NASA/TM—20205007481

SMARt-STEReO: Preliminary Model Description

Daniel E Hulse
Ames Research Center, Moffett Field, California

Sequoia R Andrade
Universities Space Research Association
Ames Research Center, Moffett Field, California

Eleni Spirakis
Universities Space Research Association
Ames Research Center, Moffett Field, California

Hannah S Walsh
Ames Research Center, Moffett Field, California

Misty D Davies
Ames Research Center, Moffett Field, California

September 2020

NASA STI Program ... in Profile

Since its founding, NASA has been dedicated to the advancement of aeronautics and space science. The NASA scientific and technical information (STI) program plays a key part in helping NASA maintain this important role.

The NASA STI program operates under the auspices of the Agency Chief Information Officer. It collects, organizes, provides for archiving, and disseminates NASA's STI. The NASA STI program provides access to the NTRS Registered and its public interface, the NASA Technical Reports Server, thus providing one of the largest collections of aeronautical and space science STI in the world. Results are published in both non-NASA channels and by NASA in the NASA STI Report Series, which includes the following report types:

- TECHNICAL PUBLICATION. Reports of completed research or a major significant phase of research that present the results of NASA Programs and include extensive data or theoretical analysis. Includes compilations of significant scientific and technical data and information deemed to be of continuing reference value. NASA counterpart of peer-reviewed formal professional papers but has less stringent limitations on manuscript length and extent of graphic presentations.

- TECHNICAL MEMORANDUM. Scientific and technical findings that are preliminary or of specialized interest, e.g., quick release reports, working papers, and bibliographies that contain minimal annotation. Does not contain extensive analysis.

- CONTRACTOR REPORT. Scientific and technical findings by NASA-sponsored contractors and grantees.

- CONFERENCE PUBLICATION. Collected papers from scientific and technical conferences, symposia, seminars, or other meetings sponsored or co-sponsored by NASA.

- SPECIAL PUBLICATION. Scientific, technical, or historical information from NASA programs, projects, and missions, often concerned with subjects having substantial public interest.

- TECHNICAL TRANSLATION. English-language translations of foreign scientific and technical material pertinent to NASA's mission.

Specialized services also include organizing and publishing research results, distributing specialized research announcements and feeds, providing information desk and personal search support, and enabling data exchange services.

For more information about the NASA STI program, see the following:

- Access the NASA STI program home page at http://www.sti.nasa.gov

- E-mail your question to help@sti.nasa.gov

- Phone the NASA STI Information Desk at 757-864-9658

- Write to:
  NASA STI Information Desk
  Mail Stop 148
  NASA Langley Research Center
  Hampton, VA 23681-2199

NASA/TM—20205007481

SMARt-STEReO: Preliminary Model Description

Daniel E Hulse
Ames Research Center, Moffett Field, California

Sequoia R Andrade
Universities Space Research Association
Ames Research Center, Moffett Field, California

Eleni Spirakis
Universities Space Research Association
Ames Research Center, Moffett Field, California

Hannah S Walsh
Ames Research Center, Moffett Field, California

Misty D Davies
Ames Research Center, Moffett Field, California

National Aeronautics and
Space Administration

Ames Research Center
Moffett Field, CA 94035-1000

September 2020

Acknowledgments

Thanks to Joey Mercer and Guillaume Brat for feedback on the models and project guidance.

This report is available in electronic form at

http://

Introduction

Wildfires have increasingly become major threat to US towns and cities, with California alone having its most destructive wildfire seasons to date in 2017 and 2018 (California Department of Forestry and Fire Protection, 2019) and 2020 already becoming one of the worst fire years on record, causing the large-scale evacuations, the destruction of towns and property, and a significant release of hazardous smoke over the entire west coast (Voiland, 2020). Thus, the U.S. Forest Service recently spent over 50% of its budget on wildfire management – funds which could otherwise be directed to science that could support fire prevention (Topik, 2015).

Aerial support plays a major role in fighting wildfires. Airtankers, helicopters, and other aerial assets support the construction of fire-lines, gather data, and transport crews and equipment. However, presently, aerial firefighting operations rely on relatively unsophisticated technologies for communications, such as over-the-air radios, which limit the ability of pilots and management to relay fire data and coordinate operations. Aerial operations in and around fires are additionally high-risk activities due to the variable, dangerous conditions and complex, technically difficult maneuvers which must be performed to, for example, conduct a retardant drop. Thus, between 2000 and 2013, of the 298 wildland firefighter fatalities, 26% were related to aerial operations (Butler, 2015). As a result, there is significant potential to both improve the performance and resiliency of wildfire response while reducing risk to human operators.

NASA's STEReO (Scalable Traffic Management for Emergency Response Operations) project leverages NASA technology to improve the operational effectiveness and resiliency of aerial firefighting operations. There are two main avenues by which STEReO endeavors to improve aerial firefighting operations. First, the addition of Unpiloted Aircraft Systems (UAS) is proposed as a cost-effective way in which to improve performance and resiliency. UAS are relatively low-cost, and are sufficiently versatile to carry out a variety of missions, with potential performance and resiliency benefits. For instance, UAS have the potential to enable operations at night or in smokey environments, which is currently difficult or impossible with piloted aircraft. Additionally, the use of UAS for dangerous missions may enable the transfer of some risk from human operators to machines. This improves both safety and performance, as UAS can be given more dangerous missions than human operators. Second, UAS Traffic Management (UTM) is proposed as a means of coordinating UAS within an integrated airspace and to improve the relay of data and communications. UTM does not require continuous monitoring of every UAS and provides relay of important data to human operators.

The SMARt-STEReO (System Modeling and Analysis of Resiliency in STEReO) project aims to model the effect of increased technological capabilities to wildfire response. In order to develop this sort of simulation, one first needs a simulation of how aerial firefighting works, including the propagation of a fire, the detection and surveillance of the fire by aircraft and other vehicles, the planning of fire-line construction and retardant/water drops, and the execution of the response by ground crews, air tankers, and helicopters. This paper documents the construction of this model and demonstrates its promise for use in evaluating aerial firefighting operational concepts.

The next sections provide a high-level overview of the model structure an parameters, a description of each model component along with how the component was modelled—including the faults, behaviors, and parameters—and then summarizes the current state of the model and potential for future work and development. Note that several figures in this document are single frames of animations, the full versions of which are provided in supplementary material.

Model Overview

The purpose of the SMARt-STEReO model is to model the performance and resilience of wildfire response at a high level to understand the effect of different operational concepts and strategies. To create this type of model, it uses the open-source fmdtools Python toolkit (Hulse, Walsh, & Zhang, DesignEngrLab/fmdtools: v0.5.3-revision2 (Version v0.5.3)., 2020) for dynamic behavioral modelling of component interactions and fault injection modelling and visualization.

Modelling in fmdtools uses an object-oriented paradigm to represent the system behaviors and structure with two main modelling aspects: functions and flows (Hulse, et al., 2020). *Functions* comprise the behaviors, states, and components which perform specific tasks in the model (as well as their fault modes and behaviors) while *flows* are the connecting variables between functions. For example, in a simple resistive circuit, the battery and resistor would each be functions while the electrical current and voltage would be flow. Functions and flows are then connected in a model graph to enable behaviors to propagate between functions over the time-steps specified by the user in the model in nominal and faulty scenarios.

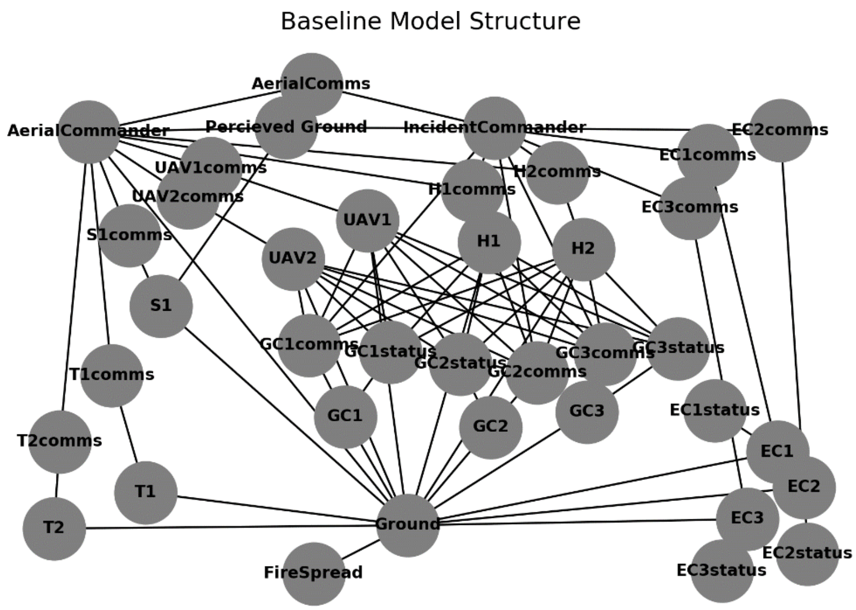

Figure 1. Structure of model with baseline parameters.

The SMARt-STEReO model consists of a model of fire propagation and a number of interacting models for the different response assets which work to fight the fire. This overall structure is shown in Figure 1, which shows flow connections (i.e. data structures) between each function class (i.e. different behaviors which perform a task).

As shown, the model is made up of the:

- Fire model, which encompasses the Ground flow— which includes the fire-grid, a grid of points with the state of the fire fuel, flammability and propagation at a given time and the locations of assets on the ground (e.g. airports, ground bases, etc.)—and the FireSpread function, which propagates the fire to new locations at each timestep.
- Ground crews (GC1, GC2, GC3), which perform land cuts to create firebreak on the fire-grid. The state of a particular ground crew is held in the GCstatus, which enables UAVs and Helicopters to change the state of the ground crews. Ground crews communicate with the incident commander and their assigned helicopters using GCcomms to share pickup/drop-off locations for constructing the fire-line.
- Engine Crews (EC1, EC2, EC3), which also perform land cuts to create firebreak. The difference between ground crews and engine crews is that ground crews are carried by helicopter while engine crews move on their own but can only access certain sides of the map—the right and lower sides in the baseline model. ECstatus is a flow which contains

the state of the crew (following the convention used for ground crews) while ECcomms is a flow used to communicate cut locations with the Incident Commander.

- Helicopters (H1, H2), which deliver ground crews to specific locations on the ground, perform water drops on/near the fire, and deliver supplies to ground crews. For each helicopter there is an Hcomms flow which is used by the aerial commander to communicate drop locations when the helicopter is in drop mode.
- Supply UAVs (UAV1, UAV2), which re-supply groundcrews with supplies when they run out. While UAVs have a flow which communicates with the aerial commander, it is currently unused.
- Tankers (T1, T2), which drop retardant near the fire to slow it down. T1comms is used to communicate drop locations and tanker readiness between the aerial commander and the tanker.
- The aerial commander/supervisor/lead plane (AerialCommander), which detects the current state of the ground in a particular part of the map and relays it back to the incident commander and assigns drop locations to the tankers and helicopters. Aerialcomms is a flow used to communicate the flight path of the aerial commander with the incident commander, as well as to receive the highest-threat parts of the fire to slow down with drops. Perceived Ground is a flow used to communicate the perceived state of the ground with the incident commander
- Surveillance planes/UAVs (e.g. UAV1), which also detect the current state of the map and relay it to the incident commander, updating a different part of the Perceived Ground flow. Scomms is used to communicate the desired flight path of the surveillance plane given the path of the lead plane.
- Incident commander (IncidentCommander), which uses the state of the ground to determine where to construct the fire-lines and send ground crews, and which edge of the fire the tankers should focus on.

Integration Demonstration

When put together, these component models make up an integrated model of fire progression and response. This response can be seen in Figure 2. As shown, ground crews (purple upside-down triangles) and engine crews (purple right-side up triangles) attempt to enclose the fire on all sides by creating fire break while the tankers (each noted with a blue X) helicopters (blue stars) slow down the fire by increasing the spread time of particular pixels between the fire and gaps in the fire-line. However, while the main fire slowing and containment

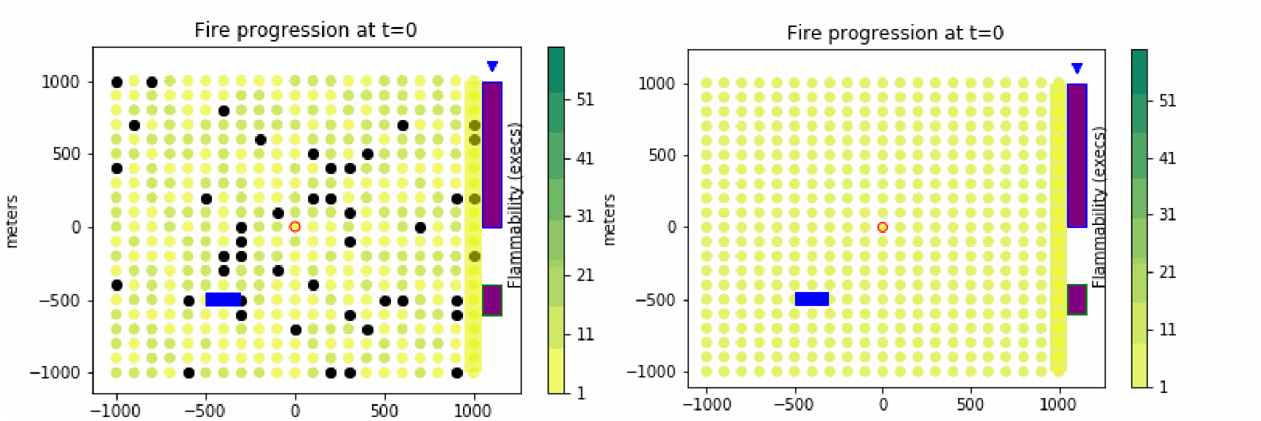

Figure 2: Fire response on randomly-generated (left, animation provided in std_sim_rand.gif) and uniform (right, animation provided in std_sim_unif.gif) fire maps. Flammability is shown as the primary grid attribute to illustrate the effect of tanker drops in the model.

occurs because of the tankers and ground/engine crews, much more is happening in the background to enable that to happen, specifically the surveillance of the fire by the lead plane and surveillance UAV (upside-down blue triangles), the relaying of ground crew and supplies to given locations by the helicopters and supply UAVs, the evaluation of threats to the fire-line by the incident commander, and the planning of drops by the lead plane.

The response ends when the fire is either completely enclosed or the fire stops spreading. In this work we use the uniform map (at right) to verify the system behavior and random map generation to ensure that the response generalizes to a variety of possible situations. This model has several parameters which can be adjusted and changed to yield different results based on the number of assets (and their effectiveness). The parameters, their ranges, and the values used in the baseline model are given in Table 1. The following sections, in addition to verifying component behaviors, will show how differing values of these response parameters changes the effectiveness of the response.

