Type 1 incidents. A simplified structure with emphasis on operations is provided in Figure 2.

Apart from the operations branch, key personnel support command, planning, logistics, and finance/admin functions. In the command function, the incident commander is filled in every incident. There may additionally be staff working directly with the incident commander: an information officer, liaison officer, and safety officer. The information officer handles the release of information to the news media and may have assistants [5]. The liaison officer manages interagency contacts [5]. The safety officer oversees personnel safety and anticipates hazards in the incident response [5]. Planning includes a resources unit, situation unit, documentation unit, and demobilization unit [5]. The purpose of planning is to gather and analyze data necessary for operations [5]. Logistics manages supplies, facilities, support, communications, food, and medical, distributed among different units [5]. Finally, finance/administration manages timekeeping, procurement, compensation, and costs, also in different units [5].

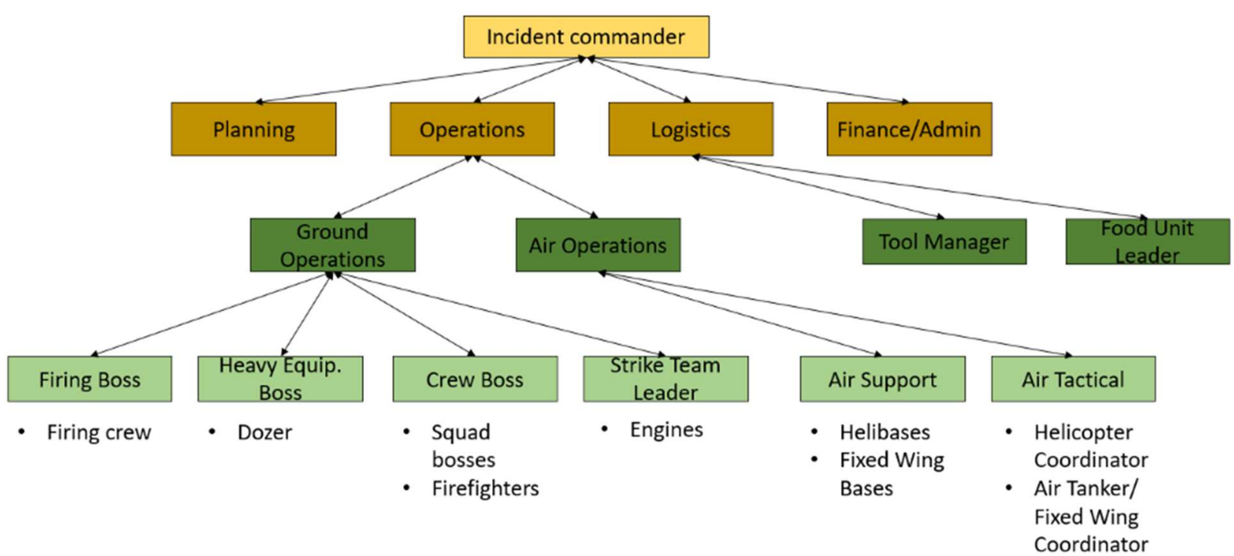

Figure 2 Simplified organizational structure for Type 1 and Type 2 firefighting operations, with emphasis on operations.

SMARt-STEReO Organization

The addition of UAS into wildfire response in SMARt-STEReO necessitates minor modifications to the organizational structure shown in Figure 2. In addition to a helicopter coordinator and fixed wing coordinator, in large-scale operations, a UAS coordinator will additionally be appointed. The addition of this role aims to prevent the newly integrated UAS from overwhelming the aerial supervisor's workload. Each UAS requires a remote operator, who reports to the UAS coordinator. UTM enables these remote operators a degree of independence, however, since they receive vital operational data from UTM. Otherwise, SMARt-STEReO is implemented without any significant changes to the organizational structure of wildfire response operations. Figure 2 Simplified organizational structure for Type 1 and Type 2 firefighting operations, with emphasis on operations.

Personnel Communications

Figure 3 summarizes personnel communications. Currently, communications are primarily through radio. Air-to-air and air-to-ground communications are usually on AM and FM channels, respectively, while airbases are on AM frequency. The NIFC CDO (Communications Duty Officer) manages radio frequencies for communications and is responsible for ensuring appropriate policies and procedures are followed. The CDO receives orders for new frequencies from the Communications Coordinator (COMC) and Communications Unit Leader (COML). The COMC is not used in all cases but is used in complex cases to reduce load on CDO. Similarly, a COML is used in Type 1 and 2 incidents. In addition to radio communications, personnel rely on visual line of sight to gauge relative positions of the aerial assets applied to an incident.

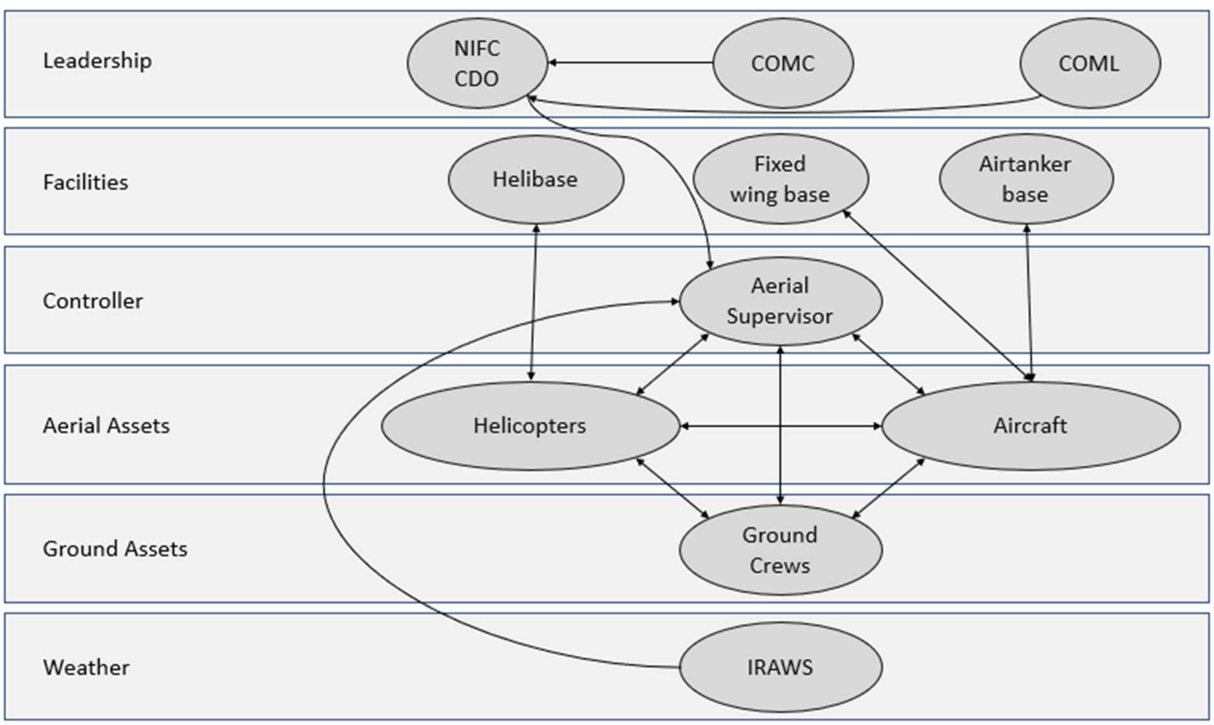

Figure 3 Current personnel communications diagram.

SMARt-STEReO assesses the effect of improved communications within this standard model of personnel communications. NASA's UAS Traffic Management (UTM) has significant potential to improve communications and data relay between piloted and unpiloted aircraft. UTM is focused on low altitude airspace operations and provides capabilities including geofencing, corridors, weather and wind advisories, route planning, re-routing, sequencing, spacing, contingency management, and separation management [12]. In SMARt-STEReO, UTM has the potential to improve coordination between piloted and unpiloted aircraft, improve the independence of UAS, and reduce the load of the aerial supervisor.

The FAA frequently enacts Temporary Flight Restrictions (TFR) around wildfires for the purpose of protecting aerial wildfire response ops [13]. To operate UAS, a Launch Recovery Zone (LRZ) is enacted in which UAS can ascend/descend to its proper altitude. While a UAS is ascending or descending, the LRZ is hot and no other aircraft may fly through it. When the UAS has reached proper altitude, the LRZ again becomes "cold". In contrast, piloted aircraft participating in UTM may be equipped with ADS-B [14]. This way, the UAS can interact with piloted aircraft [15]. This can be either a transmit/receive setup or a receive-only setup such that the two aircraft can exchange information and steer clear of one another [14]. Alternatively, piloted aircraft can opt to receive information from UAS Service Supplier (USS) to be aware of UAS operations in their area [14]. In tightly coordinated operations such as aerial firefighting, a transmit/receive setup is the most promising in terms of potential performance improvements. There are challenges, however, for flying autonomous fixed wing aircraft in such an area due to their need to take off and land at airports, which are not in the TFR zone [9]. As such, there is an opportunity for integrated air traffic management solutions to be leveraged to enable autonomous fixed wing aircraft for wildfire operations.

Currently, aerial supervisors provide aircraft with information, including weather and terrain. In contrast, UTM enables all aerial vehicles to have access to weather and terrain data from USS, rather than all weather data being sent to the aerial supervisor. Operators receive information about weather, congestion, terrain, route planning, re-routing, separation management, and contingency management [12]. This provides a degree of independence to individual assets and may reduce some strain from often taxed aerial supervisors. The data provided by UTM helps human managers make decisions about initiation, continuation, and termination of operations.

Personnel Profile

Personnel include operators on-the-scene as well as support staff. The focus of this section is the ground crews, who are an integral part of the fire suppression and containment efforts. There are four main categories of ground crews: fire crews, hand crews, engine crews, and helitack crews. Fire crews, a.k.a. firefighters, consist of a crew of approximately twenty personnel [16]. They are on-call 24/7 and may be required to work at night [16]. Crews may have differing levels of availability and experience [16]. The crew has a boss who supervises the group. Hand crews build fire lines and are the main participants in the direct/indirect attack as directed by the incident commander. Engine crews operate fire engines. Usually, 3-5 personnel are required for this task [16]. Helitack crews operate helicopters either for tactical or logistical purposes [16]. These crews may be among the first responders to a wildfire event [16].

Personnel on the ground, and some pilots, require personal protective equipment (PPE). While on the fire line and in a helicopter, flame retardant clothing is required [4]. A hardhat and leather gloves are also required while on the fire line required [4]. Firefighters use 8 inch work boots with melt-resistant soles and eye and face protection when needed required [4]. Hearing protection and/or chaps may be required around certain equipment required [4]. All PPE should be replaced visibility or flame-retardant properties are diminished [4].

Fatigue, nutrition, and hydration are also important issues for firefighters working on the front lines. There is a one hour sleep or rest requirement for every two hours worked required [4]. Any deviations from this requirement must be approved in writing by either the incident commander or agency administrator required [4]. Additionally, firefighters have significant caloric and fluid intake needs due to their heavy physical workloads – up to 5000-6000 calories per day and 5-6 gallons of fluids [4]. While working on the fire line, firefighters should eat 160 calories of carbohydrates per hour required, which can be mixed with water to meet both caloric and fluid requirements [4]. The logistics branch of fire response operations oversees food and fluid distribution.

Strategies and Tactics

Personnel on the scene are currently given wide discretion in tactical decision-making, as incident conditions may change rapidly and require swift response. General wildland firefighting tactics revolve around the construction of a line of inflammable material called a fire line. These are typically constructed by cutting or digging and can be constructed either by hand or using bulldozers. A successful fire line is one that the fire is unable to cross, or slop over. Slop over occurs when embers from the fire are blown across a line of inflammable material. Wind can be either due to local weather patterns or generated by the fire itself. This is most likely to occur in high energy fires and especially in hot, dry conditions, or if the fire line is insufficiently wide.

General Strategy

The first phase of the response, called the initial attack, is completed by the first responders to the fire. They are responsible for completing an initial overview of the fire and establishing the best course of action. Whichever unit arrives at the site first performs the initial surveillance. Smokejumpers are often the first type of unit on the scene. Best access points and other strategic locations may also be assessed at this point. Any individuals leaving the scene may be able to provide additional information to the response personnel. Based on this surveillance data, the incident commander who leads the response determines the best location for the fire line and the best methods for creating it. After the initial attack, surveillance is performed continuously, usually by aircraft. The incident commander may select a direct attack, which is used in smaller fires when the safest route is to attack the fire head-on, or an indirect attack, which is used in larger fires where it is too dangerous to put ground crews immediately ahead of the fire. For direct attack, a retardant drop is often required. Retardant drops may also be required for difficult line construction or to widen existing lines.

A fire line may be constructed by ground crews and/or dozers. If possible, the fire line will be wider at the head of the fire (the section towards which the wind blows) than at the flanks (to the left and right of the head). Fire lines should be no wider than necessary to prevent using unnecessary time and resources that could be directed elsewhere in the response. Ground crews may be moved into the area by helicopter or fire engine. Water drops cool the fire so ground crews can work safely. Retardant drops are performed before a ground crew moves in, while water drops can be performed while the ground crews are working. Backburn may also be performed by lighting a controlled fire and burning backwards from the fire line. This removes fuel in the path between the current fire location and the fire line, reducing the possibility of the fire slopping over the fire line. Flame heights determine the minimum safe working distance for ground crews. For a flame height of 10 ft, firefighters must stay 40 ft from the fire, whereas for a flame height of 200 ft, firefighters must stay 200 ft from the fire [17]. The heat of a fire is also a factor in ground crews' ability to construct a fire line. Specifically, the fire must be cooled by a tanker drop for a ground crew to be able to move in and construct a fire line. Fires with large flame heights and high heat may display dangerous behavior such as crowning across treetops, "torching" from bottom to top of trees, and spotting across fire breaks [18].

The incident commander will call for the necessary mobilization of additional troops when an extended attack is warranted. Helicopters may drop in crews, while supplies may be brought in via paracargo. The response will continue to escalate until the slop over and spotting may require additional work by ground crews and/or additional retardant drops. Finally, ground crews perform mop up to ensure any smoldering spots around the fire line are put out. General tactics are summarized in Figure 4.

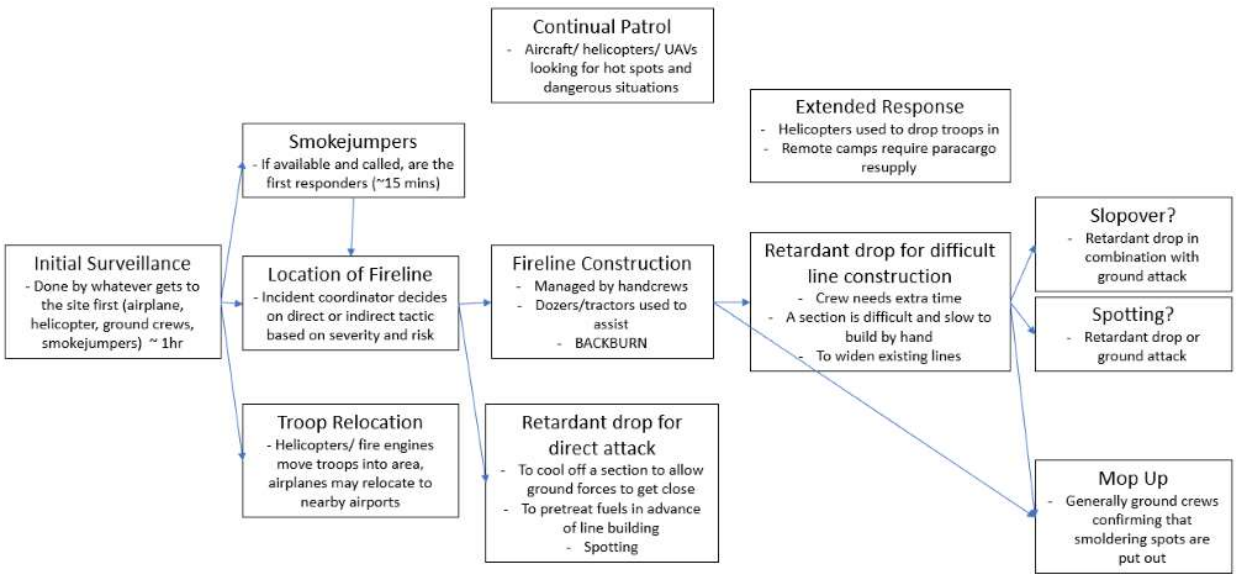

Figure 4 Tactics diagram.

Air Drops

An airtanker or sometimes a helicopter can be loaded either at an airbase or from a water source. If loading from an airbase, an established airport with an adequate water supply must be located nearby. If loading from a water source, a specialized water scooper or helicopter with a bucket is required. These aircraft can fill from a nearby lake or water source, which is useful in fires that are not located nearby an established airport. The aircraft then enter their preparation stage, in which they first make a dry run at live drop altitude without dropping, and a low pass, in which they fly at low altitude to scout the area and warn ground crews if necessary. Drops can then be performed, either as a direct attack or for difficult line construction. The drops can either target hot spots/fire spotting or as a trail drop. Depending on the drop size and tank size, it is often possible to perform multiple drops on a single tank. Detailed tactics for drops are provided in Figure 5.

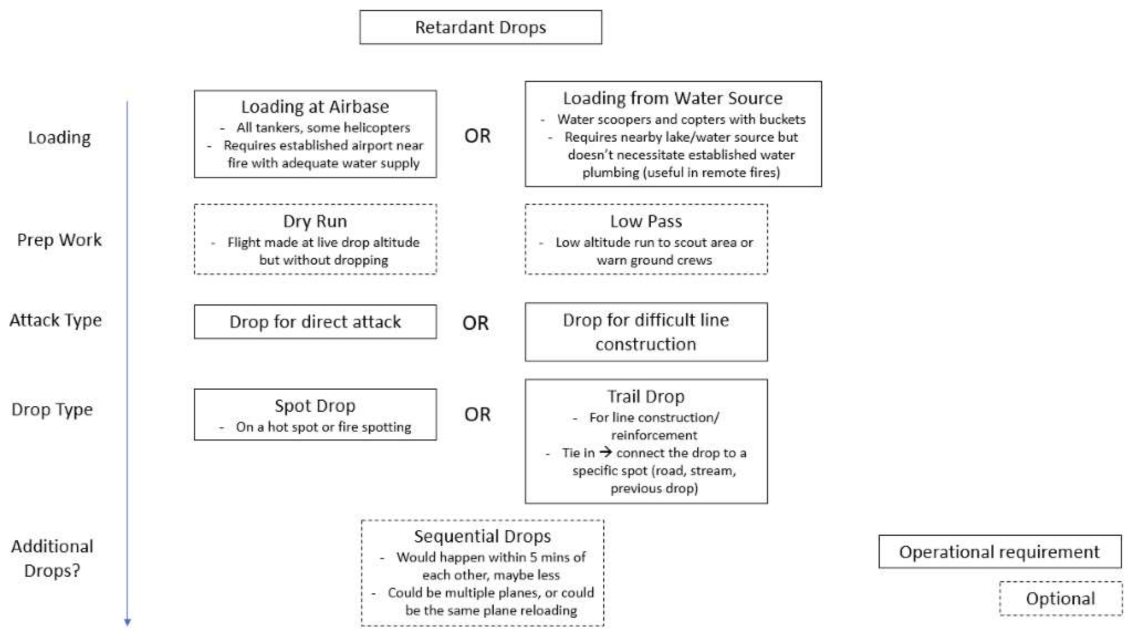

Figure 5 Retardant drop tactics diagram.

Triage for Structures

When multiple structures are present it may become necessary to perform triage to decide which structures to save. This is common in, for example, fires in wildland-urban interface (WUI) areas. Depending on certain factors related to the structure, the structure may be considered defensible or non-defensible, and certain actions may be taken accordingly. A safety zone is a safe area for firefighters and equipment [4]. A crew should not commit to protecting a structure unless a safety zone is present [4]. Size up is the initial assessment of the situation [4]. Triage depends on factors including: (1) whether a safety zone is present; and (2) whether the structure has tactical challenges [4]. If the structure is deemed defensible, firefighters may stay to implement structure protection tactics if necessary [4]. If the structure is not deemed defensible, firefighters do not commit to protecting the structure, but may perform rapid mitigation measures [4].

Operational Needs

Wildfire events can be incredibly unique, each requiring a specialized response. Challenges such as weather, positioning and availability of various resources and assets, stress conditions, and mechanical failures all complicate the response. One of the primary objectives of SMARt-STEReO is to consider the resiliency of the response – that is, can the response withstand and/or mitigate these challenges and still perform adequately? A detailed accounting of these challenges, then, is a necessary endeavor.

Operating Conditions

Operating conditions can vary widely depending on the location and severity of the fire. These conditions drive the need for the use of various assets as well as the strategy for fire containment. Specifically, fire properties, smoke, terrain, and weather are incredibly important contributors to the difficulty of containment.

Fire

Average fire size over the past ten years has been approximately 115 acres [19], costing approximately $29,000 per fire [20]. Most fires, however, are very small – approximately 2-3% of wildfires account for 95% of acres burned [7]. These large fires can be especially destructive and challenging to contain. In the western United States, wildfire season is between June and October, although wildfires can occur at any point in the year depending on conditions. Fires have different propagation speeds and flame heights depending on the environmental conditions, and firefighting tactics change depending on these variables.

Fire spread depends on the fuel available in and the flammability of a particular area. Moisture and chemical makeup are the primary indicators of how the fuel will burn. Fuel is generally designated as 1-, 100-, etc. hour fuel, meaning the amount of time to dry. One- and 10- hour fuels are relatively quick to ignite, whereas fuels of higher hour-based ratings generally will only burn when preheated by fires started in lower rated fuels. However, higher rated fuels can burn for a very long time once ignited. Additionally, fires may burn in different parts of the forest. Ground fires burn organic matter beneath material on the ground's surface [7]. Surface fires, on the other hand, burn fallen branches and leaves on the forest floor [7]. Crown fires are the most intense type and burn the forest canopy [7]. These are the most difficult to contain, but also have more difficulty spreading due to high requirements for wind, slope, and fuels [7].

Smoke

Federal land managers from the U.S. Forest Service, National Park Service, Bureau of Land Management, and Fish and Wildlife Service provide expertise in air quality and smoke management [21]. The Air Quality Index (AQI) is a typical way of monitoring smoke conditions. AQI under 50 indicates good air quality, while AQI over 300 indicates hazardous air quality. Smoke poses a threat to personnel working on the fire as well as to the general public in areas affected by wildfire smoke. Smoke from the fire can create problems with fire detection/monitoring. UAS can be used in smokey situations, i.e. using infrared cameras [9]. Finally, smoke can create dangerous operating conditions. As such, aerial operations are typically limited to clear air activities [9].

Terrain

Operating conditions are subject to complex terrain such as hills, mountains, and valleys. Terrain affects the spread of the fire. Wildfires burn faster when traveling uphill. Additionally, wind travels more quickly upslope, further compounding this effect. The amount of sunlight a slope gets – which is a function of its orientation with respect to the sun – also affects the fuel load of that area. Slopes that get more sunlight tend to have drier fuels. Lower elevations tend to receive less rainfall and therefore have drier fuels. Higher elevations are also prone to lightning strikes, increasing the likelihood of ignition. Certain ecological areas, such as riparian zones, are resistant to fire. Streams, rivers, lakes, and roads are also resistant to fire and can be used as anchor points in firefighting tactics.