Table 1: Baseline Response Parameters

Parameter	Ranges	Baseline Value
Number of Tankers	0 or more	2
Tanker Drop Size	1 or more	3 pixels
Tanker Drops Per Refuel	1 or more	3
Tanker drop effectiveness	0 or more	22 execs
Number of Ground Crews	0 or more	3
Maximum Number of Supplies	1 or more	10 timesteps
Number of Engine Crews	0 or more	3
Rest Per Timestep	1 or more	5
Number of Helicopters	0 or more	2
Number of Supply UAVs	0 or more	1
Surveillance Lag	0 or more	0 timesteps
State Information Used	'all' or 'dist'	all
Danger Fire-line priority	0-1	0

In addition to response parameters, there are parameters which can be changed to change the firefighting situation and conditions. In general, these are not changed at this state of the model but will be explored more thoroughly in future work. These are shown in Table 2.

Table 2: Additional Model Parameters

Windspeed	0 or more	0
Wind heading	0-2pi	0
Sides accessible by engine crews	[] to [r, l, u, d]	[r, d]
Sides which must be protected to prevent imminent danger	[] to [r, l, u, d]	Right side
Grid Size	(any)	2000x2000
Grid Spacing	1+	100 m
Grid type	Uniform, random, uphill, downhill	random
Fire-line	0-grid edge	900
Initial Fire Location	Any valid grid point	(0,0)

Fire Propagation Model

Description

Fire propagation is defined by the given map and wind parameters, including the area (size of the map grid, number of points to use) and grid attributes comprising:

- fuel (number of executions a fire is present on a pixel),
- flammability (number of executions before an adjacent fire spreads to a pixel),
- altitude (which modifies fire propagation speed),
- fuel type (which modifies flame length),
- flame length (which modifies fire heat production), and
- obstacle (which determines where the fire cannot spread e.g. fire break)

Each of these attributes are assigned at the beginning of the simulation using pre-determined patterns (uniform, uphill, downhill, etc) or a random map generation (described in the next section). At a single execution of the fire model, the flammability of all grid points next to the fire is reduced by a certain amount until the attribute drops to zero, at which the point(s) are added to the fire. Additionally, fuel is reduced from pixels where the fire is burning and the fire is put out at pixels where the fuel has reached the threshold of zero. To enable accurate speeds, this model is executed four times per model time-step. This model of the fire is verified below at given parameters with existing fires.

Random Map Generation. To verify the model under a variety of conditions, a random map is generated based on uniform distributions for different grid attributes. In the uniform map, these attributes take the mean value with a constant distribution.

Table 3: Random map generation parameters.

Attribute	Distribution	Parameters
Fuel	Uniform	(0, 60)
Fire	N/A	Only at (0,0)
Flammability	Uniform	(1,16)
Flame Length	Constant	0
Altitude	Constant	0
Fuel Type	Uniform	(1,16)
Obstacle	Binomial	(0.9: 0, 0.1: 1)

Behavior checks

Uniform Propagation – No Wind. A preliminary test was run to determine the correct value of the initial parameter 'time' such that a uniform fire propagation with no influences from fuel type, terrain, or wind would have the expected rate of spread. When the grid is initialized with an initial value for flammability of 8 executions, the fire travels one gridpoint in every two timesteps because the fire model runs 4 times every timestep. Since a gridpoint is 100 m from a neighbor and the timestep is 8 mins, this produces an average rate of spread for a completely uniform case of 6.25 m/min. This case is shown in Figure 3, which is the flammability of the model starting with a fuel value of 30, a fuel type of 2, and an altitude of 0 at every point. This also shows that the fire propagates at the same speed in every direction—an expected result on a uniform map with no wind.

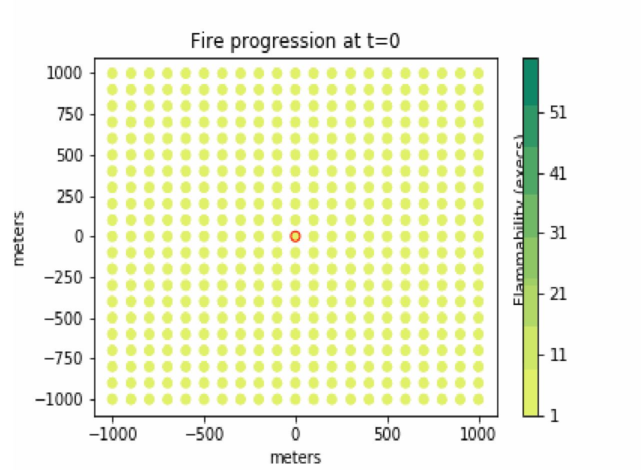

Figure 3: Fire propagation on a uniform map with no wind. Animation provided in level_fire_verification.gif.

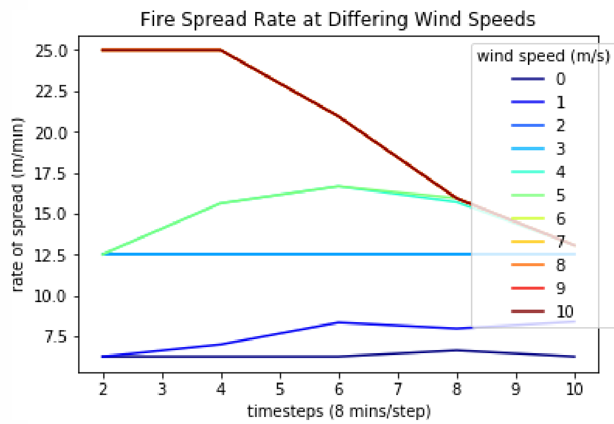

Figure 4: Fire spread rates on a uniform map.

Uniform Propagation with Wind. In the next section, the model is checked against existing wind models. In the SMARt-STEReO model, the effect of wind was achieved by assuming a linear correlation between wind speed and rate of spread in the direction of the wind. Initially, these tests were performed on a uniform grid, where all gridpoints have the same fuel type and terrain, however, because the model propagates fires to new gridpoints every 2 mins (1/4th of the model timestep), the fire can only travel to an adjacent points at rates which are multiples of 2 mins. In a uniform fire-grid, this creates only a few possible rates of spread. The modelled fire spread rates on a uniform grid for varying windspeeds are shown in Figure 4.
Propagation Over Randomized Maps with Wind. While using a uniform map results in some rounding error due to the timestep, maps are often not uniform and thus the average spread rate varies based both on the windspeed and the flammability distribution. Thus, it is important to show that the map generation and wind model work together in a way that matches existing literature on fire propagation. To test this, the model was simulated ten times at each windspeed and averaged over three timesteps at the beginning of the simulation (before the fire has

reached the grid edges). The results of this test are shown in Figure 5, which shows how closely the model compares with existing models. The Valabre model (in orange) is a commonly-used rule-of-thumb which shows the rate of spread of the fire is 3% of the wind speed

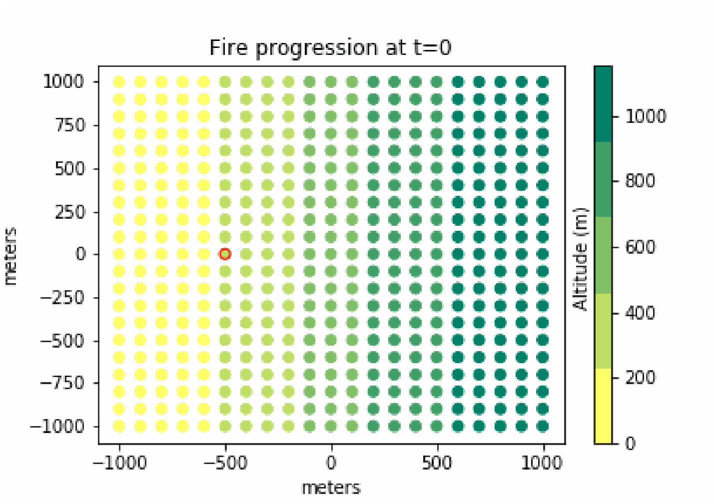

Figure 6: Uphill fire propagation. Animation provided in uphill_fire_verification.gif.

(Sauvagnargues-Lesage, 2001). The Rothermel model is also a common model used in fire prediction software (Rothermel, 1972), while (Fernandes, 2001) predicts fire propagation in shrub fuels. As shown, the plot of fire propagation mirrors the linear trend of these models fairly well, with a slope similar to the Valabre model. However, unlike these models, the fire propagation model has a non-zero y-intercept, which means the fire propagates at a high rate of spread (~9m/min) even at low speeds. While this creates a challenging situation for firefighters to fight, it suggests that the propagation model requires more calibration to be considered valid at low speeds. Nevertheless, this test shows that with the randomly-generated map patterns, wind-speed and fire propagation speed follow the expected linear trend. Future work should further calibrate this model to be accurate at low and high speeds and in different conditions.

Uniform Propagation with Slope. Fire travels faster uphill than downhill. Typically, a fire travelling up a 30 degree slope will travel twice as quickly as on level ground. To represent slope in a model, a terrain factor function was created which adjusts the flammability (time-to-propagation) value by the appropriate amount depending on the slope between a point on fire and its neighboring points. This model uses a linear model of fire rate and altitude, making a 30 degree uphill slope double the rate of spread and a 30 degree downhill slope cut the rate of spread by half. A demonstration of this is shown in Figure 6, where the `uphill` option was used in map generation, which creates a uniform 30 degree slope from the left to the right of the map but otherwise uses a uniform pattern. As shown, in this case the fire has sped up to roughly 12.5 m/min—double the rate of spread for the uniform case (it travels 1500 meters in 15 8-minute timesteps). This confirms that the effect of slope has been implemented in the model as desired.

The effect modelled for downhill fire propagation follows the opposite trend, with a 30-degree downslope corresponding to a reduction in speed of one-half. The 'downhill' pattern used in this test mirrored the 'uphill' one from above, with an uphill slope of 30 degrees. In this

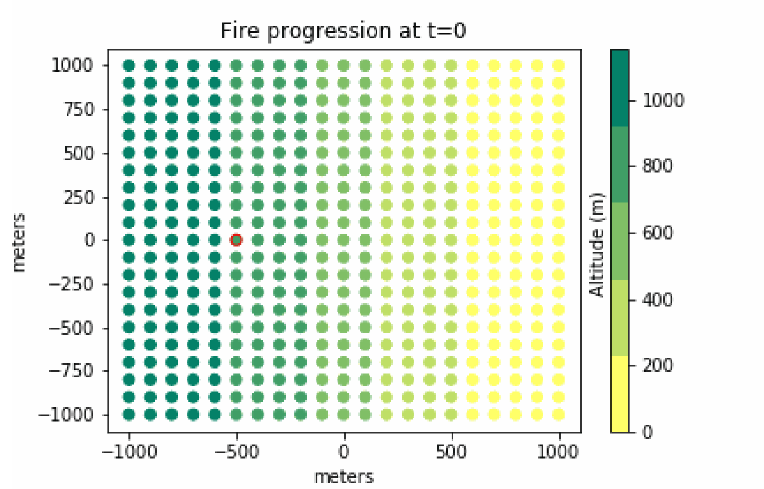

Figure 7: Downhill fire propagation. Animation available in downhill_fire_verification.gif

execution (see Figure 7) spread rounds to 4 m/min (rather than half of 6, the slowest fire propagation speed).

While this rounding effects fire propagation over slope and wind, it should be noted that the model here is meant to model the system at a high level—not capture every behavior with an exact level of precision. While these aspects of propagation could be improved by decreasing the step size (thus increasing the number of steps), doing so would come at the cost of computational time. Nevertheless, it is important to understand this limitation when using the model.

Tanker Response

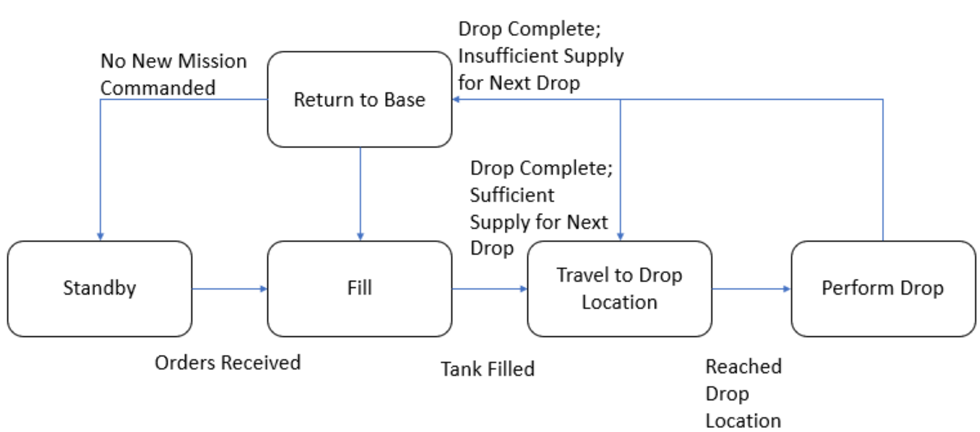

Figure 8: State Machine for Air Tanker.

Description

Tankers assist in the construction of the fire-line by dropping water or retardant. Water drops are used to cool the fire such that ground crews can operate in proximity to the fire safely, while retardant drops slow the rate of spread of the fire. Air tankers are usually based out of the nearest airport. Once they receive orders for a drop, tankers fill their tank and fly to a drop location. They are guided to the drop location by a lead plane, a role sometimes filled by the aerial commander. Tankers double check for nearby hazards and perform their drop. They must typically fly relatively low to perform the drop. After the drop is complete, the tanker may return to base. Sometimes, tankers may perform multiple drops with one full tank, meaning they can instead fly to their next drop location rather than returning to base after a drop. This process is summarized in the state machine in Figure 8.

Behavior check

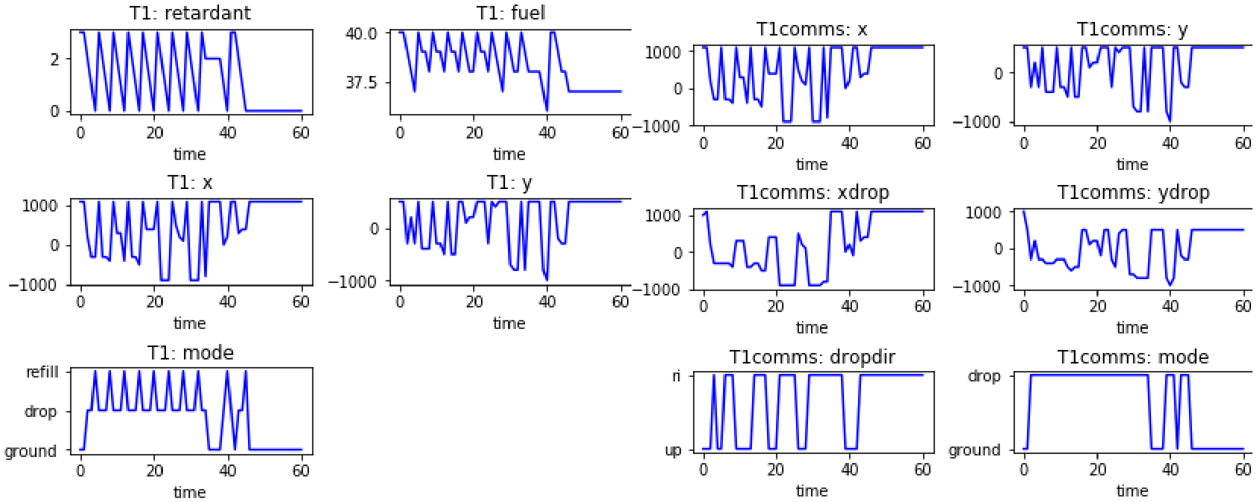

Figure 9: Tanker states (left) and communications (right) over a single simulation

The modelled behaviors for the Tanker are shown in Figure 9. As shown, the tanker alternates between drop and refill states as it runs out of retardant. This continues until time t=45, when the fire is effectively contained. While the tanker also has a fuel attribute, this attribute never reaches a threshold for refueling, since it is assumed the tanker is refueled when it is refilled with retardant. While the tanker is drop cycling (i.e. comms is in drop mode), it is given instructions on where to center the drop (xdrop, ydrop) and the orientation of the drop (horizontal or vertical) from the aerial commander. While the tanker position is also communicated, this attribute is not presently used for anything.