Weather

Wind can create significant challenges to wildfire operations. Fire danger ratings are usually rated on a scale of green (low) to red (extreme). When fire danger is low, weather and fuel conditions tend to lead to fires that spread slowly and are relatively easy to control, if they occur at all. However, in hot, dry conditions, fire will start easily, spread quickly, and be very difficult to control. Low and moderate fire danger ratings usually enable a direct attack tactic; above a high fire danger, an indirect approach is used for the safety of firefighters. Flame heights are also greater for higher fire danger ratings. Wind brings in new oxygen for the fire and can push the fire towards unburned fuels. Wind can limit aerial operations, especially for smaller aircraft such as sUAS. Strong winds may even change the direction of the fire spread, creating difficulties in planning and executing a response. Additionally, wind can blow embers, igniting new areas. For estimating a fire's rate of spread given a wind speed, the 10% rule can be used in many situations [22]. Applied to certain vegetations, namely conifer, dry eucalypt, and temperate shrublands, the forward spread rate of the fire can be estimated as 10% of the open wind speed [22]. More sophisticated fire propagation models are also available. Finally, low humidity may also increase the spread of the fire. Extended drought periods can lead to very dry fuel.

Mission Profiles

Operations vary during daytime and nighttime, due to constraints in nighttime operations. Additionally, specialized procedures may be required during stress or failure conditions.

Normal Conditions, Daytime

Daytime operations include crew movements as well as surveillance. The initial attack includes a lead plane/helicopter for surveillance. After some time, the aerial supervisor orders a tanker to drop water to build a fire line. The lead plane flies in front of the tanker and indicates the drop location by releasing white smoke. The aerial supervisor communicates to move the ground forces out of the drop area. Daytime operations are illustrated in Appendix A.1 Daytime Operations.

Normal Conditions, Nighttime

During nighttime operations, personnel movement is limited but includes surveillance and analysis. Conditions are often cooler at night, meaning fire spread may slow in some cases. Any necessary nighttime operations must utilize appropriate lighting and communications [4]. Flying manned aircraft over the fire may be dangerous at night, so UAS operations may be used to gather data. Nighttime operations are illustrated in Appendix A.2 Nighttime Operations.

UAS have the potential to extend operational time of aerial operations to night operations and operations in smokey conditions. Aerial ops are only active for roughly 8 hours a day in typical wildfire response scenarios since aerial operations are typically limited to clear air and daytime activities [9]. UAS is a potential solution to increasing the usage of aerial ops, potentially more effective than night vision devices (NVDs) since they can be used in smokey situations (i.e. using infrared cameras) as well as nighttime situations [9]. In this way, UAS use could increase the support window by approximately three times [9]. Also, roughly 20% of fires are outside of the range of conventional aerial ops [9]. A variant of conventional UAS is optionally piloted aircraft, which can be piloted during the day and can be unpiloted at night or in heavy smoke conditions [9]. This solution would leave daytime/clear conditions operations untouched, and would simply extend those operations into night and smokey conditions [9]. Thus, the number of new contracts, personnel, etc. would be minimized and no new aircraft would need to be added to the wildfire event.

Stress Conditions

Some operating conditions may be particularly hazardous. High smoke levels, especially when roads are impaired [4], create hazardous conditions for personnel, especially at night. As one potential option, thermal infrared (TIR) sensors are still effective even in thick smoke [23]. Excessive carbon monoxide exposure could also lead to impairment in personnel [4]. This is especially hazardous for pump and chain saw operators; these operations should be closely monitored. In general, indirect attack strategies reduce the risk of carbon monoxide exposure. When risk of exposure is high, workers can be rotated to reduce risk of impairment.

Failure Conditions and Contingency Actions

Possible failure conditions include: (1) tracking issue/position data lost, (2) degraded navigation performance, (3) on-board equipment failure or degradation, (4) flight path deviation, and (5) critical ground crew tool breaking. In general, anomalies may be detected by operators or via health monitoring [12]. Note that some faults can apply to either UAS or other aerial assets. However, the causes and contingency actions may look slightly different for each. This section focuses on UAS faults, but other aircraft may have comparable faults.

Tracking Issues/Position Data Losses – The operator will first try to resolve the communications loss issue. The operator and UAS continuously ping each other to confirm communications are working properly. If this back-and-forth is interrupted for 5 seconds, the automatic contingency action activates [24]. The UAS automatically returns to its launch location and may additionally provide visual indication of loss of communications, e.g. a flashing light [24]. The operator will retry communications with UAS as it returns to its launch location, then take over manual control [24]. If the operator notices that the comms are weakening, they can command the UAS to return to its launch location [24]. The operator also informs the aerial supervisor. If the UAS is unable to complete its mission, the aerial supervisor will reallocate mission to another UAS/helicopter,

Degraded Navigation Performance – If fewer than six satellites are in view, activate the contingency plan [24]. The UAS automatically lands [4] or enters loiter mode (maintains altitude) and waits for manual control [24]. It may additionally provide a visual indication of loss of navigation, e.g. a flashing light [24]. The operator takes over manual control of UAS (if applicable). If the operator notices that the navigation is weakening, they can command the UAS to return to launch location [24]. The operator must inform the aerial supervisor, who reallocates its mission to another UAS or helicopter if necessary. With 24 satellites, GPS can identify ground locations within 320 ft 95% of the time [25]. However, steep terrain and dense forests can hinder GPS performance [25]. GPS issues can also occur with piloted aircraft, specifically with jamming/space weather degrading GPS performance. GPS may be used to report fire positions during surveillance missions [25]. Many aircraft have a secondary means of navigation, however.

On-Board Equipment Failures/Degradations – Equipment failures/degradation degrade UAS performance/capabilities. The mission may still be able to be completed if the performance degradations are small. In many cases, however, the UAS must either return to base or perform an emergency landing. If the mission can no longer be safely completed, Safe2Ditch will activate. Safe2Ditch assesses UAS remaining capabilities, assesses candidate landing sites, selects a landing site, uses machine vision to confirm landing site is safe, and lands the UAS safely. The operator informs the aerial supervisor, who reallocates the mission to another UAS/helicopter, as necessary. There are many possible UAS equipment failures. For example, sensor faults are relatively common faults in UAS [26]. The sensor can fail in different ways, some leading to zero output and others leading to a degraded output [26]. We are interested in a fault that requires an emergency landing and cessation of progress towards mission. In this case, the priority is finding a safe landing site to prevent loss of the asset or any further damages. The mission can be reallocated to a different asset. In piloted aircraft, a human operator will perform actions comparable to Safe2Ditch.

Flight Path Deviations – UAS may deviate from their flight path for several reasons. The danger is that the UAS may either fly into a no-fly zone or crash into another asset. If the UAS gets too close to a no-fly zone, Safeguard will activate. If the UAS gets too close to another aircraft, ICAROUS will activate. If the UAS is or is on a trajectory to be within the contingency boundary, it will land safely. If the UAS is or is on a trajectory to be farther than the contingency boundary, Safeguard will cut its power. If the UAS is or is on a trajectory to be within an unacceptable safety margin from another aircraft, it will perform an avoidance maneuver. If the UAS crash lands, the operator informs the aerial supervisor that UAS will not be able to complete mission. In this case, the aerial supervisor reallocates the mission to another UAS/helicopter. With UTM, piloted aircraft and UAS can exchange information and steer clear of one another [14]. In the case of Safeguard cutting the power to the UAS, it will not land safely – it will be destroyed. In the case of Safeguard directing the UAS to land, it is assumed that the UAS will land safely. All of these systems are assumed to work perfectly when activated. If this fault occurs within a piloted aircraft and causes the aircraft to fly too close to another aircraft, the human pilot will perform detect and avoid actions comparable to ICAROUS. However, due to danger to the human pilot, the aircraft cannot crash land to avoid a no-fly zone (following Safeguard actions). Instead, the human pilot must perform a maneuver to redirect the aircraft into an acceptable area.

Critical Ground Crew Tool Breaking – Periodic deliveries by helicopters/UAS are part of normal operations. However, if a critical piece of equipment breaks, the ground crew's supply level could fall below the threshold required to perform work. In this case, the condition is off nominal. The ground crew alerts aerial supervisor that a replacement is needed. Work halts while waiting for the replacement. The aerial supervisor summons a UAS/helicopter for a delivery mission. The UAS/helicopter possibly interrupts current mission, depending on priority. It then delivers the equipment to the ground crew and returns to its default mission.

System Overview

Numerous assets, both on the ground and in the sky, contribute to the wildfire response system. SMARt-STEReO applies NASA technology to the system with minimal modifications to the basic system architecture. This section describes both conventional assets as well as assets introduced by SMARt-STEReO, with the inclusion of assets proposed in SMARt-STEReO driven by required system capabilities, described below. Note that the coordination of multiple agencies and organizations is required in many large wildfire events, including law enforcement for evacuations and agencies supporting those affected by wildfires. However, SMARt-STEReO focuses primarily on the wildfire suppression efforts, particularly on those with which aerial operations are involved.

System Capabilities

Select system capabilities, focusing on the capabilities of aerial operations, are summarized in Figure 6 and described below. These are the key, high-level capabilities that are required from an operational standpoint to achieve the mission objective of containing and/or suppressing the wildfire incident.

Transport Cargo/Personnel

Ground crews must be transported to various locations along the incident fire line to fulfill their roles, either by ground or air. Additionally, cargo and supplies must be transported to appropriate locations during the incident. This includes water, equipment, and tools. There are often difficulties associated with this task, as wildfires can occur in remote areas with access challenges. Smoke and/or terrain conditions may also be hazardous. Safety of firefighters and other personnel is always the foremost concern.

Sense Positions of Aerial Assets

For safe operation and effective coordination, pilots must be able to assess the relative positions of other aircraft and key strategic locations during operation. There are several challenges to this, including smoke and difficulties prioritizing information. Some operations may also take place in remote areas with low visibility and difficulties maintaining a strong signal for certain communications channels.

Collect Data

Surveillance and fire monitoring are essential tasks in aerial firefighting. Fire conditions can change rapidly, but fire maps are not always current. Additionally, key strategic locations, such as water sources, must be located to properly formulate firefighting tactics. Real-time or near-real time, high resolution mapping would be ideal for tactical decision-making. However, obtaining maps that are both current and high resolution can be challenging.

Apply Flame Retardant or Water

High energy fires are associated with difficulties in safe fire line construction, namely spotting, crowning, and torching as well as rapid spreading which can be hazardous to crews. Flame retardant can be applied to slow the spread of fire to new fuel. Water drops cool the fire to allow ground crews to work safely. Both are important functions in assisting the construction of a fire line but must be implemented safely and efficiently as they are associated with hazards and costs themselves.

Prioritize Commands

Currently, pilots listen to all communications frequencies and prioritize them based on importance. Experience and training can help operators manage this task. UTM has capabilities to ensure airspace is available for emergency responders; it is possible that such capabilities could be extended to prioritizing airspace during wildfire response for urgent tasks as well as for emergencies such as personnel injuries.

Manage Aircraft Performance

Aircraft performance is delegated to the pilot, including refueling and any mechanical failures. Performance must be monitored and managed for both piloted aircraft and UAS. It is essential that systems are in place such that UAS performance can be monitored, to avoid the occurrence of collisions and losses and to ensure mission success.

Assess Environmental Conditions

Local weather, terrain, and air quality have significant bearing on fire behavior and crew safety and must therefore be monitored closely. Firefighters typically have good local knowledge of the area, allowing them to use judgment and experience for these assessments. However, there are also systems available for obtaining current data on these conditions, for example as implemented in UTM.

Relay Commands

The tactical decision making of the aerial supervisor is relayed in the form of commands. Radio is the primary means of relaying commands between aircraft. With remotely piloted UAS, it is important that commands can be appropriately relayed to remote pilots with minimal lag.

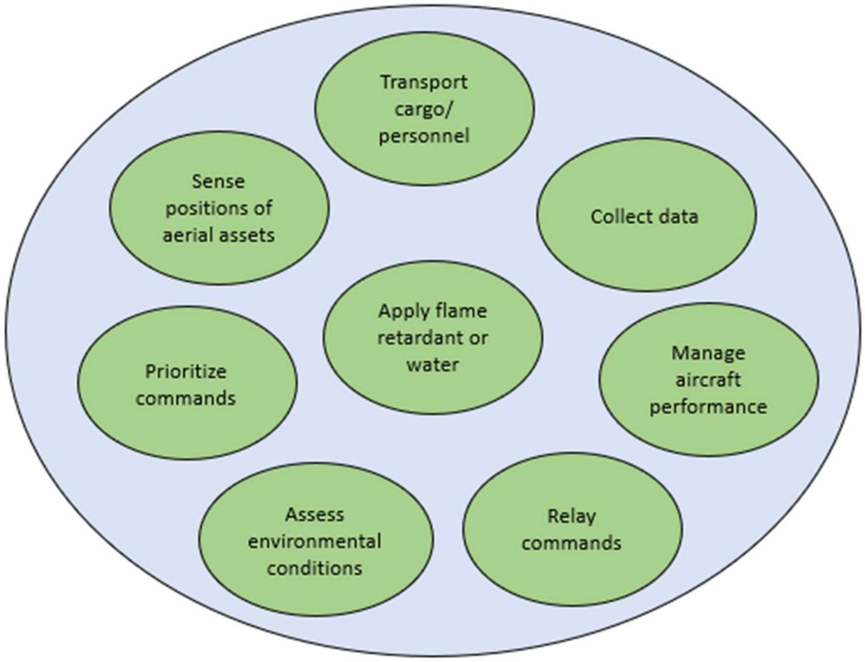

Figure 6 System capabilities diagram.

Assets

Complex incidents could see numerous ground and aerial assets coordinating to contain the fire. Assets required for an incident scale depending on the size of the incident. Firefighting assets and their typical use cases are summarized in Table 1 and are described in more detail below.

Table 1 Firefighting assets and their use cases.

Category	Type	Use Case	Reference
Engines/Tankers	Engine	Direct fire attack	[17]
	Tactical Water Tanker	Direct fire attack	[15]
	Non-Tactical Water Tanker	Support, i.e. refills and dust abatement	[15]
Dozer/Tractor Plow		Fire line construction	[15]
ATV/UTV		Cargo transport and administrative use	[15]
Aerial Supervisor	Air Tactical Ground Supervisor (ATGS)	Directs air traffic	[17]
	Aerial Supervision Module (ASM)	Directs air traffic	[17]

	Helicopter Coordinator (HLCO)	Directs air traffic	[17]
	Lead Plane Pilot	Directs air traffic	[17]
Airspace Coordinator (ASCO)		Coordinates with FAA and manages TFRs/maps	[27]
Aerial Supervision Module/ Lead Plane (ASM/LP)		Aerial supervision; directs air tanker to drop location	[17]
Airtankers	Type 3 (S-2T, SEAT)	Drops water	[17]
	Type 2 (Convair 580, Q400)	Drops water	[17]
	Type 1 (LAT)	Drops water	[17]
	VLAT (DC-10, 747)	Drops water	[17]
	Water scooper (CL215/415)	Scoops and drops water	[17]
Smokejumpers		Initial attack and assessment, moves firefighters, construct helispot, temporary aerial supervision	[28]
Helicopters	Landing	Cargo and personnel transport	[17]
	Non-Landing	Longline, paracargo, water/ retardant drops	[17]
UAS	Fixed wing	Fire monitoring	
	Multirotor	Logistics delivery	

Engines – Fire engines for wildfires typically have off-road capabilities. They come in different sizes depending on their tank capacity and pump rate. Type 3, 4, 6, and 7 engines are typically used, with the Type 4 engine having up to a 750 gallon capacity [29]. Engines may be used for tactical purposes, i.e. direct attack on fires, or non-tactical purposes, i.e. dust abatement or refilling other tankers.

Dozers – Dozers are used primarily for fire line construction. They construct fire lines by scraping fuel away from the earth, clearing a path of inflammable material. Many dozers are operable on moderately sloped terrain and in challenging soil conditions. Dozer operators must be in contact with other personnel being applied to the incident. Front and rear lights should also be used in case of operation at night or in heavy smoke conditions. Dozers are productive in situations in which the area is reasonably accessible, but hand crews may be needed for areas with difficult access or in very steep terrain.

Aerial Supervisor – The aerial supervisor manages and coordinates aerial assets being applied to an incident and work together with ground crews for tactical decision making [30]. Currently, they additionally relay weather conditions to operators; however, SMARt-STEReO delegates this role to USS providers. This role may sometimes be combined with the helicopter coordinator and/or the lead plane.

Airspace Coordinator – The airspace coordinator works with the FAA and manages the TFR. This role determines any possible interference of the incident airspace with the National Airspace System (NAS), including general aviation or nearby airports [31].

Lead Plane – Lead planes direct the larger airtankers as they perform drops on the incident. The lead plane indicates the drop location to tanker aircraft by releasing white smoke. This role is sometimes combined with aerial supervisor.

Airtankers – Airtankers drop water or retardant on a fire. Some specialized tankers, called scoopers, can refill from a lake without landing. Others require a return to base to refill. There are varying sizes of air tankers, with some capable of carrying over 8000 gallons of retardant.

Smokejumpers – Smokejumpers are specialized crew that parachute out of aircraft to an incident. They are often among the first responders to an incident. They are trained and equipped such that they require minimal support, even working for long periods of time in remote areas. They can perform tasks such as an initial attack and assessment, the construction of a helispot, and even act as temporary aerial supervision.

Helicopters – Helicopters can perform a variety of tasks in aerial firefighting. First, they can be used for personnel and cargo transport. They transport crews to and from the incident, as well as delivering necessary supplies when needed. They may also perform bucket drops and, in some cases, perform surveillance missions. They are also often among the first to respond to an incident during the initial attack.

UAS - There are two main motivations for using UAS in firefighting applications. First, UAS can replace piloted aircraft for certain dangerous tasks, reducing risk taken by human operators. Aircraft operations in firefighting are high risk, low altitude [2]. From 2000-2013, 26% of wildland firefighter fatalities were aviation related [2]. Replacing dangerous tasks with UAS is a potential solution to reducing fatalities in dangerous aerial operations. Tankers have one of the more dangerous missions due to their low operating altitude during drops. Second, UAS's versatility, flexibility, and technology may improve system performance. Underlining these benefits, UAS can be relatively inexpensive – an important consideration in budget-strapped operations. The US Forest Service recently spend over 50% of its budget on wildfire management – taking funds away from science that could prevent fires in the first place [32].

Rotary UAS are generally more well suited to low altitude, precision operations and fixed wing versions are better suited to surveying large areas quickly. UAS can also come in varying levels of autonomy, with some being remote piloted and having higher levels of autonomy. Use of optionally piloted air tankers and other fixed wing aircraft is desirable but comes with the challenge that they need to take off from an airport, and unpiloted a/c are not yet fully integrated into the NAS. For this reason it is likely desirable to first integrate better sensors, navigation, and vision (i.e. for improved operation in smokey environments/at night) into fixed wing aircraft before opting for an unpiloted option [9]. Drone operations may occur at the same altitude as low flying aerial operations [13]; as such, it is important that the introduction of UAS into wildfire response be accompanied by an appropriate traffic management system, such as UTM.

Operational Environment

The operational environment includes facilities, equipment, hardware, and software. SMARt-STEReO is designed such that changes to the required operational environment for wildfire response are minimized. One important characteristic of the operational environment in wildfire response is its dependence on the coordination of multiple agencies and organizations. Additionally, each incident is unique in terms of availability and proximity of certain facilities and resources. SMARt-STEReO is designed to integrate into such an environment and remain available in most operational scenarios.

Facilities and Equipment

The airbase requirements will vary depending on the aerial assets needed for the incident. Airtankers likely have the most significant requirement for an airbase and will often take off and land from a nearby established airport. Helispots can be more flexible, and temporary helispots can be constructed for specific incidents. Fixed wing and airtanker bases on the ground near the fire allow for takeoff, landing, and refueling of these assets. Helitack operations achieve similar objectives as aircraft operations but require their own helibase for takeoff, landing, and refueling. The location of the incident base should be selected based on accessibility, communications availability, safety, proximity to the fire location, and accessibility to water, among other factors [4]. Facilities are summarized in the conceptual diagram in Figure 7. Locations are not to scale.

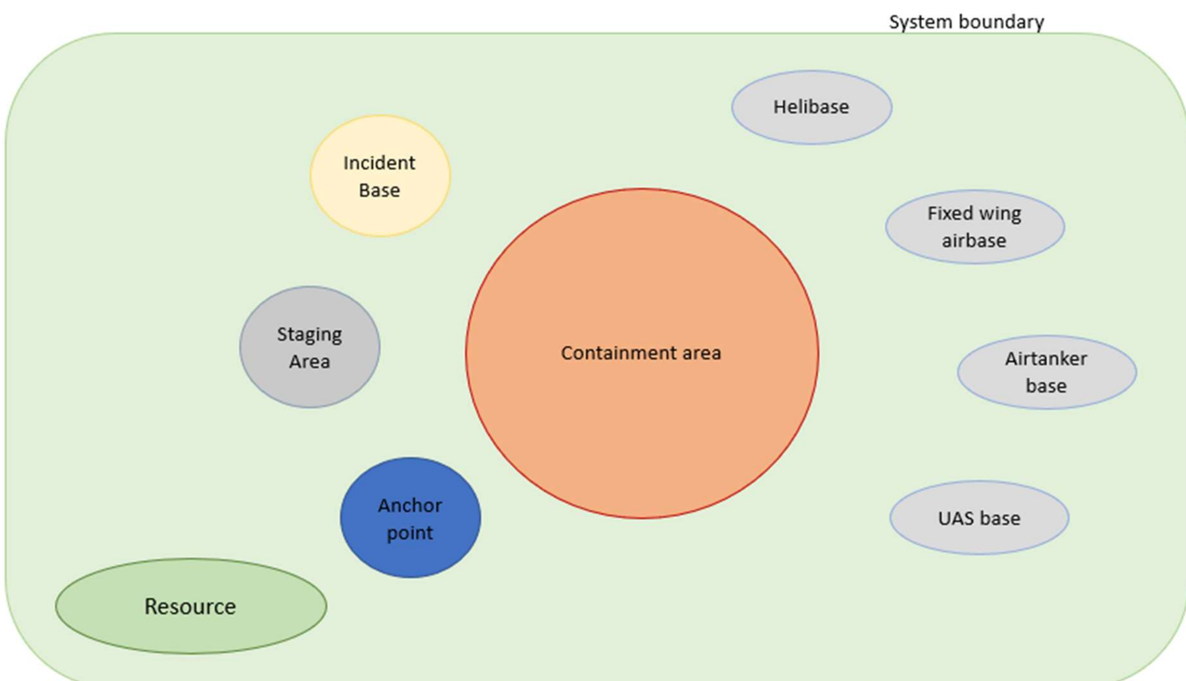

Figure 7 Conceptual map of facilities. Locations are not to scale.

Ground crews and engine crews use hand tools, water, and foam to create fire breaks, put out fires, and prevent structures and vegetation from burning. Hand tools include may include a shovel, McLeod (a two-sided blade), and/or Pulaski (an ax/adze combination). Ground crews also require PPE and water/food to maintain safety of personnel. Smokejumpers additionally require parachutes. Personnel working on the fire may also carry portable fire shelters. Tankers carry retardant, which is primarily made up of water and fertilizer.