Behaviors under Faults

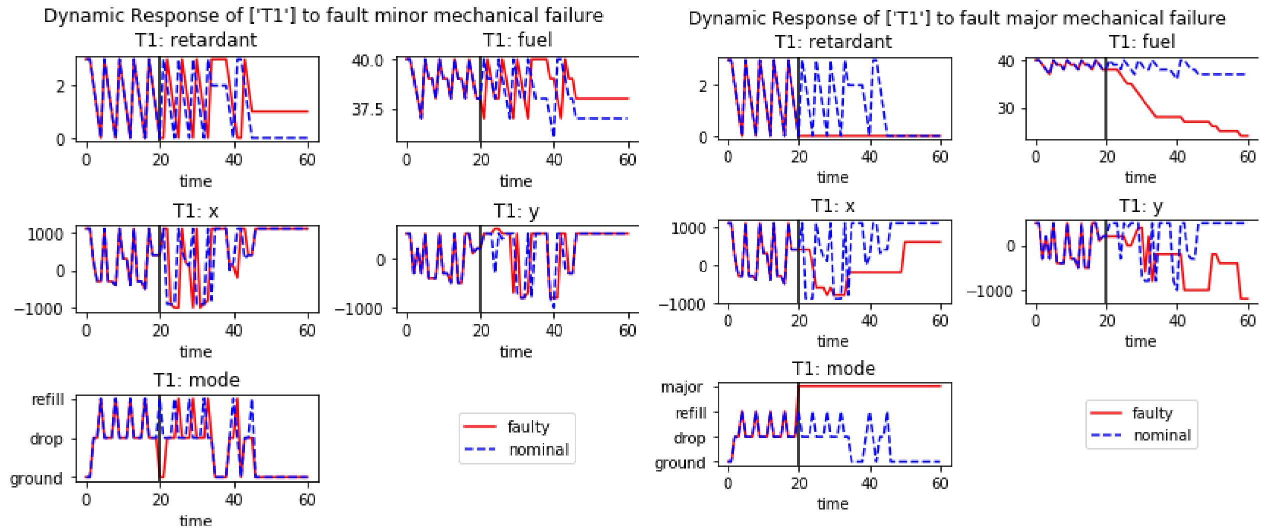

Figure 10: Behavior of Tanker under minor (left) and major (right) mechanical faults.

The tanker has three coded faults: a minor mechanical failure, major mechanical failure, and loss of comms. As shown in Figure 10, under the minor fault, the tanker goes back to the ground base, where the fault is fixed. Then it continues performing drops. In the major mechanical failure scenario, on the other hand, it enters a failure mode which it cannot recover from, meaning it can no longer conduct drops.

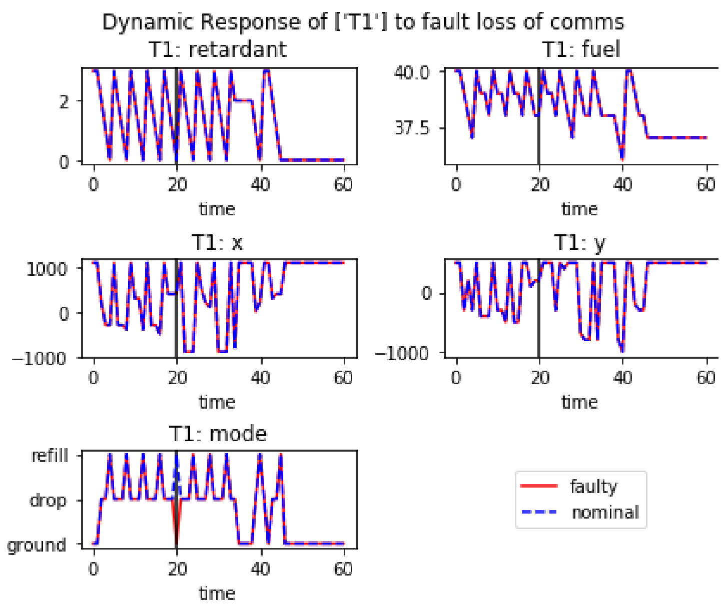

Figure 11: Tanker response to loss of comms fault

In the loss of comms fault, shown in Figure 11, the tanker returns to base, after which the error is fixed. This results in a lost set of drops, if the tanker still had retardant, or no effect if the tanker was already going back go base.

Future work should incorporate more faults and verify the modelling assumptions for these faults. For example, there may be mechanical faults or communications errors which are not immediately fixable. To model these, the simulation may need to either keep the tanker on the ground for longer to fix the fault or assume the fault is not fixed (and continues to cause poor performance).

Effect in Simulation

Changing tanker parameters can make tankers more or less effective at slowing the spread of the fire. In this section, the effect of different tanker parameter values is explored to verify the effect of tankers in the model (e.g. show that they really do slow the spread of fire) and show how sensitive that effect is to changes in tanker parameters.

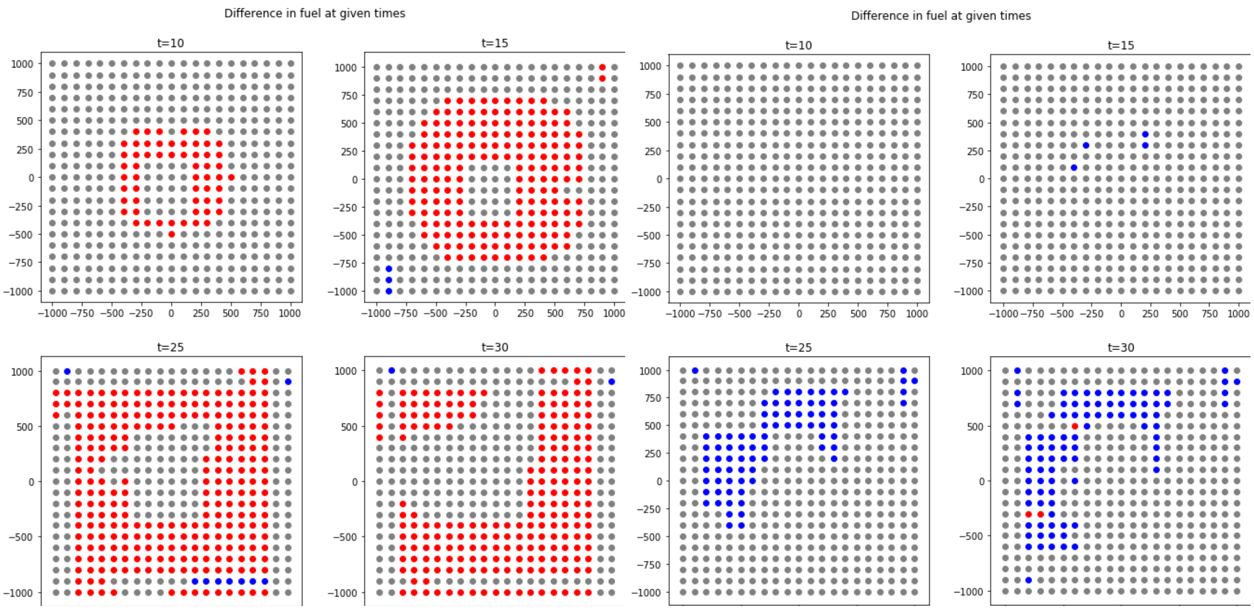

Figure 12: Effect of fewer (0, left) or more (3, right) tankers. Red indicates fuel reduction while blue indicates saved fuel.

The effect of increasing or decreasing the number of tankers is shown in Figure 12. As shown, when there are no tankers, the fire spreads much quicker, eventually crossing the fire-line before it is completed on the upper, left, and lower sides (see t=25 and t=30). Adding more tankers also slows the fire, as indicated by the blue pixels, however the result is much less dramatic, especially early in the propagation of the fire. Other parameters in the model have been explored, including:

- Drop size—the number of pixels a drop includes
- Drop effectiveness—how much execution time a drop adds to an area
- Number of drops—how many drops a tanker can perform before going back to base.

In general, they have roughly the same effect as adding more or fewer tankers. However, there is a balance to these parameters which affects the ability of tankers to function in the model. More tankers and a larger drop size have a similar effect of making a line of drops longer, making it difficult for the fire to get around, while a higher drop effectiveness makes it take a long time for the fire to cross the individual pixels. A higher number of drops means the tankers make drops quicker and in more places.

While the baseline parameters were chosen to make the fire fightable at the (provided) number of tankers (2) and number of drops (3), future work needs to validate their use in this context—specifically the drop effectiveness (which, if too high can lead the fire to put itself out before it crosses the line, which may not have a real-life equivalent), drop size (which is limited by how much retardant a tanker can carry).

Helicopter Response

Description

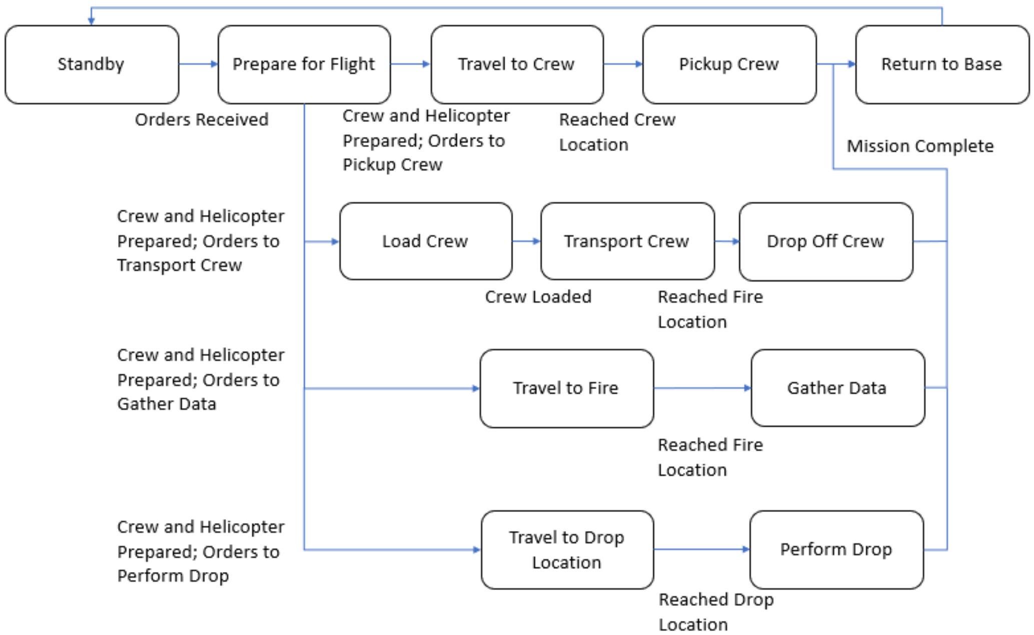

Figure 13: State machine for helicopter.

Helicopters play a flexible role in aerial operations for wildfire response. Specifically, they may perform drops, move crews, or perform surveillance missions. They may also deliver equipment. From their heli-base, when they receive an order, they will generally prepare for flight and travel to the appropriate location: either the location of a ground crew to pick up, or to an area in which they will perform a surveillance mission. In the case that they are transporting a crew to a fire-line location, they will first load the crew and then travel to their drop-off location. Once the location has been reached, they will perform the mission to which they have been assigned: either picking up a crew, gathering data, dropping off a crew, or performing a drop. Helicopters may be able to skip the return to base step and resume their next mission in some cases, for example after dropping off a crew. This process is summarized in Figure 13.

Behavior check

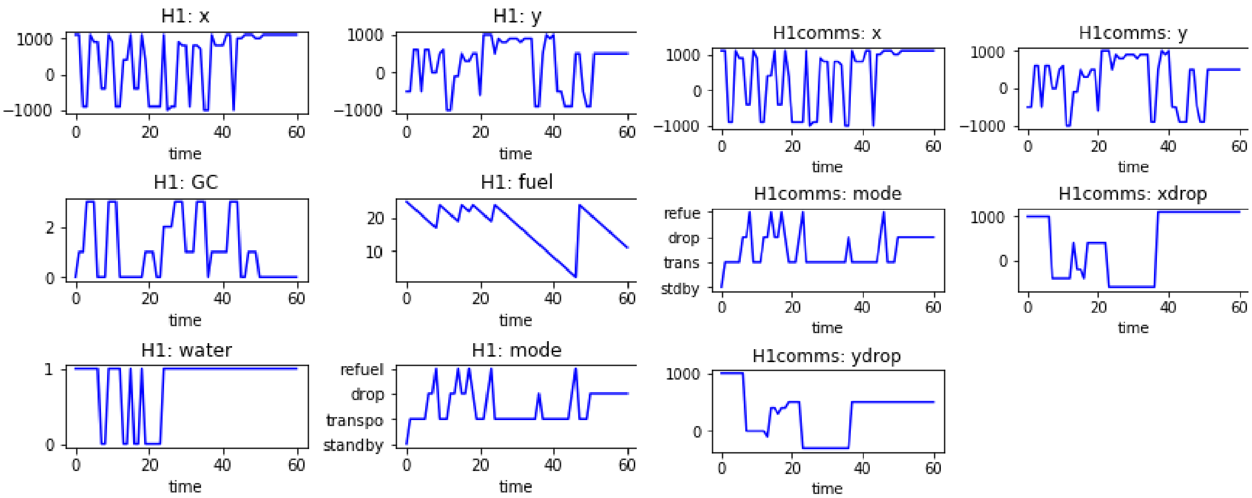

Figure 14: Modelled behavior of the helicopter states and communications.

As modelled, the helicopters go between transporting crews, conducting Drops, and refueling, as shown in Figure 14. Additionally, the helicopter is assigned to different groundcrews (H1: GC) depending on which one needs to be picked up or dropped off. The helicopter goes into refuel mode depending on if the helicopter needs water (H1: water) to perform a drop or fuel (H1: fuel) has reached a low enough threshold. The mode is also communicated to the aerial commander through the Hcomms flow to determine whether it should be sent a drop location (H1comms: xdrop and H1comms: ydrop). While the position of the helicopter is also communicated, this information is not currently used in the model.