Hardware and Software

Currently, aerial assets are equipped with transponders and radio communicators. SMARt-STEReO increases hardware and software needs for aerial assets. Specifically, SMARt-STEReO UAS will be equipped with Safeguard, ICAROUS, and Safe2Ditch. Safeguard stops UAS from flying into no-fly zones. It continuously detects UAS proximity to its perimeter and issues commands to prevent the aircraft from flying into a no-fly zone. It the UAS gets too close to a no-fly zone (the “contingency boundary”), Safeguard instructs it to perform a contingency maneuver, such as landing. If it is unsuccessful in executing this maneuver and instead reaches the termination boundary, Safeguard cuts power to the UAS. These determinations are made based on flight trajectory estimations. ICAROUS enables detect-and-avoid capabilities for stationary objects and maintains a safe distance from other aircraft. It executes avoidance maneuvers when safety limits are violated or are expected to be violated. This technology enables UAS to autonomously avoid collisions, independent of a pilot on the ground, allowing UAS to be operated outside of line of sight. Further, this technology facilitates the future integration of UAS into a shared airspace. ICAROUS core functions include (1) detect-and-avoid, (2) geofence monitoring, (3) obstacle avoidance, (4) stand-off distance, and (5) return to mission [33]. Safe2Ditch is a crash management system allows disabled UAS to reach safe emergency landing areas. The goal is to enable UAS to be used in areas with people. It uses knowledge of the area and an understanding of the disabled vehicle’s remaining capabilities to determine a safe landing area, then uses machine vision to confirm that the landing area is clear.

Expected Benefits of SMARt-STEReO

The concept of operations proposed in SMARt-STEReO is expected to provide several benefits to wildfire response operations. Specifically, it is expected that the introduction of UAS and UTM to wildfire response will improve performance, resiliency, and trust. Modeling and analysis efforts in SMARt-STEReO constructs and analyzes a system model of wildfire response. The model and analysis results are presented in a separate part of the SMARt-STEReO project. The rationale for the expected gains is explained in this section.

Performance

The operational concept proposed in SMARt-STEReO reallocates some tasks conventionally completed by helicopters to UAS. This reduces the strain on helicopters, allowing them to perform more bucket drops, potentially speeding up fire line construction. UAS may also extend the operational window of wildfire response into smokey conditions or into nighttime. Extending the time-period in which operations can be conducted could improve performance. They can also fly lower than helicopters, further enhancing their monitoring capabilities. Additionally, UTM allows UAS and piloted aircraft to operate within the same airspace at the same time, further increasing opportunities to deploy these resources. Finally, there is frequently some delay in the start of the fire to the time that aerial resources can be deployed. UAS are relatively inexpensive and could potentially be more widespread in their use than other aerial resources and can be more rapidly deployed. This time savings has the potential to enable firefighters to gain a significant head start compared to conventional operations, allowing them a higher possibility of containing a fire before it becomes out of control. This gain has the potential to reduce acres burned and subsequent damages, as well as requiring fewer expensive resources over the course of the incident.

Resiliency

It is critical that the emergency response system can withstand and/or recover from faults. In the event there is a fault in a UAS or another asset, contingency actions must be in place such that the system maintains essential functionality and/or resumes essential functionality shortly. Safeguard, Safe2Ditch, and ICAROUS all enable resiliency by preventing accidents and/or losses if there is, for example, a mechanical issue with the UAS. The addition of UAS also increases the likelihood that a mission will be completed even when one aerial asset is no longer able to complete the mission. For example, if a helicopter is unavailable for a tool delivery, a UAS can be used instead.

Trust

With the introduction of any new technology, it is important that the end users feel that the technology is trustworthy. In general, trust is subjective, and based on human perception and social behavior. However, there is an existing framework, the ability-benevolence-integrity (ABI) model, that is well accepted in the literature and provides a structured way of addressing trust. Within the ABI model: (1) *Ability* refers to capability and influence; (2) *Benevolence* refers to the interests/motivations of the agent; and (3) *Integrity* refers to the system's ability to fulfill its intended functionalities [34]. These three factors are understood to be independent of each other. Various methods, mostly qualitative but some quantitative, have been used to model these three factors. Surveys and interviews are one example [35]. Other authors have argued that ABI does not completely describe trust, and that other factors, such as transparency and humanness, are needed [36]. Transparency describes understandability of the system by operators, although more information is not always better as too much information may overwhelm operators [36]. Transparency covers explainability, a major concern in AI, and may have some overlap with predictability (integrity). Humanness refers to a machine's ability to interact with people in a "polite" way, such that it is perceived positively and leads to a pleasant interaction [36]. In this document, we will focus on the original ABI model, although it is recognized that there may be other factors important to trust that are not covered in ABI. SMARt-STEReO focuses on trust in relation to the integration of UAS and UTM into the wildfire response system. Table 2 demonstrates which aspects of the concept of operations proposed in SMARt-STEReO address which aspects of trust in the ABI model.

Table 2 Trust in SMARt-STEReO according to the ABI model.

ABI Model	**Description**	**SMARt-STEReO Contribution**
Ability	Ability refers to capability and to the influence. *Perceived* ability, with respect to system operators, is also an important component to trust.	SMARt-STEReO models the influence of NASA tech on system-level performance, i.e. comparisons of the system's performance with and without UAS/UTM. SMARt-STEReO does not cover perceived ability.
Benevolence	UAS/UTM must be perceived as having good intentions towards human operators. Technology that prioritizes	Transfer of risk from human operators to autonomous vehicles may be considered benevolence, which is

	human safety over UAS preservation may contribute to this goal.	included but not analyzed directly in SMARt-STEReO.
Integrity	Integrity stems from UAS/UTM adhering to an accepted set of principles consistently (sometimes referred to as predictability and dependability). Reliability and security contribute to integrity. Resiliency contributes to integrity by ensuring intended functionalities are preserved.	Reliability and security are not the focus of SMARt-STEReO. Resiliency, however, is explicitly considered as a major contribution of SMARt-STEReO. Predictability may also become important for certain autonomous technologies, especially any machine learning algorithm that learns from experience and is not *a priori* predictable. Research in explainability of AI may address these concerns but is outside the scope of SMARt-STEReO.

Future Work

This report defines a preliminary concept of operations for the SMARt-STEReO system. However, significant work remains in developing the SMARt-STEReO system. For instance, specifications for the UAS themselves have not been defined. Roles such as surveillance and delivery will likely require specific performance standards and capabilities that may not be met by all UAS. Additionally, cost analysis has not been performed to ascertain the feasibility of procurement for fire agencies. While UAS are known to be relatively inexpensive, especially compared to piloted aircraft, detailed cost analysis must be performed to weigh costs and benefits to the purchasing organization. Finally, there are many future avenues for UAS applications that have not been explored in this report. Applications were chosen in this report based on immediate feasibility, but future testing and development could enable the use of UAS in other areas. For instance, there is strong potential for UAS usage for ignition missions, monitoring for looters, and data relay, among others. Future work is required to assess the feasibility and potential gains of such applications.