Additionally, while it is not shown above (since that role was taken by the UAVs), helicopters also have a supply mode which restocks the supply level in a groundcrew when needed.

Faults

The helicopters have four modelled faults—minor mechanical failure, major mechanical

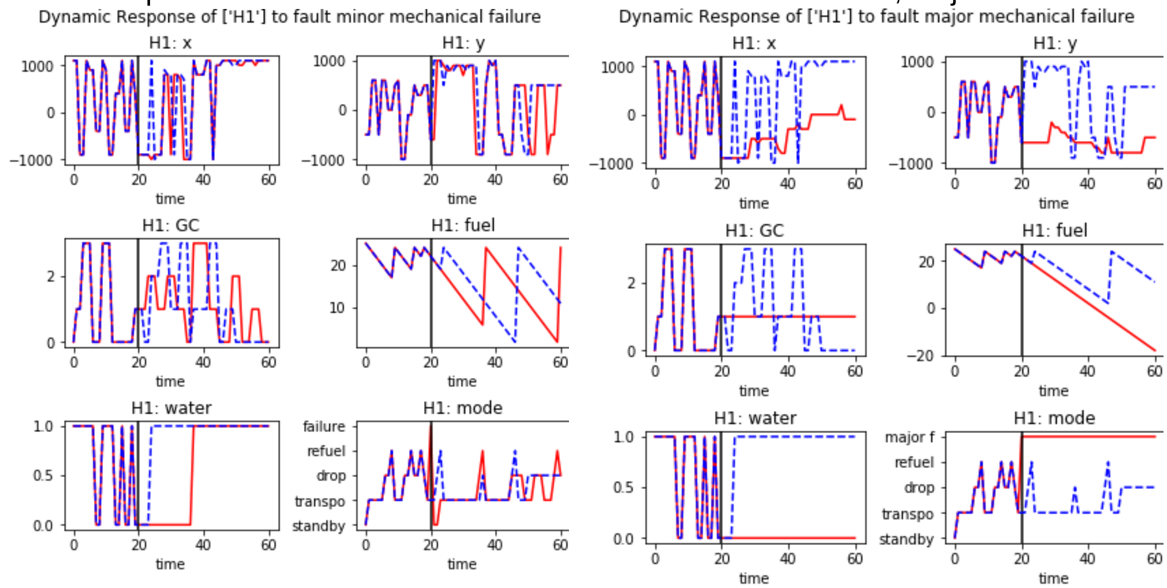

Figure 15: Modelled response of helicopter to minor (left) and major (right) mechanical faults.

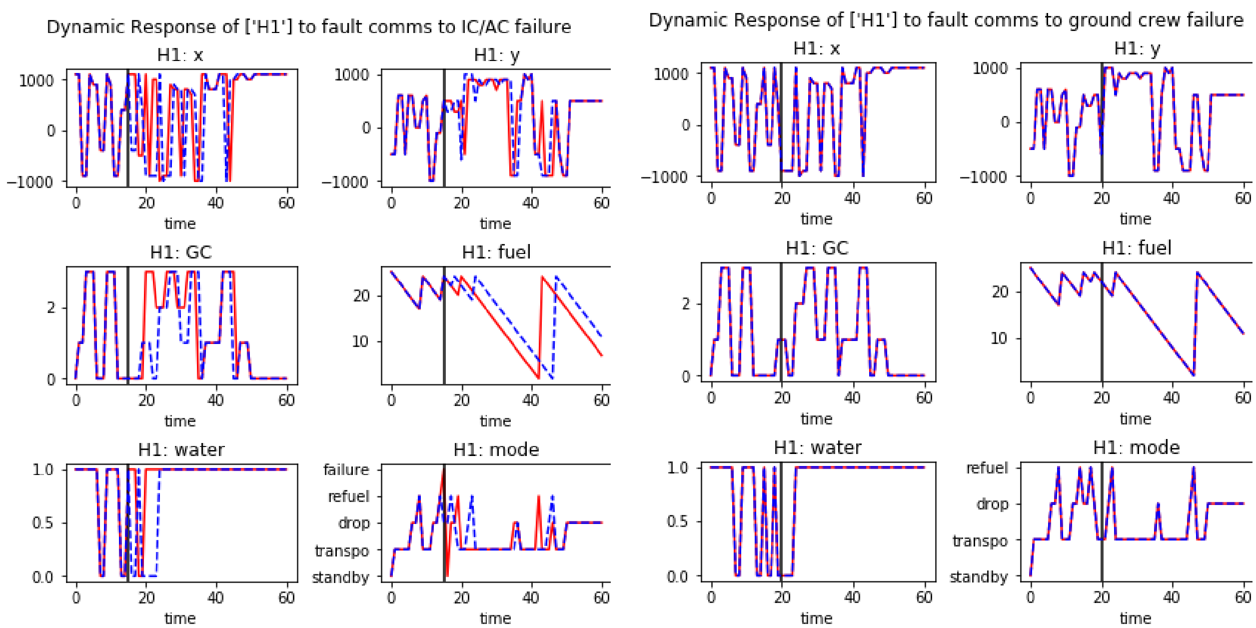

Figure 16: Modelled response of helicopter to IC/AC fault (left) and comms to ground crew fault (right).

failure, comms to ground crew failure, and comms to IC/AC failure. As shown in Figure 15, the minor mechanical failure causes the helicopter to go into standby mode, after which it goes back into operation after a few timesteps. On the other hand, the major mechanical failure causes the helicopter to go out of operation for the rest of the simulation, entering a "major failure" mode with no exit conditions.

As shown in Figure 16, under the communications fault with the incident and aerial commanders, the helicopter again immediately goes into a standby mode, after which the fault is fixed and it continues to alternate between states. Presently, it does not appear that the comms to ground crew fault does anything.

Thus, future work should add faults with more interesting behaviors (e.g. intermittent communications and other faults which are not immediately fixable) and add more realism to the faults shown here (specifically the ground crew communications fault).

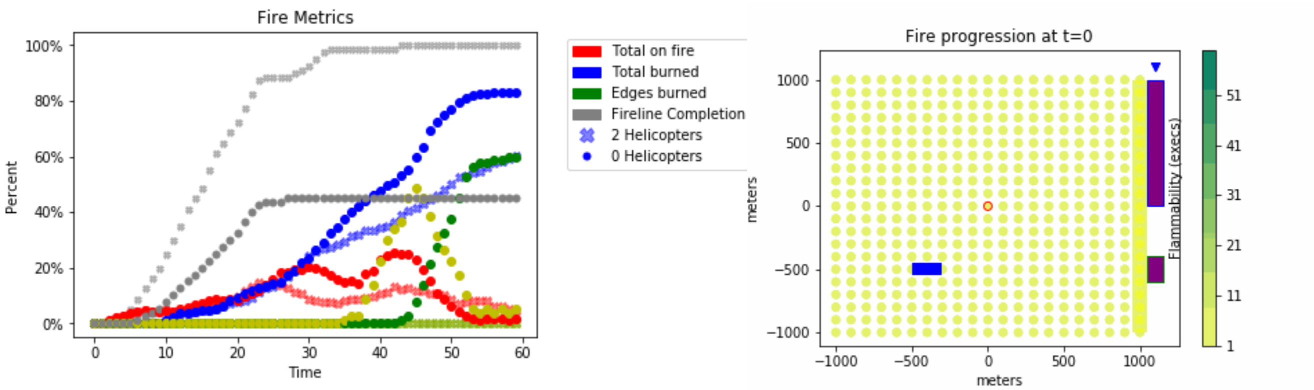

Figure 17: Model response without helicopters. Animation (right) is provided in noheli_int_test.gif.

Effect in Simulation

The effect of helicopters can be evaluated by changing the number of helicopters in the simulation. As shown in Figure 17, without helicopters in the simulation, the ground crews are not able to be transported, and thus the upper and left fire-lines cannot be constructed. As a result, the fire spreads out of these sides.

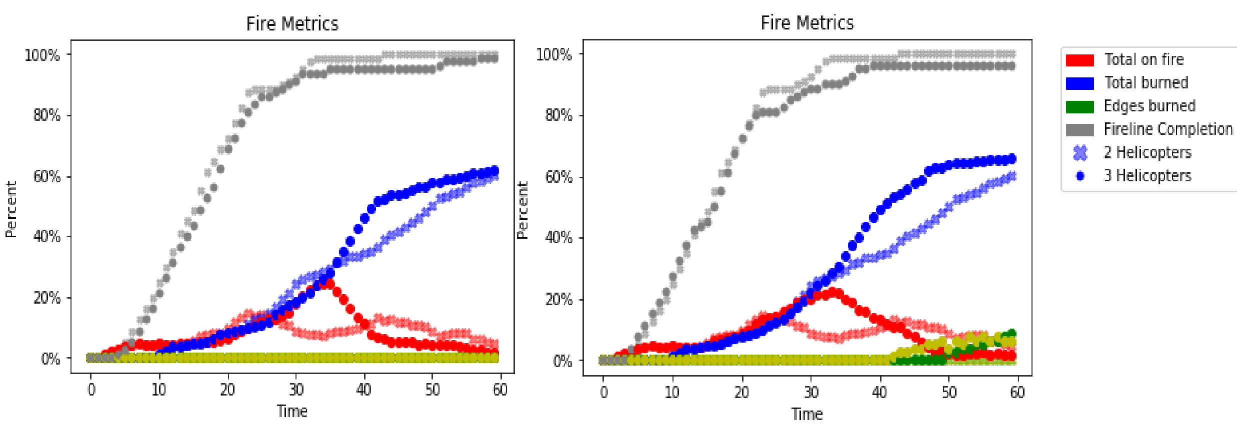

Figure 18: Fire response with one helicopter (left) and three helicopters (right).

However, while the effect of not having helicopters in the model is quite dramatic, the effect of adding helicopters is not. This is shown in Figure 18. While the fire-line is completed slightly quicker with the second helicopter than a single helicopter and the fire seems to propagate less quickly, this difference is not very large. This because while another helicopter can get the ground crews to a location quicker, they do not change the actual speed of making the cuts, making the effect an offset (rather than a big change). Additionally, in the model the assumed effectiveness of helicopter drops is much less than tankers and they are sent to lower-priority areas. Thus, the lack of change may also come from the assumptions of the model.

This change is more concerning at higher numbers of helicopters (see Figure 18, right), where the helicopters hinder fire-line completion. It is not clear why this is happening and should be addressed in future iterations of the model.

Ground Crew Response

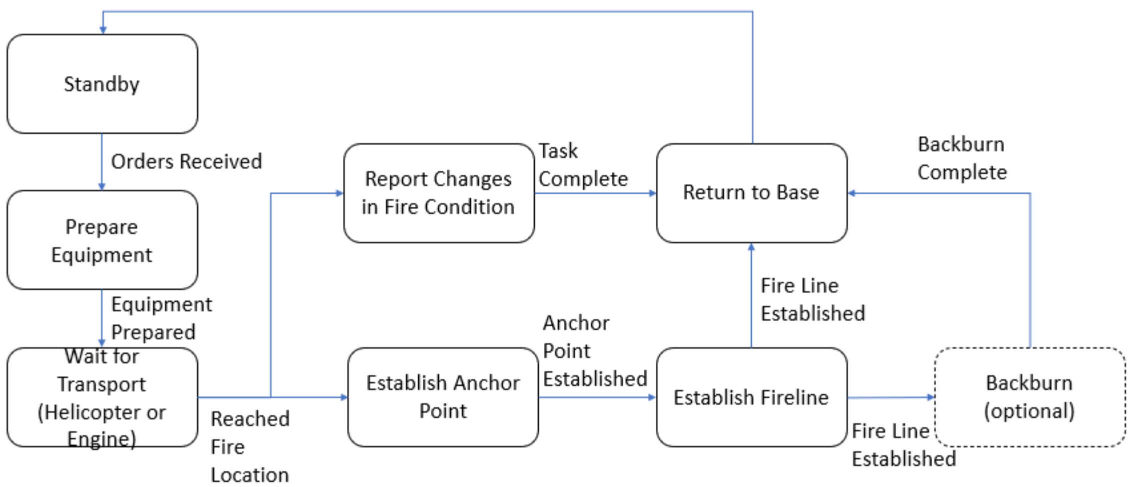

Figure 19: Ground crew state machine.

Description

Ground crews are key players in wildfire response, and in general the purpose of aerial operations is to support ground crew efforts. The main job of ground crews is to construct a fire-line to contain the fire, generally by clearing flammable materials and sometimes by backburning. Fire-line placement depends on terrain, fuels, fire behavior, and resources (National Wildfire Coordinating Group, 2014). Ground crews are transported to their appropriate location via a helicopter or fire engine. Once they have reached the fire-line location, their main task is to establish an anchor point and then construct the fire-line. An anchor point prevents the firefighters from being surrounded by flames. After the fire-line is established, there is an optional backburn step before their mission is complete. While they are performing their main task, ground crews must also report any changes in fire condition. This process is summarized in Figure 19.

Behavior check

As shown in Figure 20, the crews start in a rest mode at the base, are then helicoptered to the fire-line, after which they perform a land cut in a single x or y- direction. When the supplies attribute goes to zero, the ground crew waits for supplies before continuing the land cut. When they are finished, depending on the amount of fatigue they have, they either ask to go to a new

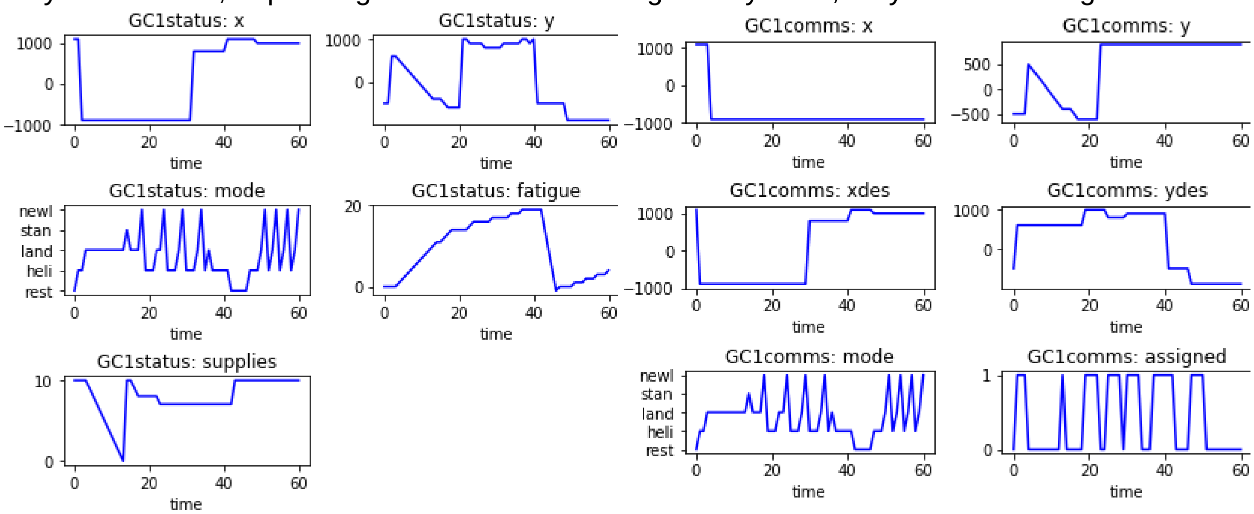

Figure 20: Ground crew behaviors and communications over time.

location or return to base, where they stay until fatigue goes to zero. When the crew has a location to go to (i.e. is in rest or newloc mode), it sends its position (x,y) and desired position (xdes, ydes) through the GCcomms flow to the helicopter to tell it where to pick it up and where to take it. The GCcomms: mode and assigned properties additionally communicate whether the crew is ready to be picked up and whether a helicopter has been assigned to pick it up.

One notable aspect of this simulation is that the crew starts out performing a long land cut and then goes to several different places where it only cuts a few pixels. This is because of the nature of fire-line construction in this model—the firecrews start by putting a fire-line in the most central part of the map and then spend the rest of the simulation closing the gaps in the corners.

Additionally, there may be some issue with the model where the ground crews are still being assigned to construct fire-lines after the fire-line has been completed. Future work will need to investigate this so that the ground crews go to base at the end of the simulation.

Fault Behaviors

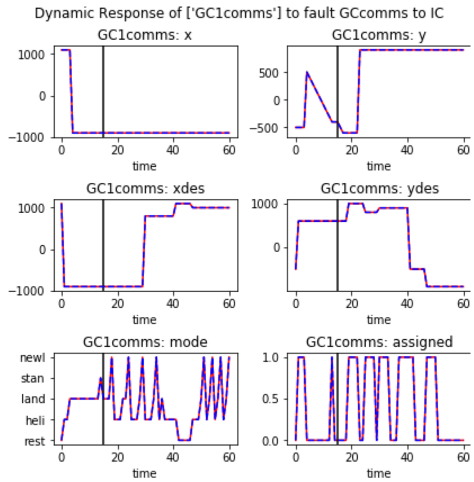

Figure 22: Ground Crew with lost communications to incident commander fault

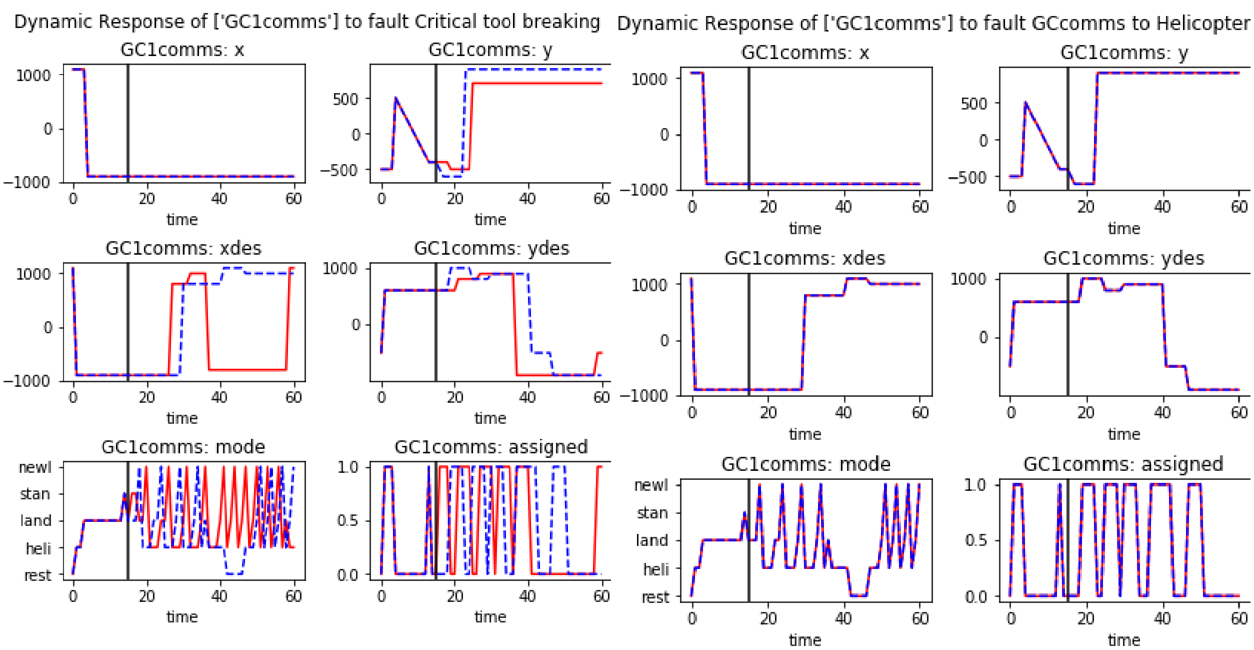

Figure 21: Effect of ‘critical tool breaking’ and ‘comms to helicopter failure’ faults ground crew communications.

The ground crews have three modelled fault modes—a critical tool breaking, faulty communications with the helicopter, and faulty communications with the incident commander. Figure 21 shows the response of the ground crew communications to the tool break and faulty communication faults while Figure 22 shows the response of ground crew communications to lost communications to the incident commander. As shown, losing the critical tool leads to a delay in operations, since the ground crew must wait to receive that tool to operate again. However, the communications faults do not appear to have an effect in the model. While the reason for this needs to be investigated, it is likely that this is because the faults were injected when the ground crews were communicating. In future work a method will need to ensure that these faults are always injected at the proper time.

Effect in Simulation

Ground crews create fire break to contain the fire. Thus, having more ground crews in the simulation should complete the fire line quicker. As shown in Figure 23, having fewer ground crews (0 or 1) results in a slower completion of the fire line, which in turn results in a breach.

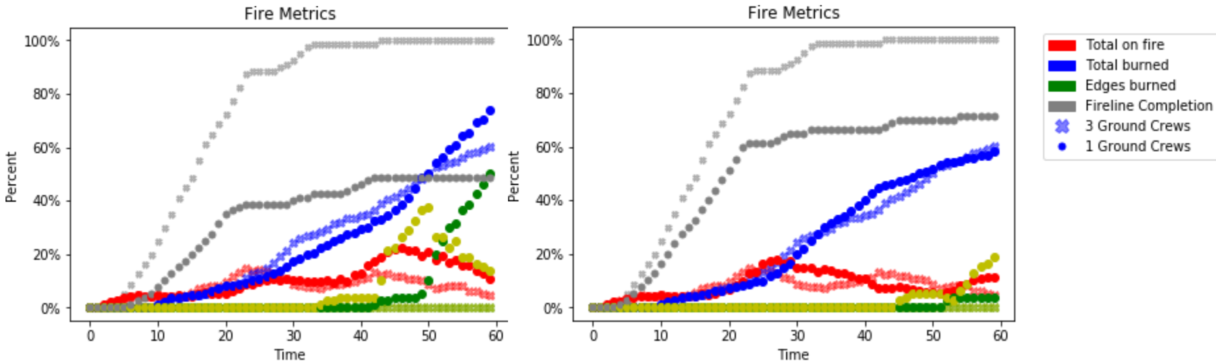

Figure 23: Fire response with zero (left) and one (right) ground crews in the simulation

However, this trend does not appear to increase in this model beyond 2, as shown in Figure 24. At two ground crews, the performance is very similar (if a little slower) than at three ground crews, while at four ground crews, the performance is worse. This can be attributed in part to the way fire-lines are planned and executed, in which each side is split into sections for each of the ground crews to handle. Since there are two exclusive-ground crew sides in this model, the most gain in performance comes from giving each side a ground crew. After that point, there is opportunity for ground crews to conflict with each other as they make cuts on the same side. Thus, for more ground crews to help fire-line construction, fire-line planning needs to be revised to better coordinate the ground crews.

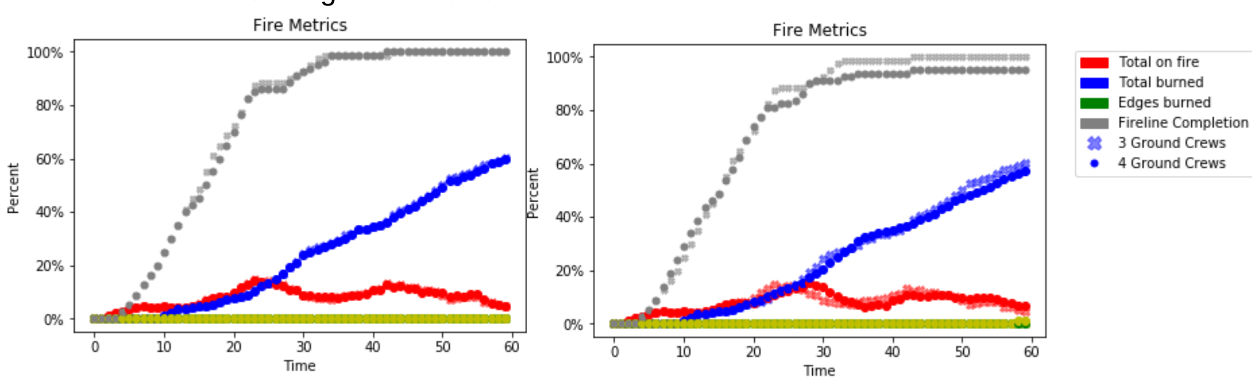

Figure 24: Fire response with 2 (left) and 4 (right) ground crews.

Engine Crew Response

Description

Most engines are used for direct attack (Department of the Interior and Department of Agriculture, 2020). Two to three personnel at minimum are required for the operation of a fire engine (National Wildfire Coordinating Group, 2014). Fire engines also transport ground crews to fire-line locations and assist in the construction of the fire-line. They can also pickup ground crews that need to be transported back to base. This process is summarized in Figure 25.

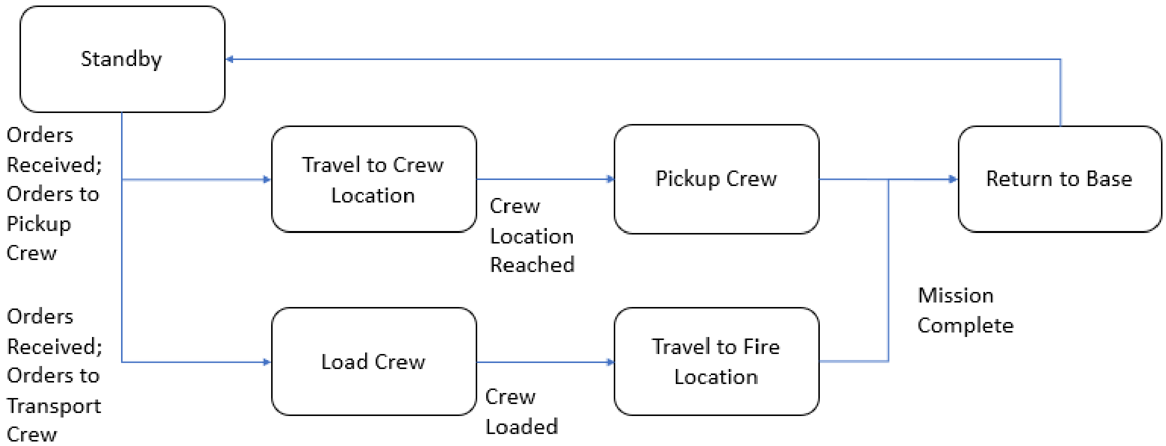

Figure 25: State machine for fire engine.

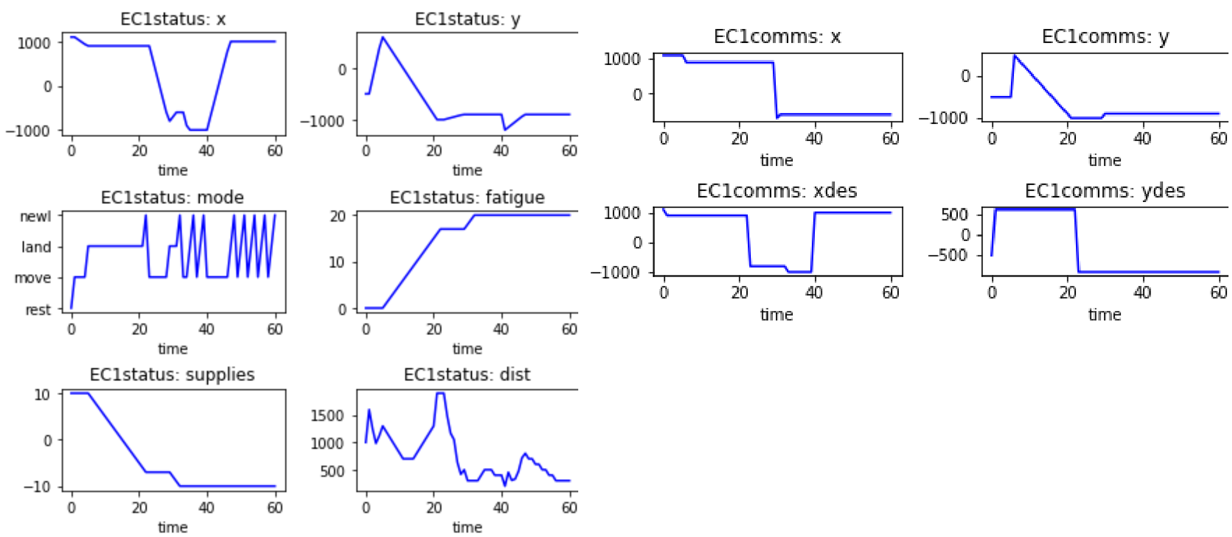

Figure 26: Behavior of Engine Crews and engine crew communications in the model.

Behavior check

For consistency, engine crews are coded similarly to Ground Crews. As shown in Figure 26, the engine crews first move to a location and then conduct a land cut in a position provided by the incident commander. When that cut is complete, they move to a new position, until they reach a limit for fatigue. At this point, the engine crews should go back to the base to rest.

However, it appears this is not working as desired and instead the engine crews go to base and then then attempt to leave despite being fatigued. While the slack of engine crews working can be taken up by ground crews, ground crew rest and redeployment cycles need to be incorporated for the model to act as intended.

Additionally, as shown, while the engine crews do have a supplies attribute, it is currently not used based on the idea that engine crews can be supplied without an aircraft. Future work should either remove the attribute or include engine crew supply drop missions in the model. It also appears that the engine crews oscillate between moving and looking for a new location after the fire-line has been completed. To fix this, some conditions need to be added to cause the engine crew to enter rest mode upon completion of the fire-line.