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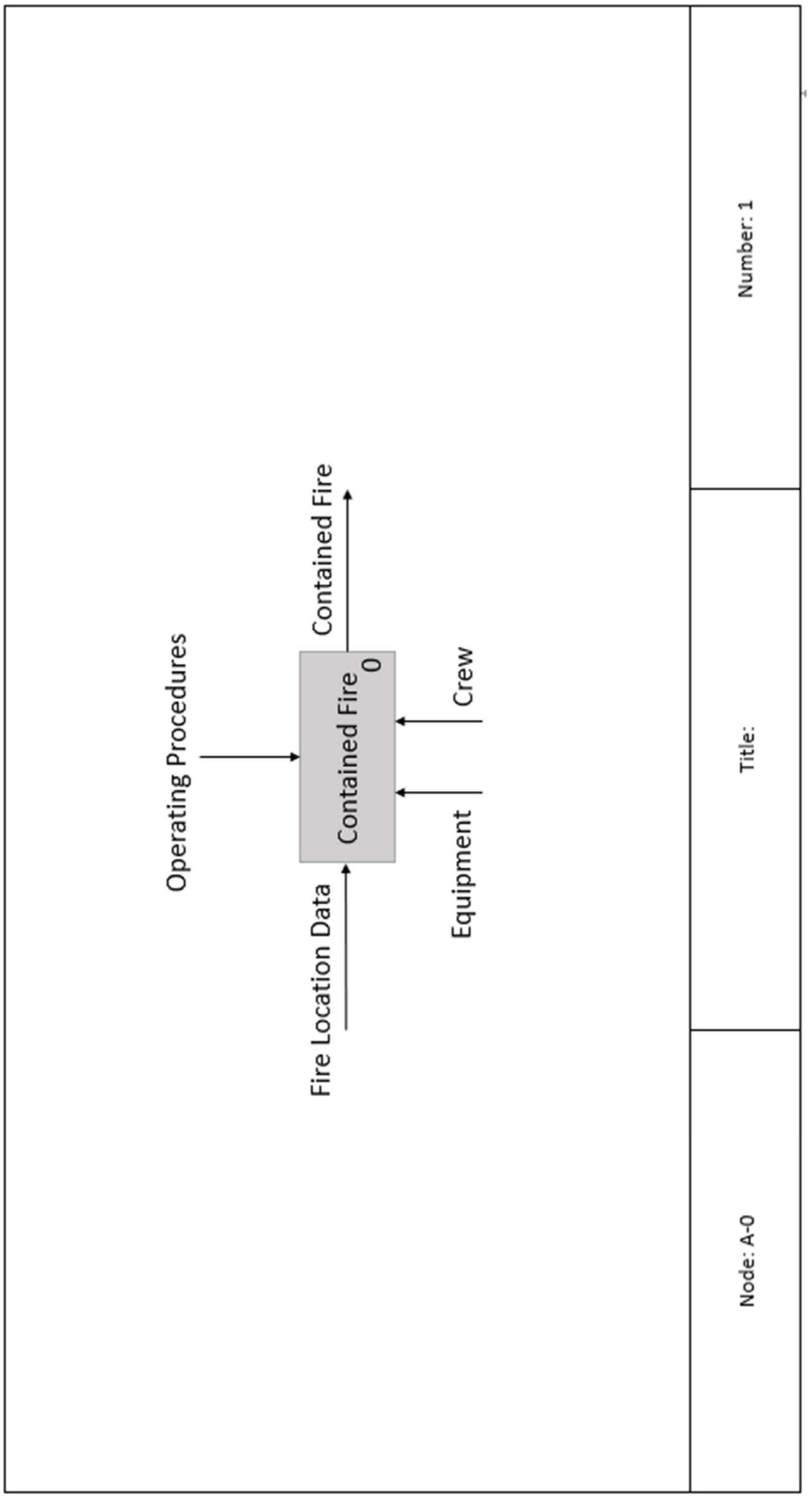
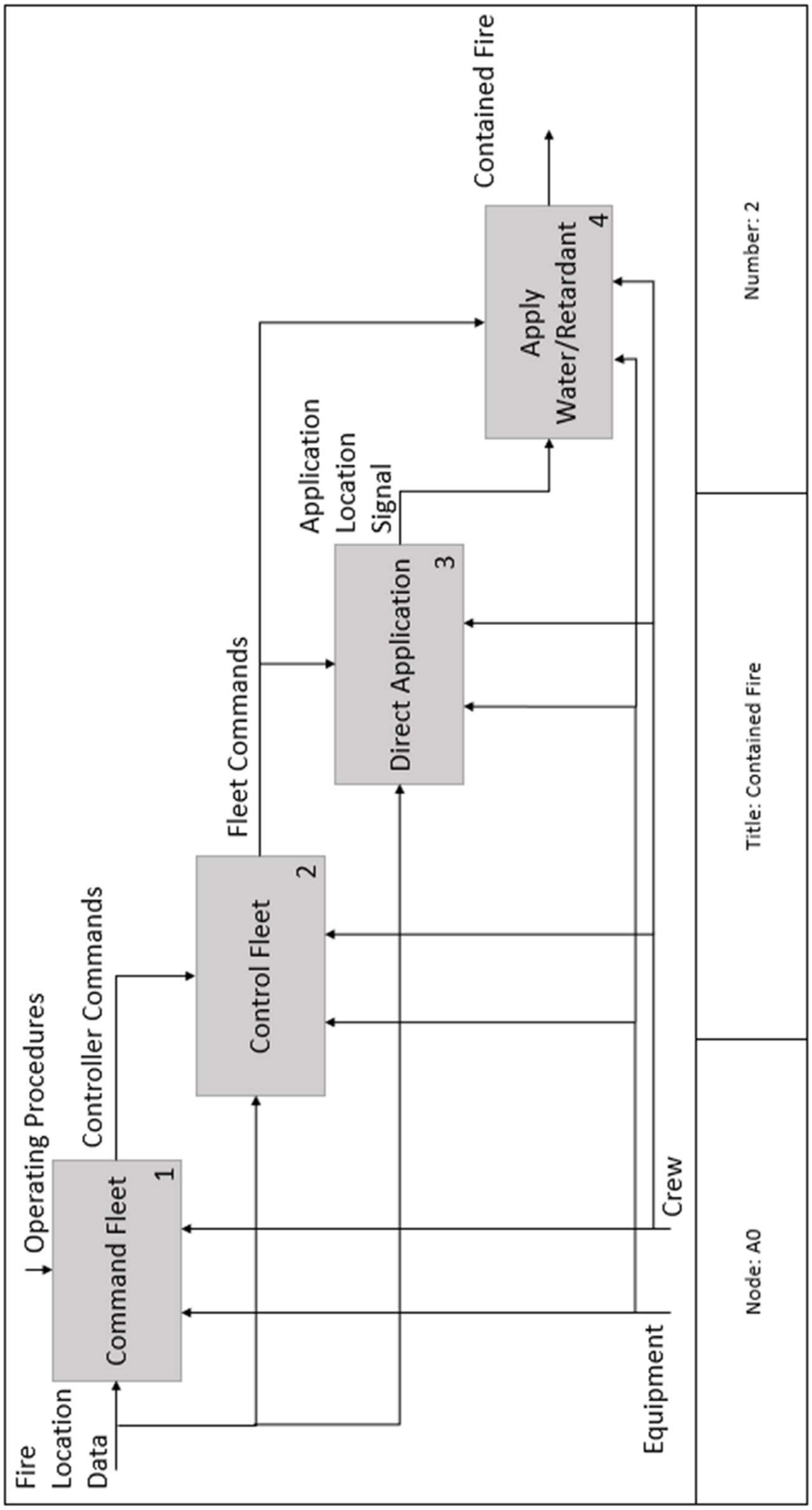
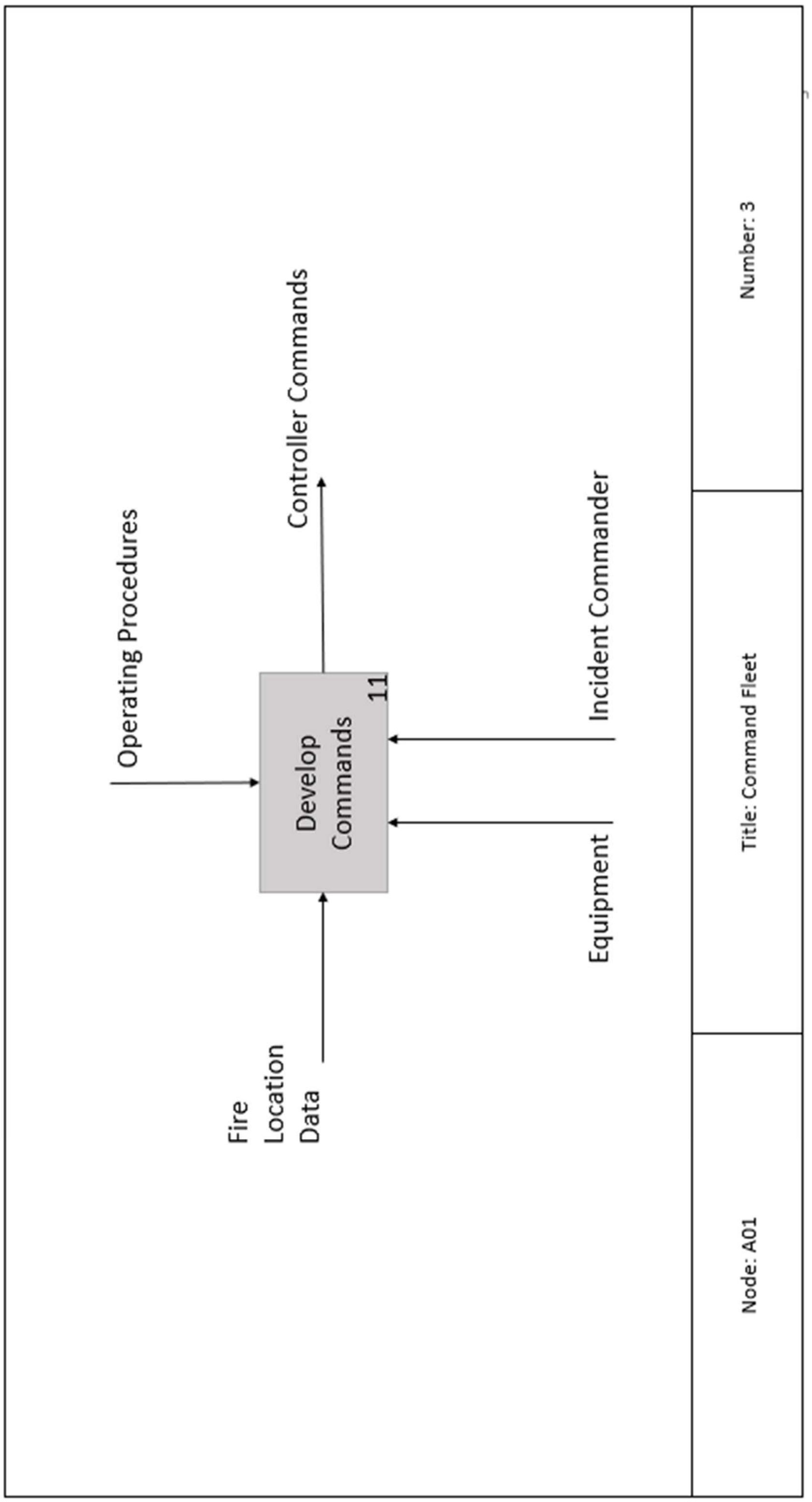
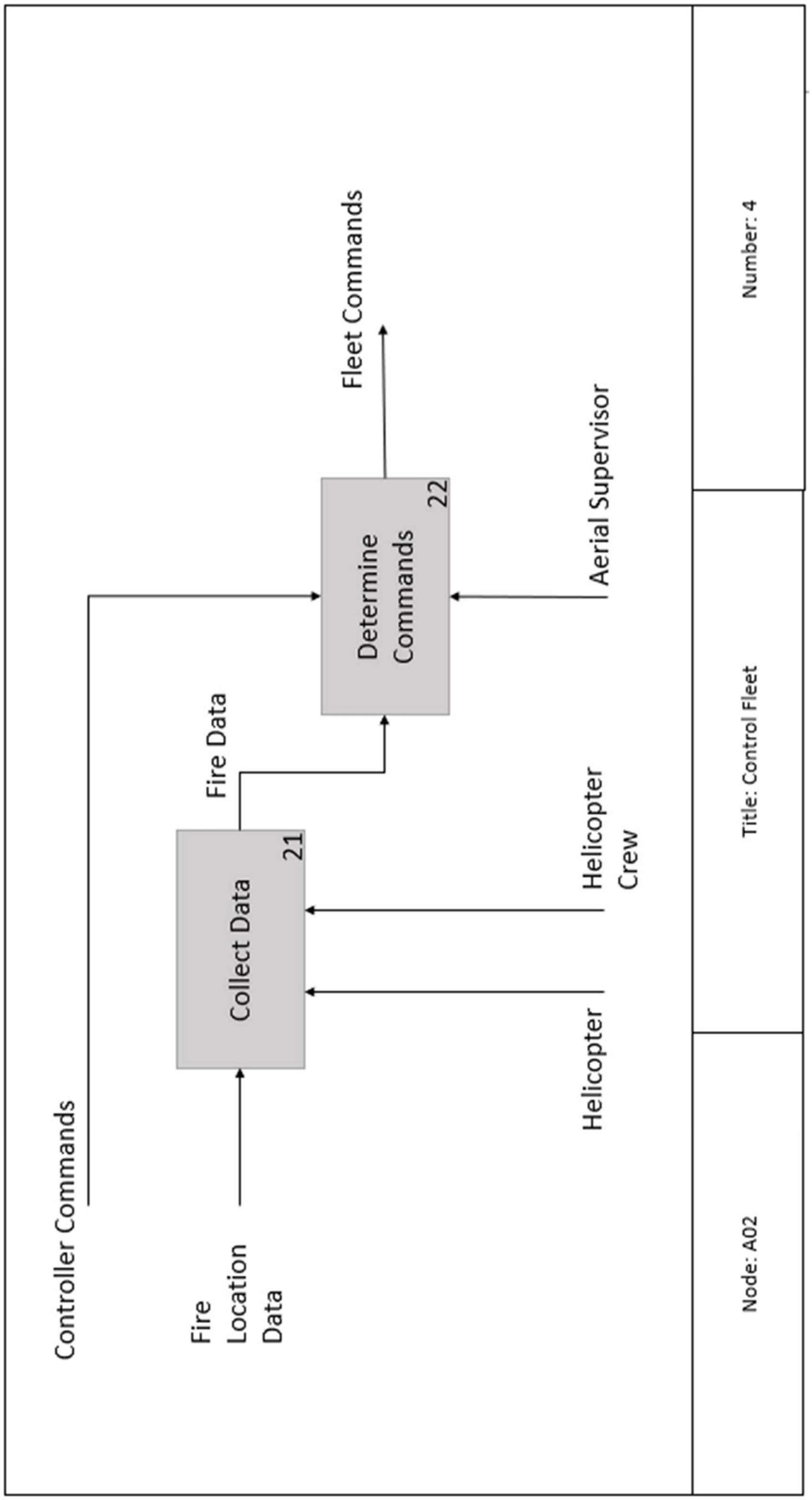
Appendix A: IDEF0 Diagrams