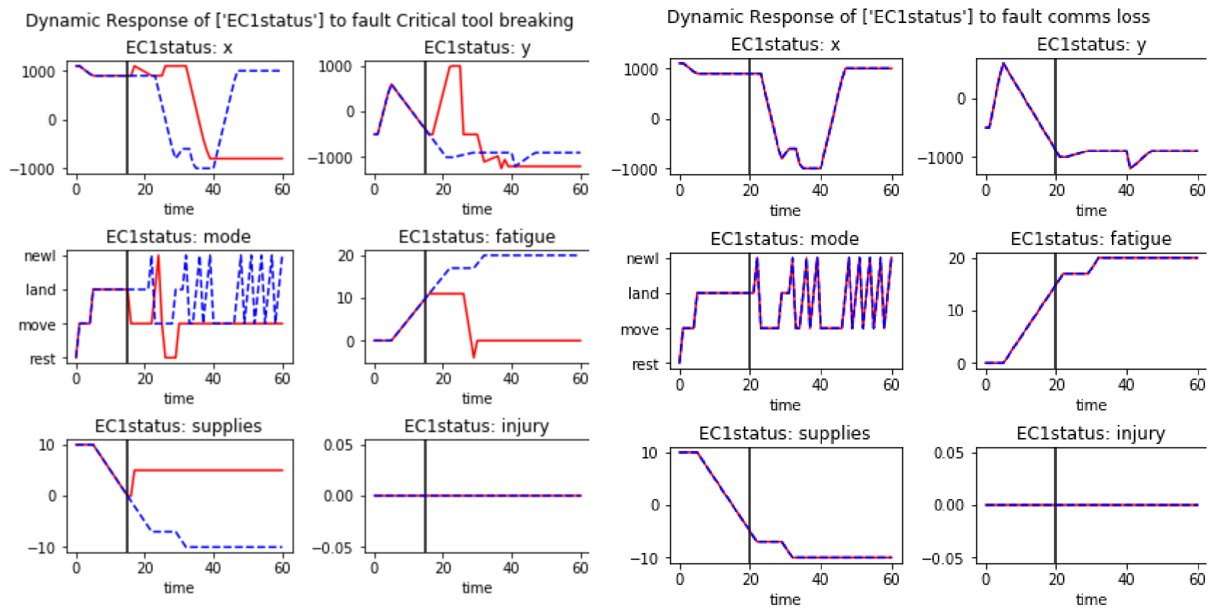

Figure 27: Response of Engine Crews to Tool Breaking and Communications Faults

Faulty Behaviors

The engine crews have two faulty behaviors, a critical tool breaking and lost communications, which are each shown in Figure 27. As shown, when there is a tool break, the engine crew must go back to the base, and then moves around for the rest of the simulation (ostensibly because another crew took up the slack). As with the ground crews, the communications loss fault does not currently do anything in the model and should be investigated in future work.

Effect in Simulation

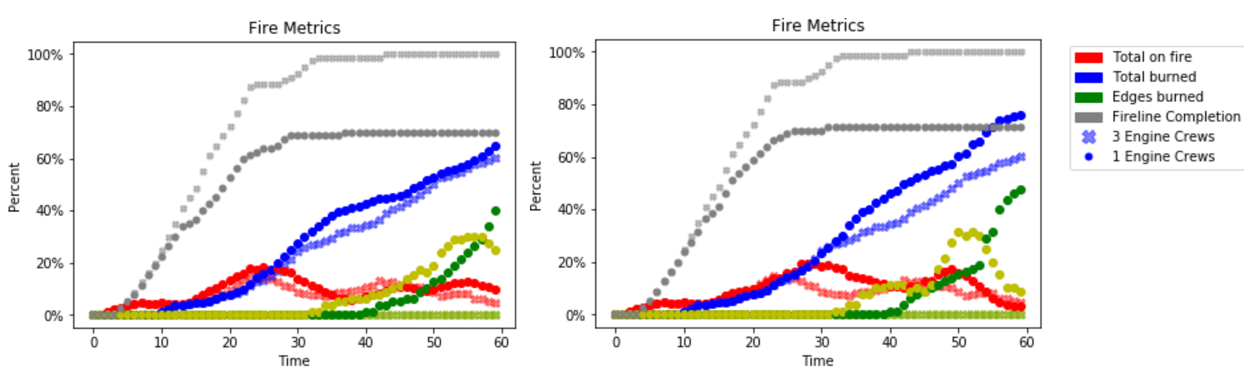

Figure 28: Effect of Zero (left) and One (right) engine crew in the model.

The effect of engine crews in the model is similar to that of ground crews. The main difference between both is that while ground crews can be deployed anywhere (but require helicopters to transport them to and from their desired locations), engine crews can only be deployed on specified sides of the map (the lower and right sides, in our scenario). However, as shown in Figure 28, there is less improvement from adding a single engine crew to the model as there is a single ground crew. It's not quite clear why there isn't a greater difference, except that the ground crews can compensate for engine crews, since they can be deployed on all four sides (as opposed to when there are no ground crews and two sides cannot be protected).

Similar to the ground crews, the effect of engine crews does not increase substantially beyond adding two, as shown in Figure 31. The major gains in fire-line effectiveness come at the addition of the second engine crew, and it no longer increases at the fourth engine crew. The reason for this is likely because of the way the fire-lines are planned—it helps to have a single engine crew start on each side because the accessible sides are assigned a lower priority to the ground crews. Thus, without an engine crew on each side, it will be exposed until it becomes a high enough priority to get sent to ground crews. To fix this, ground crew and engine crew fire-line assignment should be made more adaptive to the numbers of each asset.

UAS Response

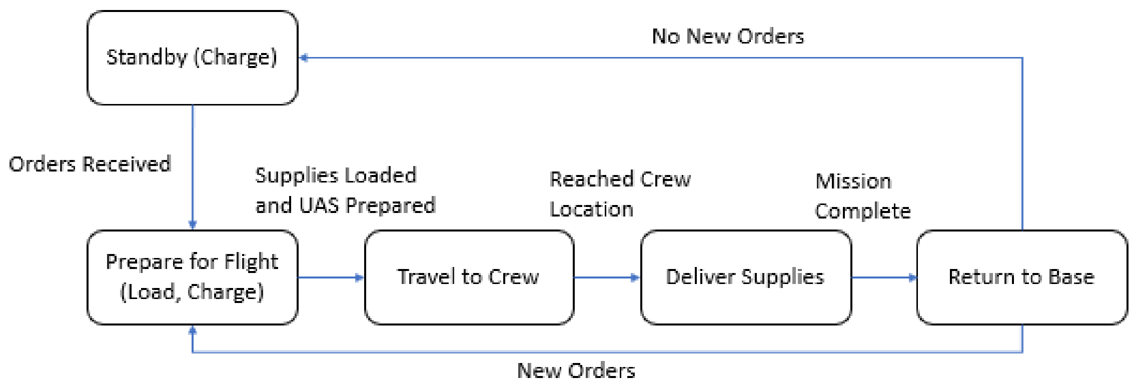

Figure 29: State machine for supply UAS

Description

Multirotor UAS are used for low altitude, precision operations. In this model, they are specifically used for logistics delivery missions. UAS recharge at their base and, when commanded, load supplies to prepare for their mission. Once prepared, they travel to the

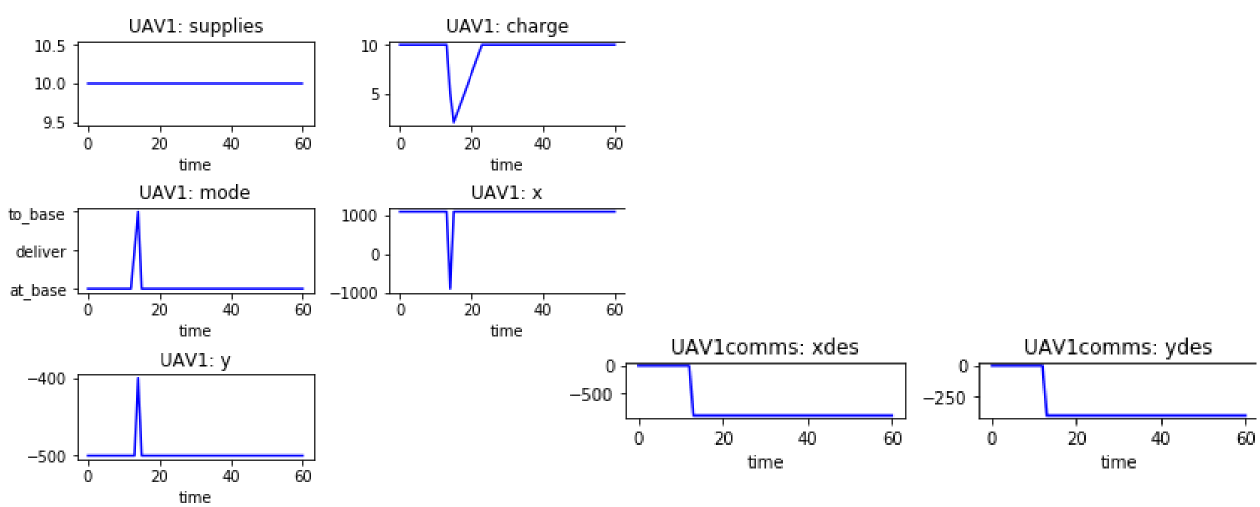

Figure 30: UAV behaviors over the nominal simulation.

location of a ground crew in need of supplies. They then deliver the supplies to the ground crew and return to base. At this point, they may need to recharge before completing their next mission. This behavior is summarized in the state machine in Figure 29.

Behavior check

The modelled behaviors of the UAV are shown in Figure 30. As shown, the UAV waits at base until a ground crew needs supplies, at which point it is sent its location (through UAVcomms), and it delivers supplies. It then flies back to the base and charges. When it is fully charged, it can perform more supply missions. In this case, only one supply mission is performed. Supply UAVs currently do not have modelled faults. They will need to be incorporated in future work.

Effect in Simulation

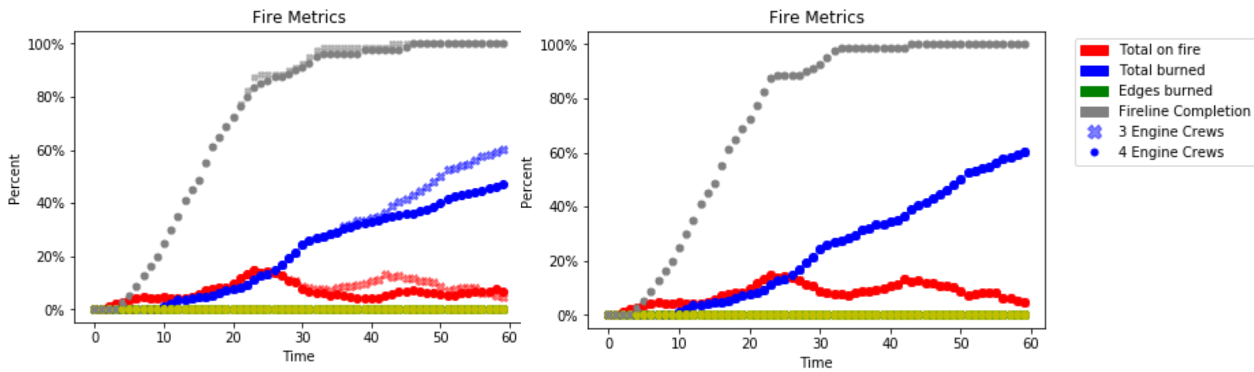

Figure 31: Fire response with 2 (left) and 4 (right) engine crews.

Supply UAVs reduce ground crew supply delays and take some unnecessary load off helicopters, enabling them to perform more drops, rather than deliver supplies. The effect of this is shown in Figure 32. As shown, the effect is very modest, with the fire-line being constructed slightly quicker. This is in part because (as discussed in the helicopter section), there is an over-supply of helicopters and the effect of helicopter drops (which they are performing instead of supply drops) is itself modest in comparison to tanker drops.

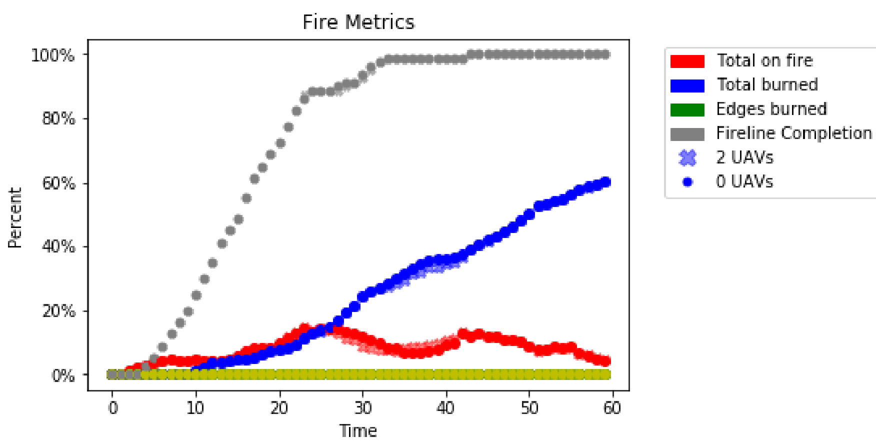

Figure 32: Fire progression with/without supply UAVs

Surveillance Response

Description

Fixed wing UAS are used for surveillance missions. Before a flight, UAS refuel if needed. Then, they travel to the fire location and gather data while following a path designated by the aerial supervisor. Typically, they will return to base when their fuel is low. Then, they will refuel and continue surveillance. This behavior is summarized in Figure 33.

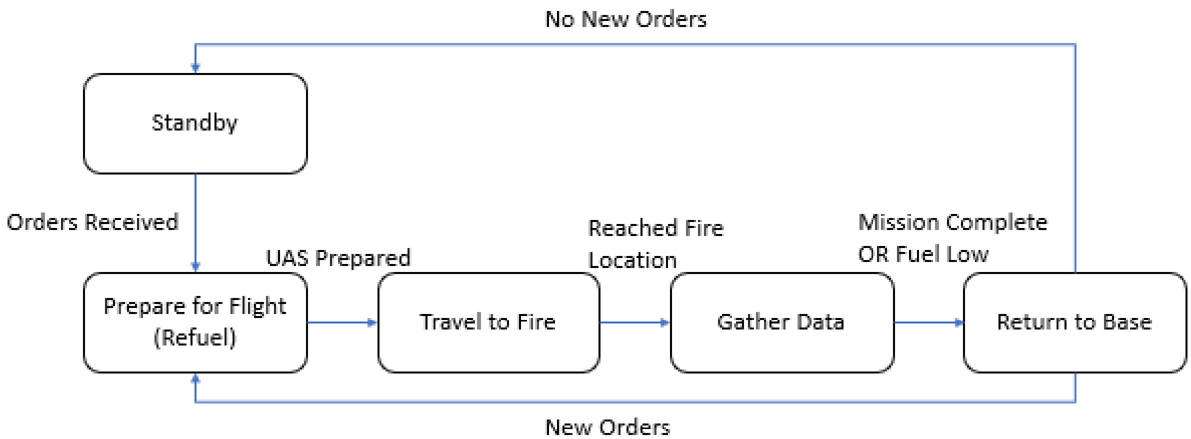

Figure 33: State machine representation for Surveillance UAVs

Behavior check

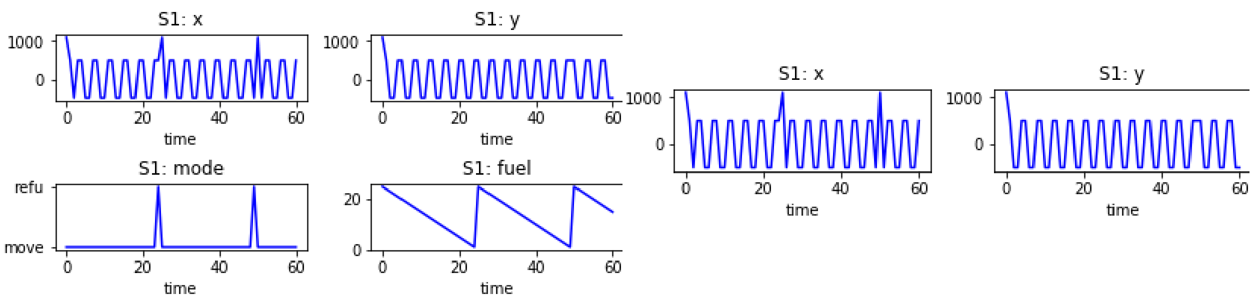

Figure 34: Behaviors and communications for surveillance UAVs

As shown in Figure 34, surveillance UAVs fly in a set path given to them by the aerial supervisor. They fly in this path until they need to refuel, and then return to the pattern after they

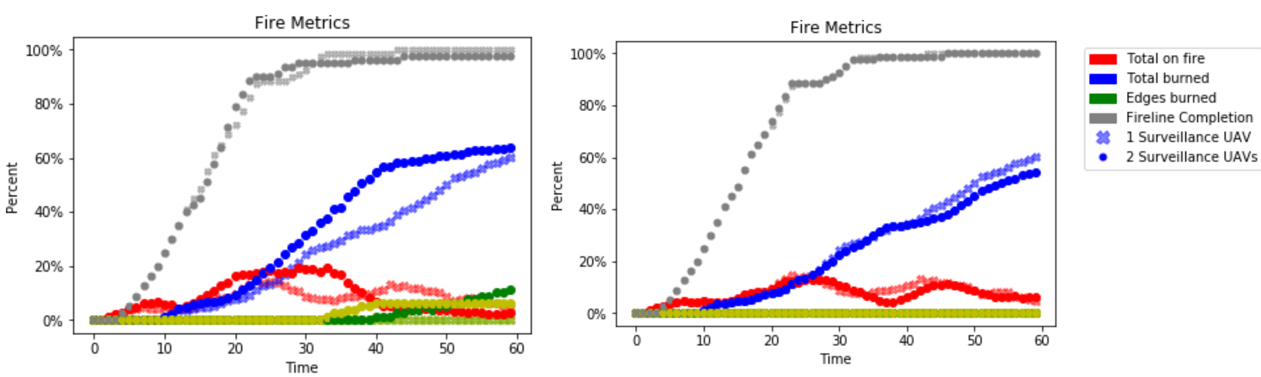

Figure 35: Fire response with zero (left) and two (right) surveillance UAVs.

are done. Currently there are no faults modelled in the surveillance UAVs—they will need to be added in future work.

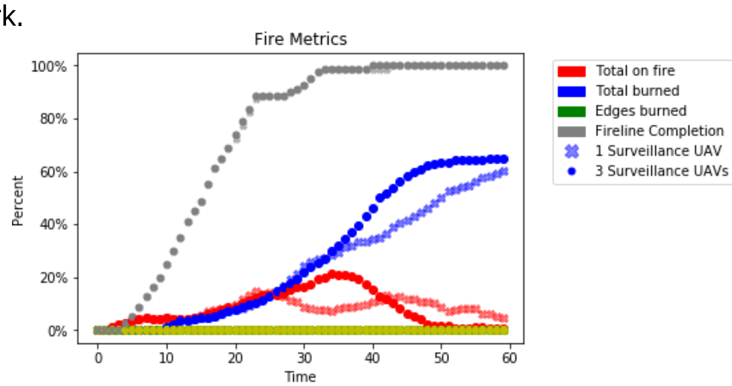

Figure 36: Fire response with three surveillance UAVs.

Effect in Simulation

Surveillance UAVs increases the state awareness of the Incident Commander and Aerial Supervisor—reducing the lag between the actual state of the fire and the perceived state of the fire—which enables them to make better firefighting decisions. This effect is shown in Figure 35. As shown, as the number of surveillance UAVs increases, the curve of pixels on fire becomes flatter and the line of percent pixels burned becomes less steep.

However, there is an exception to this rule shown in Figure 36 for 3 UAVs (the maximum number allowed). In this case the fire-line is completed quicker, but the fire propagates faster. While this fire is still contained, it indicates that there may be a particularity of fire response model on the uniform map which causes a poor response with full state information. This simulation will need to be checked in future work to determine whether this is a bug which will affect all simulations or a particularity of this simulation.

Incident Commander Response

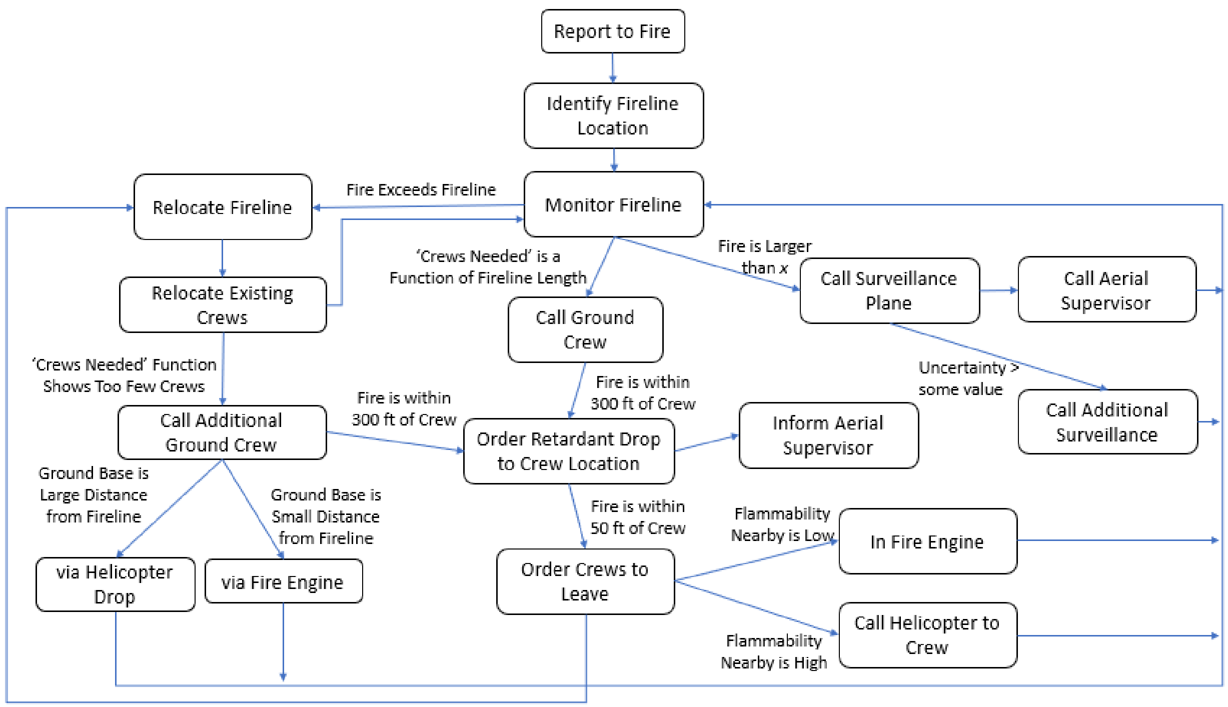

Figure 37: State machine representation of incident commander tasks.

Description

The incident commander is the primary individual in command of the wildfire response and is therefore responsible for much of the firefighting strategy. In larger responses, some management may be delegated to operation coordinators and unit leaders. The incident commander identifies the fire-line and continuously monitors the fire-line. If the fire exceeds, or is expected to exceed, the fire-line, the fire-line is relocated, along with existing crews. Additional crews are called as needed and are transported either by helicopter or fire engine depending on the distance from the fire-line. Depending on the status of the fire-line construction, the incident commander calls retardant and/or water drops as well as surveillance planes. They additionally coordinate ground crew locations, commanding them to move if they are nearby a drop location. This process is summarized in Figure 37.

Behavior check

The incident commander has no modelled internal states since it is presumed to operate on the ground in a safe location. The best way to observe its behavior is to view the communications with the groundcrews and Aerial commander (GCcomms and Aerialcomms). However, it runs through several methods at each timestep to identify threats, communicate those threats to the aerial commander, and determine where ground crews should create firebreak.

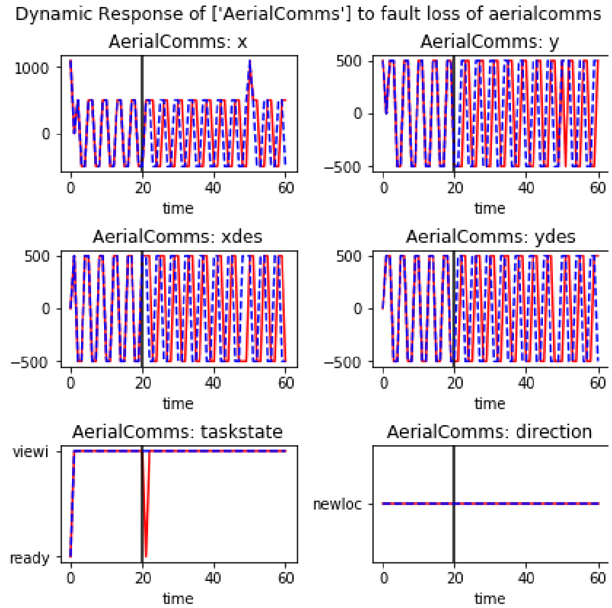

Figure 38: Behavior of Aerialcomms under "loss of aerialcomms" fault in Incident Commander

The Incident Commander currently has one fault: loss of aerial communications. As shown in Figure 38, this fault causes the aircraft to pause until the fault is removed, resulting in a delay in its movement. Further faults should be incorporated in the Incident Commander in future work.

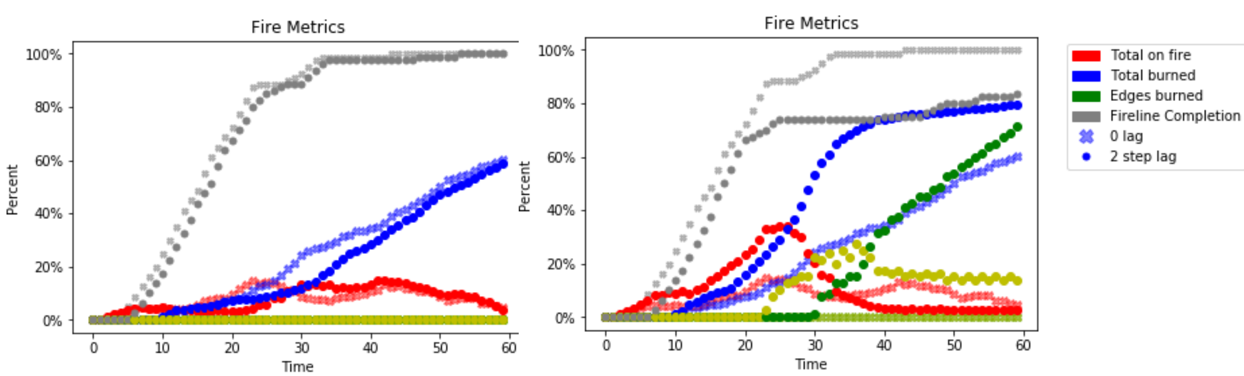

Figure 39: Effect of fire response with increased lag (1 time-step at left, 2 time-steps at right) in the incident commander

Effect in Simulation

The Incident Commander has two main parameters which can be changed to alter the response—communication lag and side priority. Communication lag, shown in Figure 39, is modelled as the time between ground being perceived by a surveillance plane and it being used for decision-making by the Incident Commander. As shown, increased lag makes it take more time for ground crews and tankers to respond, resulting in decreased performance (eventually resulting in a breach, if lag is high enough).

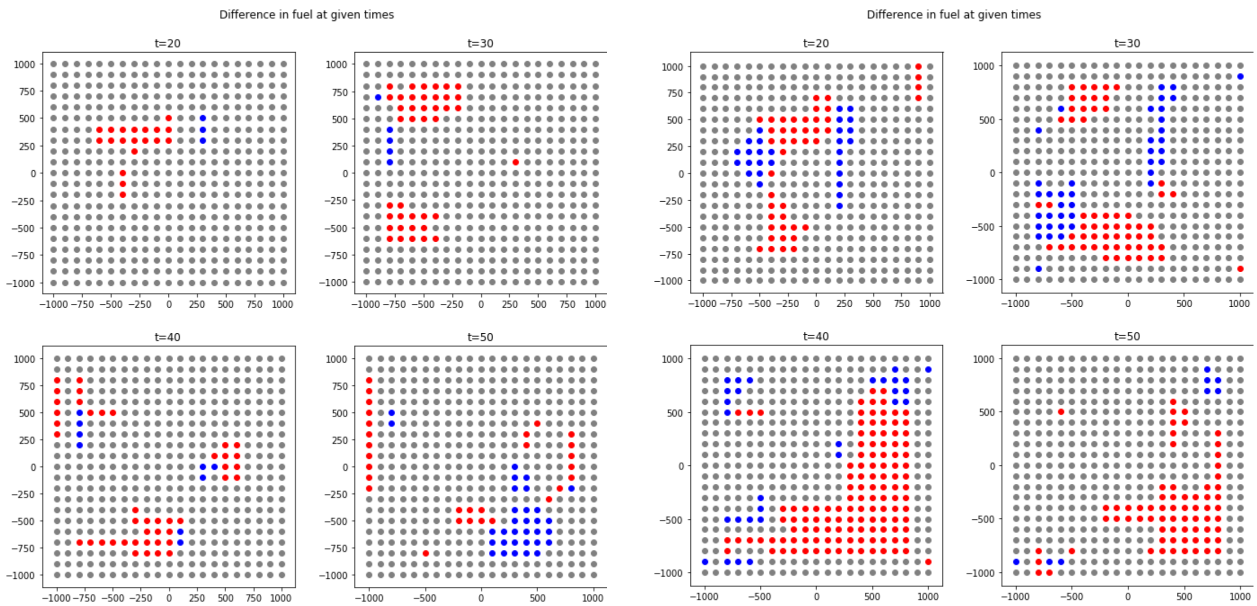

Figure 40: Comparison of response with a side preference of 0.1 (left) and 0.3 (right) with no side preference.