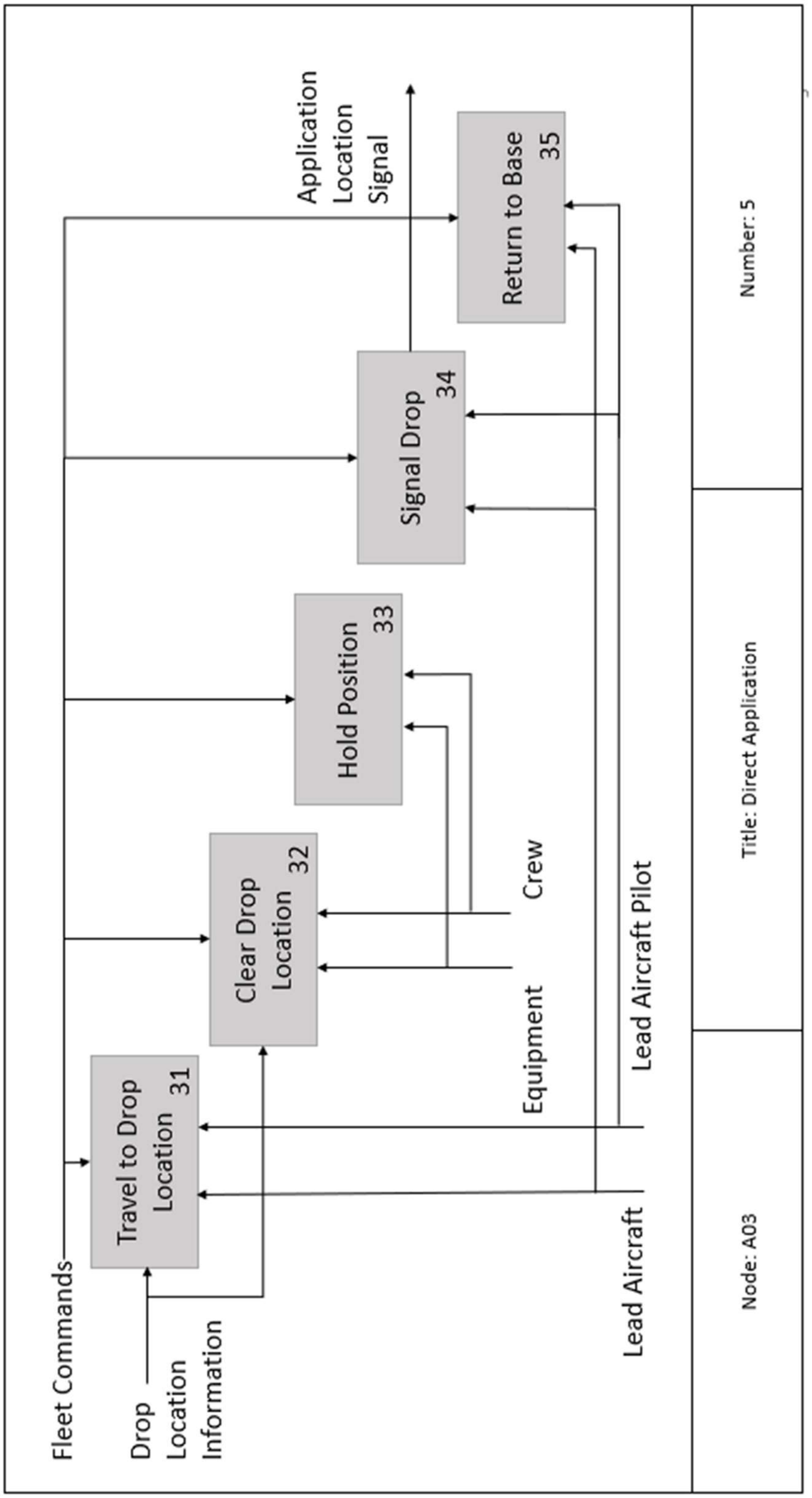
A.1 Daytime Operations

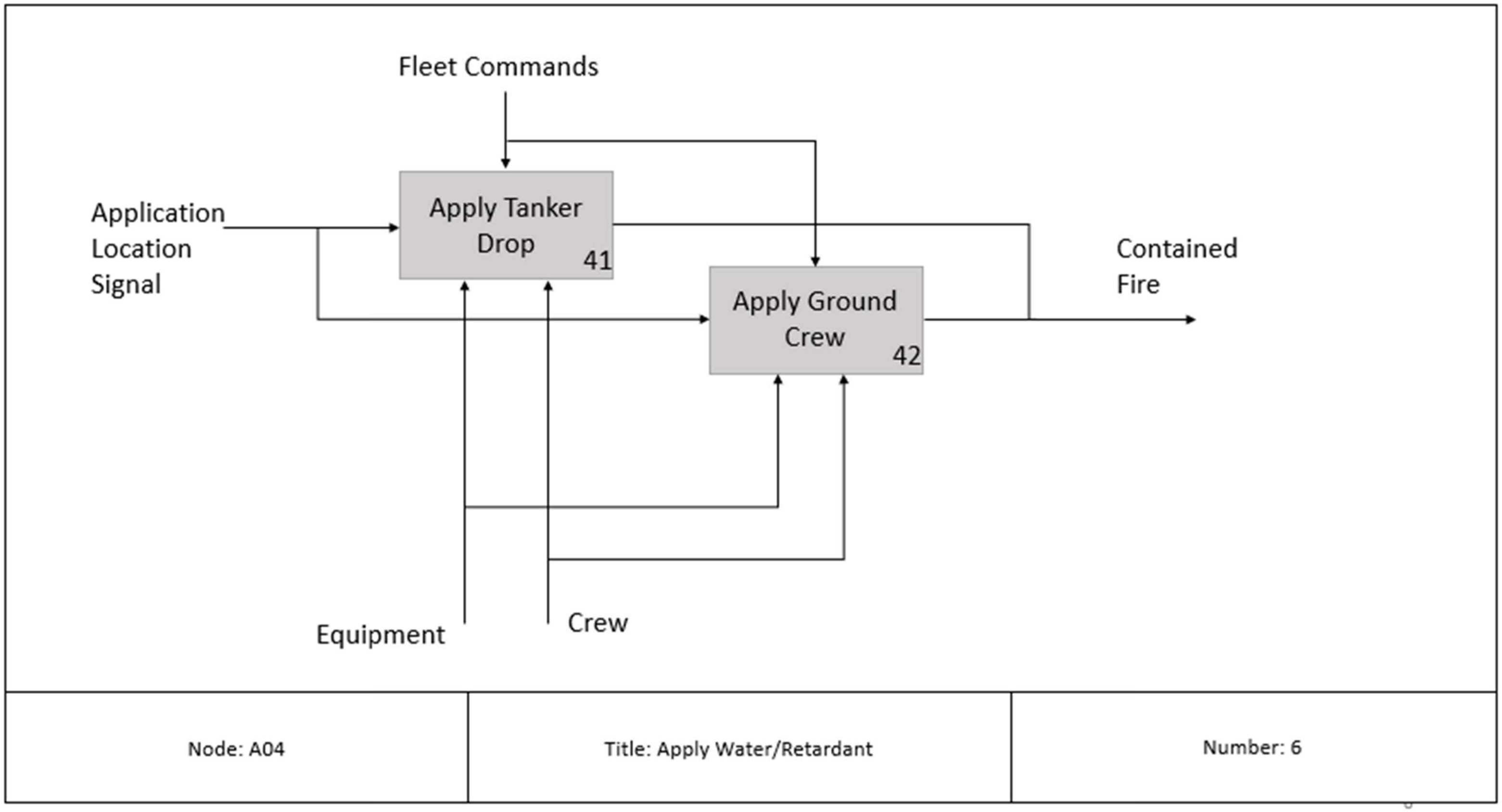


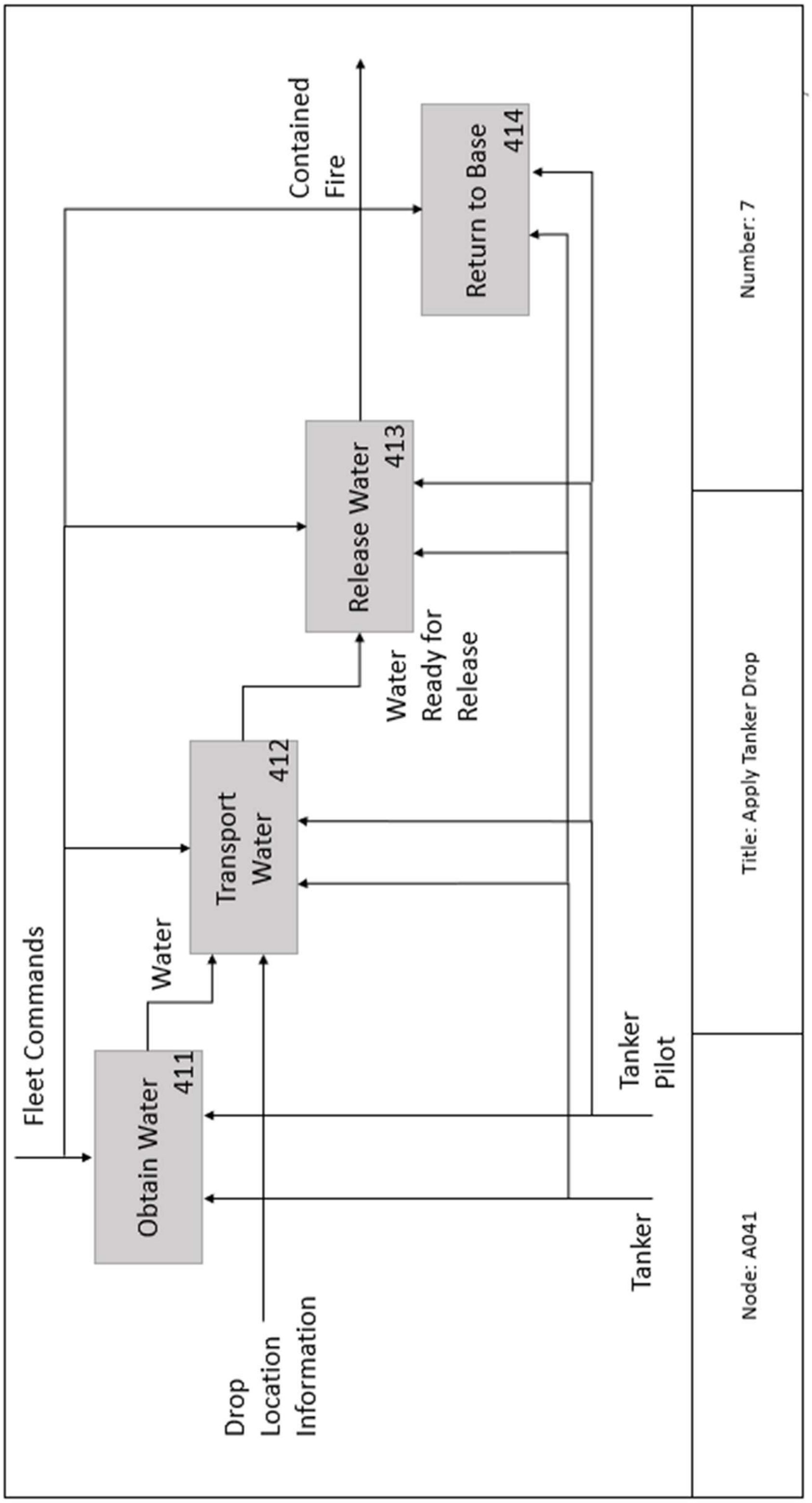

Fire
Location
Data
Operating Procedures
Command Fleet
1
Controller Commands
Control Fleet
2
Fleet Commands
Direct Application
3
Application
Location
Signal
Apply
Water/Retardant
4
Contained Fire
Equipment
Crew
Node: A0
Title: Contained Fire
Number: 2