The side priority is the factor by which the distance between the fire line and the fire must be increased or decreased in the threat response to give more priority to especially dangerous sides (e.g. the fire propagating towards a city). As shown in Figure 40, increasing this factor from zero causes the fire to propagate more towards the left than the right (where the city is), at first. However, because of this increased priority, there is not enough time to protect the other sides, leading to a breach in the fire-lines. As a result, while this factor may better protect a single side, at these parameters it causes a breach in the fire-line when there would not be a breach otherwise. Future work should show whether this parameter actually increases safety on the dangerous side on the net over a variety of maps, to show whether it can lead to increased safety in these circumstances.

Aerial Supervisor Response

Description

The aerial supervisor functions as an air traffic controller (ATC) in the sky. They manage the aerial assets that are applied to the wildfire event. Currently, this is done primarily via radio communication. In more complex operations, some of the tasks of the aerial commander may be delegated to an airspace coordinator and helicopter coordinator. The aerial commander periodically requests a position report. It also manages aircraft entering and exiting the airspace, including responding to intruders, although this behavior is not currently modeled. Additionally, although these roles can be fulfilled by separate aircraft, in this model, the aerial commander

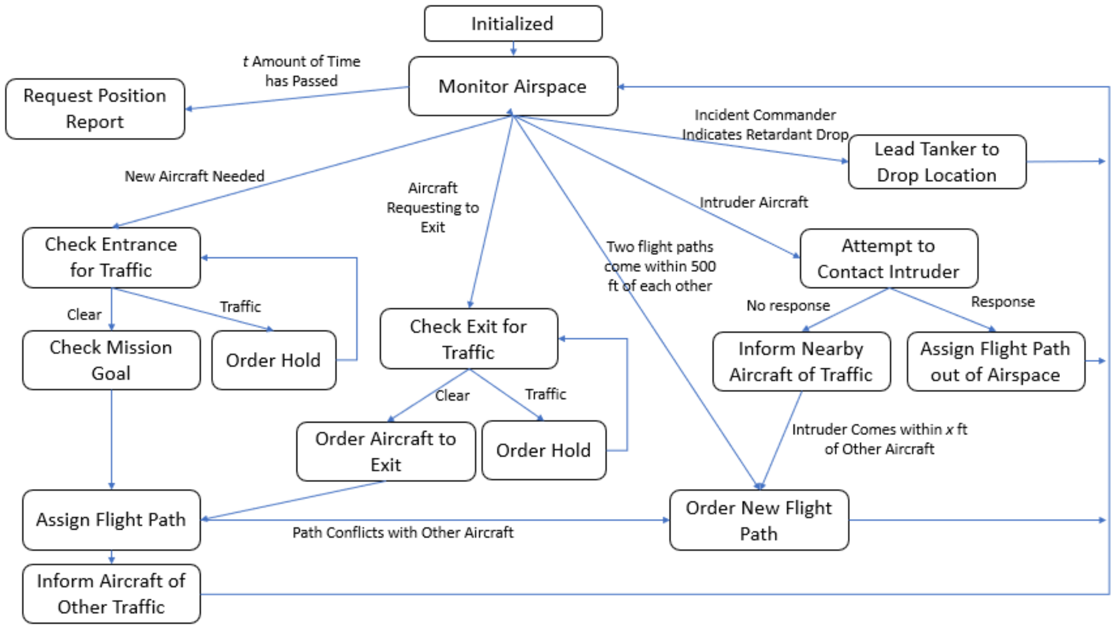

Figure 41: State machine representation of Aerial Supervisor tasks.

functions as the lead plane by leading the tanker aircraft to its drop location. This process is summarized in Figure 41.

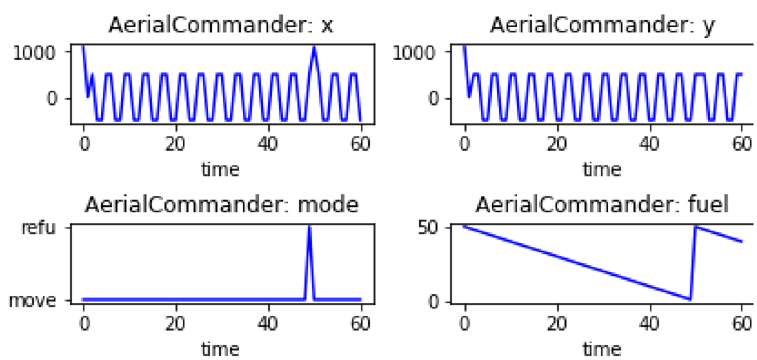

Figure 42: Aerial Commander behaviors over a single simulation

Behavior check

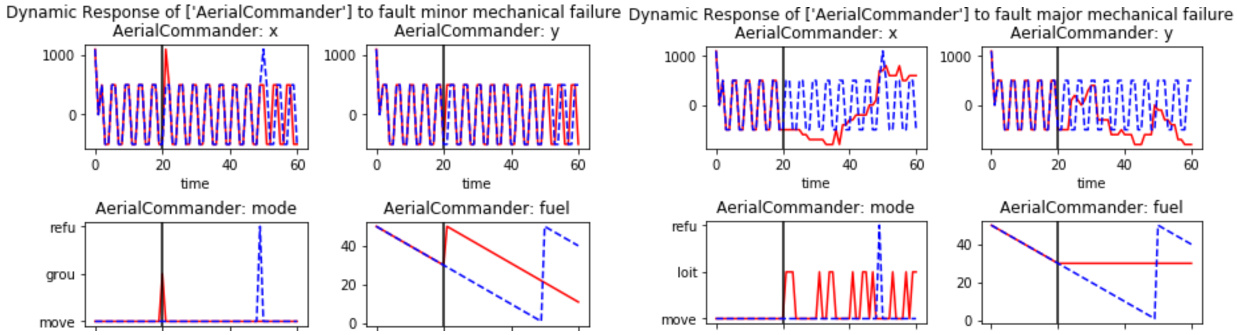

Figure 43: Behavior of the Aerial Commander to minor (left) and major (right) mechanical failures.

As shown in Figure 42, the Aerial Supervisor flies around a set number of points around the fire until it needs to refuel. At that point, it goes back to base, refuels, and continues its flight. However, the aerial commander does have other modelled behaviors, such as the relaying of perceived fire information to the Incident Commander (shown in Figure 44) and the planning

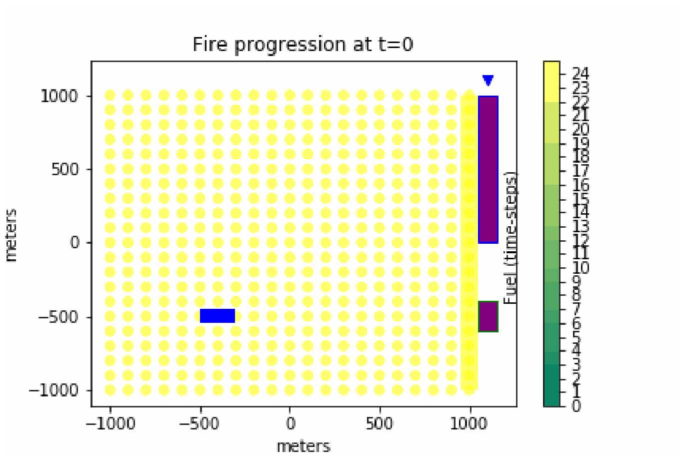

Figure 44: Perceived Ground seen by the Aerial Commander and Surveillance plane over one random simulation. Animation provided in perceived.gif.

and communications of drop locations to tankers and helicopters. Future work should provide a way of visualizing these communications.

Fault Behaviors

The aerial supervisor has three modelled faults: a minor mechanical failure, a major mechanical failure, and lost communications with the incident commander. As shown in Figure 43 (left), in the minor mechanical failure the plane goes back to base, after which the problem is fixed immediately and the plane returns to service. However, in the major mechanical failure scenario, the plane crashes, resulting in erratic position over time.

The lost communications fault does not change the Aerial Commander behavior (in terms of position and mode) but does lead to decreased performance due to a lack of threats being communicated (and thus no more drop locations sent to tankers/helicopters). This can be observed in Figure 45.

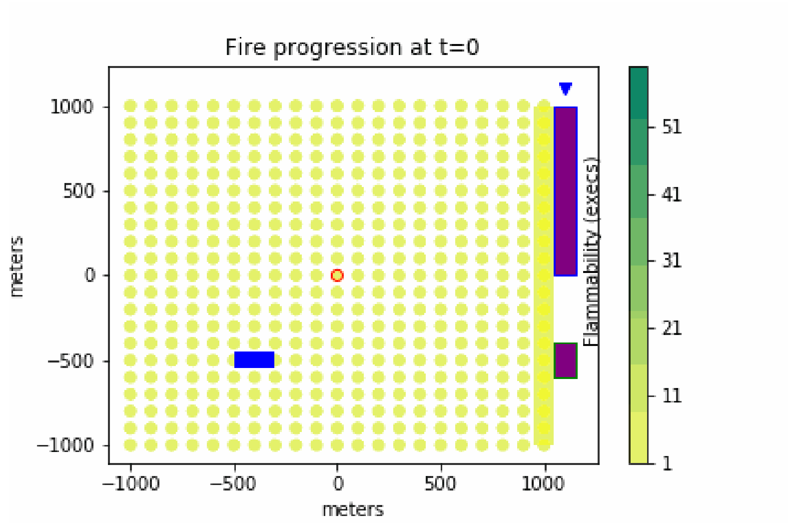

Figure 45: Fire response when communication with the incident commander is lost at t=15. Animation provided in incident_commander_fault.gif

Effect in Simulation

The aerial commander does not have parameters which can be changed, except for lag, which was included in the incident commander section.

Discussion

The SMARt-STEReO model provides an integrated model of fire propagation and response. As with any model, there are assumptions and limitations which keep the model from matching real-life fire propagation. While many of these limitations which relate to specific component models are discussed in the previous sections, some of the broader limitations of the current work include:

- **Scenario generation**. Currently, the model can take in different wind directions, wind speeds, grid maps (with different fuel, flammability, altitude, etc. distributions), sides to protect, and locations of firefighting infrastructure. However, it is limited in that it can only generate random maps using set parameters. To ensure that the response of the model generalizes to a variety of firefighting situations, it is important to be able to generate realistic scenarios. Thus, future work should determine how to generate realistic grid maps, and distributions for wind speeds and trajectories over time which will emulate a more generic modelling scenario.
- **Fire-line planning.** Currently, ground crews and engine crews work by creating a box around the edge of the map, with some priority given to gaps where the fire is closest to. While this response is effective and simple to implement from a modelling standpoint, a real fire crew might try smarter strategies, such as constructing fire-line closer to a side if it has time to do so or only constructing fire-line on the edge of the fire which is burning.
- **Weather and smoke.** Currently, the only attribute of the fire constituting weather in the model is wind, which is assumed constant throughout the simulation. However, winds are often what make fires most difficult to fight, due to their variability and ability to change the

ground conditions (many recent fires have been attributed irregularly dry winds). Additionally, smoke can hinder the ability of aircraft to conduct surveillance, perform drops, and operate in parts of the airspace around the fire. Thus, to better emulate some of the real challenges in aerial firefighting, whether needs to be incorporated through a dynamic changing wind, changing terrain flammability, and smoke attributes that prohibit aerial operations in certain locations.

- **Response effectiveness.** As described previously, several drop parameters (effectiveness, size, etc.) have been tuned to make the fire fightable in the nominal simulation. These parameters need to be made consistent with the real effectiveness of fire retardant to better model real firefighting scenarios. Additionally, while firebreak is assumed to be perfectly effective in this model, there are real firefighting scenarios where fires have jumped constructed fire-lines. The turnaround time for aircraft landing/refueling (a single timestep) is very fast, also. Thus, in addition to tuning tanker response parameters, firebreak effectiveness and aircraft travel/refuel time needs to be tuned to best emulate real firefighting situations.
- **Air traffic management.** Additionally, there is little modelling of important air traffic management considerations such as queuing, entry-exit from a given airspace, and conflicts between aircraft. This is an important modelling consideration for UTM, since the role of controlling the airspace is often performed by the aerial supervisor over radio, which would need to change to communicate with supply and surveillance UAVs (and UAVs performing other roles).
- **Faults.** Finally, while some faults are incorporated in this model, including major and minor mechanical failures and communications disruptions, future work needs to incorporate more faults to better represent the risks both to the response and to operators. Specifically, there are currently no modelled faults in UAV assets, which are a critical modelling consideration for understanding their effects to air resilience.

Nevertheless, this model can already provide some strategic insights for understanding aerial firefighting. As presented in the sections about tankers, helicopters, and ground and engine crews, it is clear that increased operational capability in terms of physical assets can lead to a more effective fire response. Additionally, as presented in the incident commander section increased communications capabilities (e.g. from increasing state information or removing communications lag) can increase the effectiveness of responders by helping them respond to the fire quicker and in smarter ways (e.g. by fighting more hazardous sections more aggressively). Future work should address the limitations identified here to better understand how changes to aerial firefighting infrastructure can affect response effectiveness and resilience.

References

Butler, C. R. (2015, July 31). Aviation-Related Wildland Firefighter Fatalities – United States, 2000-2013. *Morbidity and Mortality Weekly Report (MMWR), 64*(29), 793-796.

California Department of Forestry and Fire Protection. (2019). *Community Wildfire Prevention and Mitigation Report.* Sacramento, CA: CALFIRE. Retrieved from https://www.fire.ca.gov/media/5584/45-day-report-final.pdf

Department of the Interior and Department of Agriculture. (2020). *"Firefighting Equipment" in Interagency Standards for Fire and Fire Aviation Operations, Technical Report NFES 2724.* Boise, ID: National Interagency Fire Center.

Fernandes, P. A. (2001). Fire spread prediction in shrub fuels in Portugal. *Forest ecology and management 144*, 67-74.

Hulse, D., Walsh, H., & Zhang, H. (2020, May 15). *DesignEngrLab/fmdtools: v0.5.3-revision2 (Version v0.5.3).* Retrieved from Zenodo: http://doi.org/10.5281/zenodo.3828048

Hulse, D., Walsh, H., Dong, A., Hoyle, C., Tumer, I., Kulkarni, C., & Goebel, K. (2020, September 14). *fmdtools: A Fault Propagation Toolkit for Resilience Assessment in Early Design.* doi:doi:10.31224/osf.io/d48k6

National Wildfire Coordinating Group. (2014). *Wildland Fire Incident Management Field Guide, Technical Report NFES 002943.*

Rothermel, R. C. (1972). *A mathematical model for predicting fire spread in wildland fuels.* International Forest & Range Experiment Station, US Forest Service.

Sauvagnargues-Lesage, S. a. (2001). Experimental validation in Mediterranean shrub fuels of seven wildland fire rate of spread models. *International journal of wildland fire 10 (1)*, 15-22.

Topik, C. (2015, September 18). Wildfires Burn Science Capacity. *Science, 349*(6254), 1263.

Voiland, A. (2020, 9 9). *Historic Fires Devastate the U.S. Pacific Coast*. Retrieved from NASA Earth Observatory: https://earthobservatory.nasa.gov/images/147277/historic-fires-devastate-the-us-pacific-coast