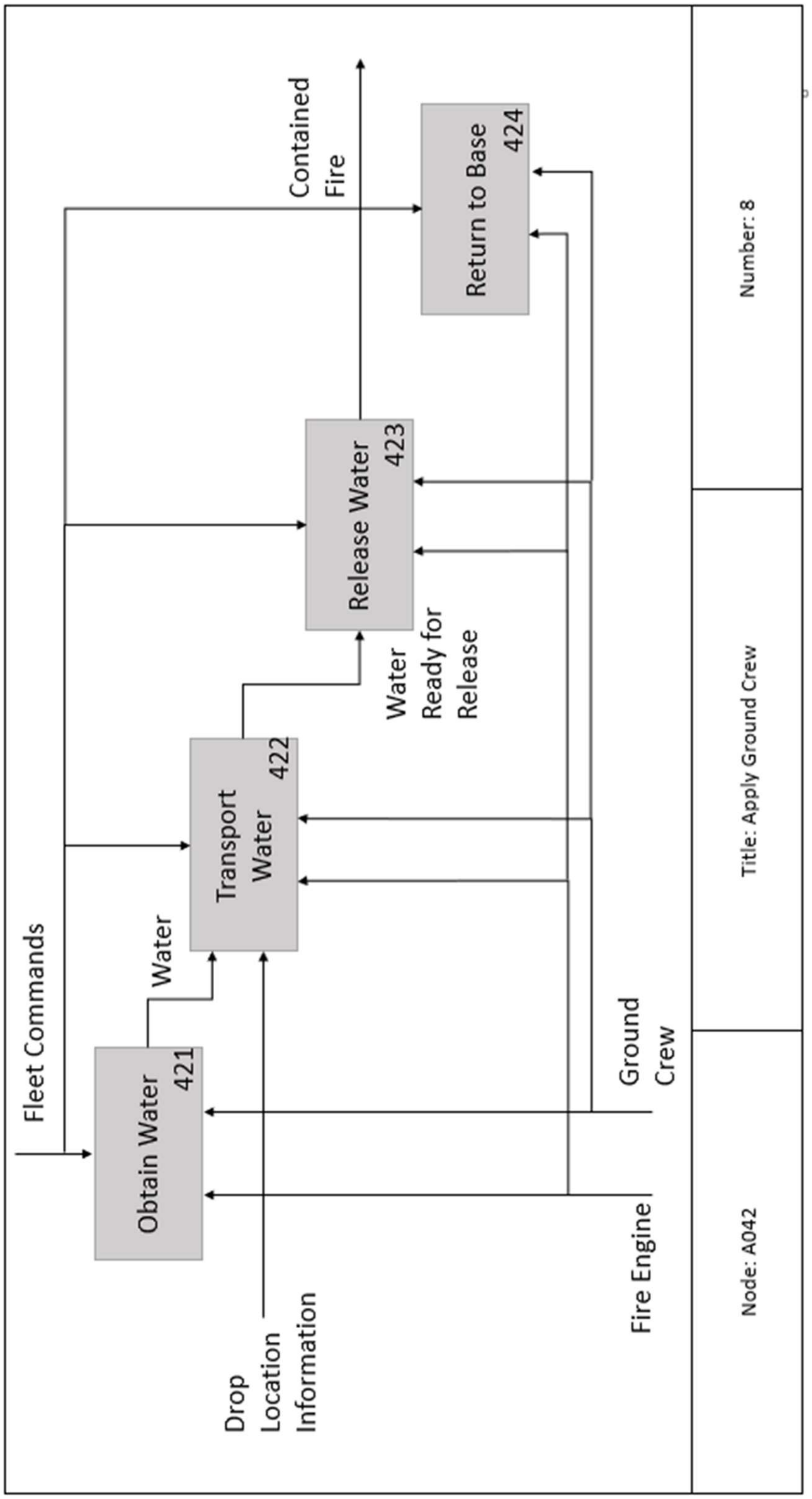

Operating Procedures
Controller Commands
Develop Commands
11
Fire Location Data
Equipment
Incident Commander
Node: A01
Title: Command Fleet
Number: 3


Controller Commands
Fire Location Data
Collect Data
21
Fire Data
Determine Commands
22
Fleet Commands
Helicopter
Helicopter Crew
Aerial Supervisor
Node: A02
Title: Control Fleet
Number: 4


Fleet Commands
Drop Location Information
Travel to Drop Location 31
Clear Drop Location 32
Hold Position 33
Signal Drop 34
Return to Base 35
Application Location Signal
Equipment
Crew
Lead Aircraft
Lead Aircraft Pilot
Node: A03
Title: Direct Application
Number: 5

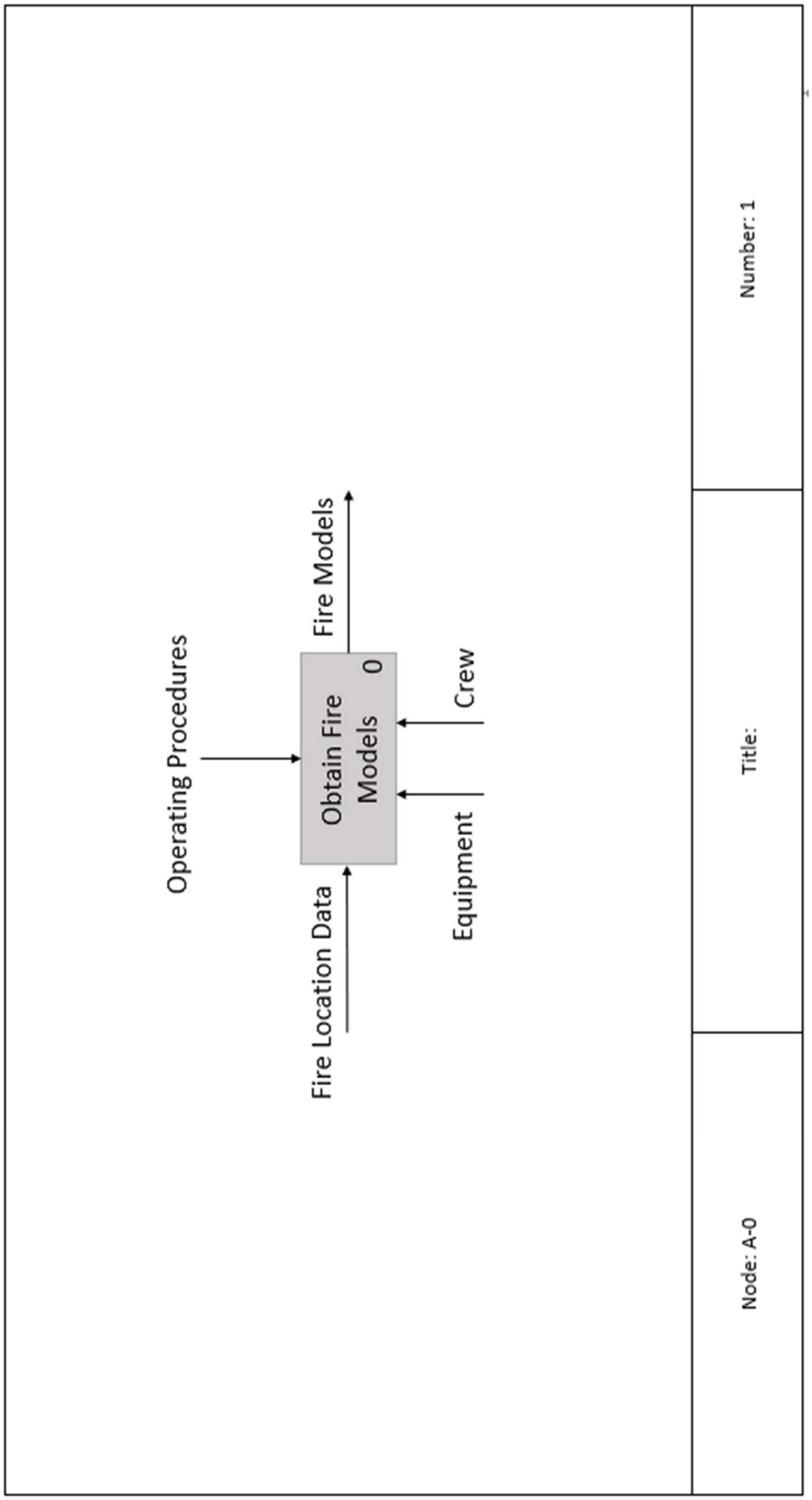

Fleet Commands
Application
Location
Signal
Apply Tanker
Drop
41
Apply Ground
Crew
42
Contained
Fire
Equipment
Crew
Node: A04
Title: Apply Water/Retardant
Number: 6

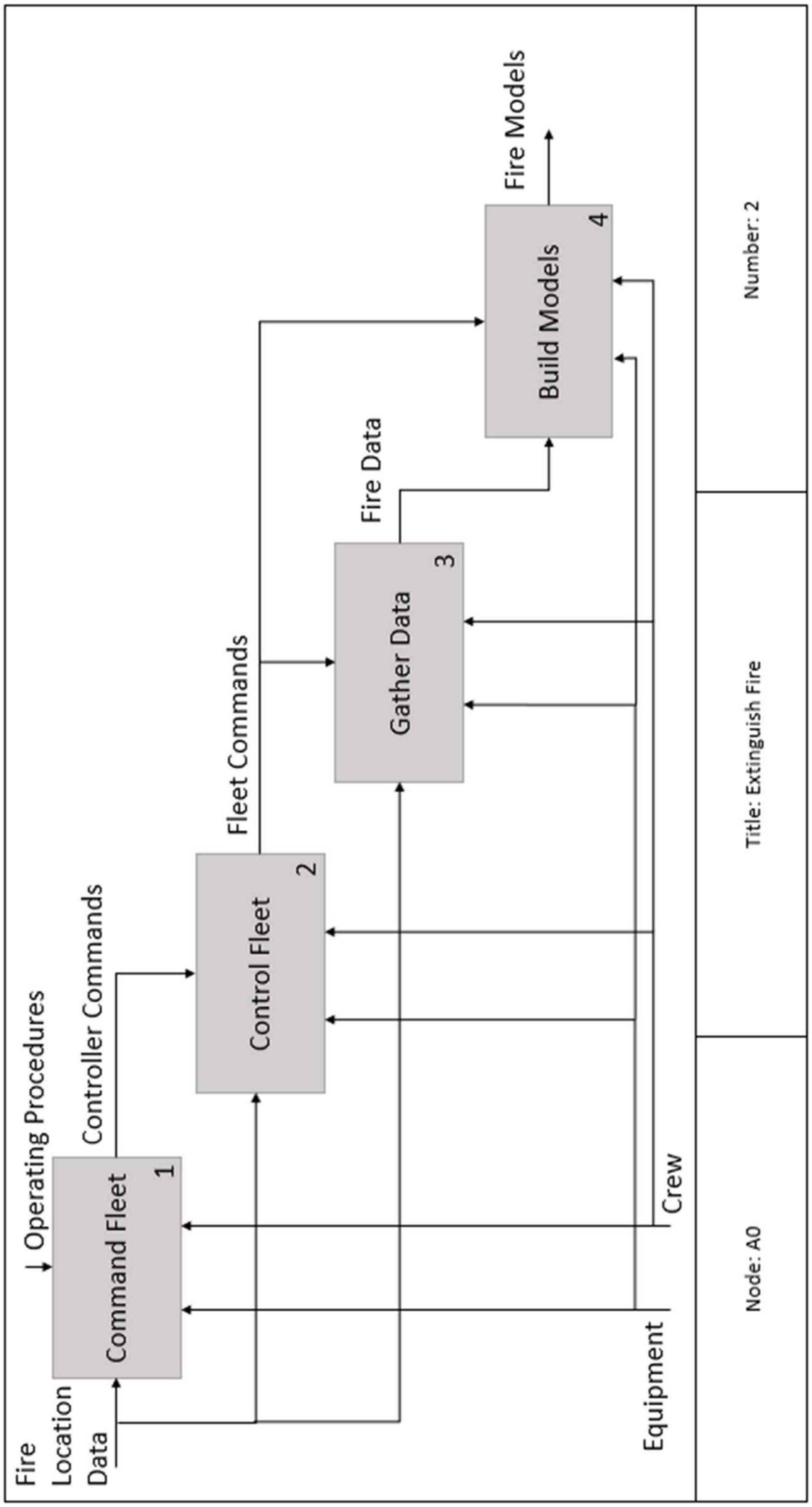

Fleet Commands
Obtain Water
411
Water
Transport
Water
412
Release Water
413
Water
Ready for
Release
Return to Base
414
Contained
Fire
Drop
Location
Information
Tanker
Tanker
Pilot
Node: A041
Title: Apply Tanker Drop
Number: 7



Fleet Commands
Obtain Water
421
Water
Transport Water
422
Water Ready for Release
Release Water
423
Contained Fire
Return to Base
424
Drop Location Information
Fire Engine
Ground Crew
Node: A042
Title: Apply Ground Crew
Number: 8

A.2 Nighttime Operations





Fire Location Data
Operating Procedures
Command Fleet
1
Controller Commands
Control Fleet
2
Fleet Commands
Gather Data
3
Fire Data
Build Models
4
Fire Models
Equipment
Crew
Node: A0
Title: Extinguish Fire
Number: 2