Evaluation and Improvement of System-of-Systems Resilience in a Simulation of Wildfire Emergency Response

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Abstract—**Because of the increasing threat that wildfires pose, there is interest in leveraging new technologies to improve firefighting. Specifically, Unmanned Aerial Systems (UAS) and UAS Traffic Management (UTM) promise to improve firefighters' situational awareness, coordination, communications, safety, and strategy. While these technologies could be beneficial, there has been little formal investigation into how much benefit would occur and whether these benefits would outweigh hazards introduced by these systems. To better understand the impacts of these technologies, this paper presents a high-level dynamic simulation for evaluating wildfire response performance and resilience incorporating fire propagation, surveillance and communication, response planning, and the resulting mitigation actions. This simulation is then used to study the impact of communications and surveillance improvement, considering (1) the effect on fire containment and ground crew injuries and (2) the effect of introduced and existing disruptive fault scenarios. Simulating this model over a large number of scenarios finds that these changes can improve containment and reduce ground crew injuries. While these improvements generalize over both existing and introduced single-fault scenarios and thus result in a more resilient system, they could be negated if the introduced communications infrastructure is prone to full-scale outages.**

Index Terms—**Resilience, Systems-of-systems resilience, Systems-of-systems architecture, Systems Simulation, Multiagent Systems, Risk analysis.**

I. Introduction

WILDFIRES have been increasing in size and frequency over the past several decades [1], caused primarily by climate change-driven growth in wildfire-conducive weather patterns (i.e., droughts and aridity) [2], and secondarily by factors related to forest management [1]. Simultaneously, the wildland-urban interface in the United States has grown as a part of overall U.S. population and land use trends [3], leading to catastrophic fire seasons. For example, the 2018 fire season resulted in $148.5 billion in total (direct and indirect) economic losses to the state of California–roughly 1.5% of state annual GDP [4]. This was followed by the record-breaking 2020 fire season, which endangered wildfire interface communities and reduced air quality across the west coast [5].

Stakeholders now recognize the importance of building resilience into communities to prevent and mitigate the hazardous consequences of wildfires [6]. Because of the exploding cost of fire suppression, there has been a shift in focus from solely fighting fires as they occur towards using preventative forestry and land use strategies to better prepare communities for wildfire events [7], [8], [9]. While this focus on prevention is a necessary aspect of making communities more resilient to wildfires, improving suppression tactics can also ensure hazards are optimally mitigated during response operations. Given the current state of wildfire suppression technology, there is significant opportunity to lower suppression costs and fire damage by increasing response effectiveness. Current operations rely on trusted but technologically unsophisticated approaches for surveillance, communications, and fire containment–relying primarily on human pilots and radio communications. Given recent advancements in communications and flight technologies, there is now an opportunity to use Unmanned Aerial Systems (UAS), UAS Traffic Management (UTM), and other technologies to increase situational awareness and planning, take on missions that would otherwise be infeasible, lower pilot danger, and increase overall resilience [10], [11], [12]. Given the relative newness of Unmanned Aerial Vehicle (UAV) technologies (and of this application) and the complexity of the system-of-systems (SoS) environment, the magnitude of impact these technologies could have is unclear, both in the short and long term. Thus, to understand how best to improve the resilience of wildfire response tactics, it is important to assess the impact of these technologies when integrated in the overall SoS in terms of their effects on effectiveness, safety, and resilience.

This is challenging. Unlike a traditional engineered system made of discrete parts, the systems which make up a SoS are more independent and decentralized [13], making their behaviors more difficult to predict and control precisely [14], [15]. This makes it difficult to assess the performance impacts of new technologies, since the connection between subsystem and system performance is less direct. As a result, to design these systems it is often necessary to use models which can range from conceptual diagrams to dynamic, executable simulations of SoS behavior [15]. Simulations can additionally be used to evaluate not just the direct performance impacts of design changes, but the indirect performance effects of the resulting changing operations, which can inform trade assessments in the early design process [16], [17]. Incorporating resilience in SoS also requires using a specialized framework to efficiently consider how the SoS responds to disruptions. Interdependency analysis [18], [19], network simulation [20] and formal methods [19] have been put forward to model resilience, while the use of system importance measures [21], and genetic algorithms [22] have been proposed for resilience-based design. However, these approaches were not developed for disaster response, where the resilience of the system to the ongoing disaster is as much a consideration as its resilience to a fault scenario. Thus, there is a need for a modeling approach to jointly consider resilience in both nominal and off-nominal conditions to best understand and improve the resilience of SoS in disaster response applications.

SoS modelling of wildfire response operations is a new and open research area, thus prior work in this area is limited. In contrast, physics-based fire propagation models without SoS dynamics or suppression operations were first established in 1972, and most wildfire simulations created before the early 2000s focus on the behavior of the fire itself [23], [24], [25], [26], [27], [28], [29]. Integrated wildfire propagation and containment modeling was first presented in 2008 with the DEVS-FIRE model, however, this work did not evaluate the effect of different containment strategies [23], [26]. Since 2010, Wildfire managers in Canada rely on Prometheus, a deterministic vector propagation model which accounts for fire breaks [30]. In 2015, geographic information systems (GIS) coupled with existing physical fire models were used to evaluate how different fire break locations effect fire spread [31]. More recently in 2019, Deng and Liu highlighted potential benefits of UAVs in fire response using a back-propagation model, however their modelling focused on rescue tasks, rather than firefighting [10]. Seraj et al. developed a high-level combined model of fire propagation and UAS response in 2020, yet their work focused mostly on using it as a testbed for reinforcement learning algorithms, rather than for evaluating technologies [32]. In 2021, Chakrabarty and Ippolito developed a simulation of fire propagation and response to show how future UAS/UTM wildfire systems could operate, but this model was limited to firefighting in a single type of fire and did not compare performance [12]. Simultaneously, GIS-based simulators were developed to evaluate the impact of suppression, yet these models only included conventional manned aerial assets and no ground crews [33]. Finally, Pakasha et al. developed a SoS model (using the SoSID simulation framework [34]) of aerial firefighting and used it to evaluate a number of design and operational concepts for UAVs by varying fleet size, vehicle architecture, carrying capacity, response time, and cruise speed in 2021 [35]. While this framework was able to address important performance-related considerations in aerial firefighting, it did little to address the resilience of the SoS to disruptions, an important consideration when the mission is inherently hazardous.

A. Contributions

The goal of this work is to understand the performance and resilience impacts of technological improvements in wildfire response. Specifically, the aim is to study how incorporating UAVs and more advanced communications technologies can effect firefighting effectiveness and resilience. Rather than only conceptualize how these technologies can improve situational awareness and planning, a simulation can not only quantify how and to what extent they help, but also assess the impact of adverse interactions or fault modes that these technologies introduce. Towards this goal, this paper makes two contributions. First, it presents the System Modeling and Analysis of Resiliency in Scalable Traffic Management for Emergency Response Operations (or, SMARt-STEReO) model–a high-level, integrated, and parameterized simulation of fire propagation and response, which includes fire propagation dynamics, coordination and planning, aerial firefighting, and fireline construction. Second, it uses this model and a nested fault sampling approach to study how decreased communications lag and increased surveillance effects both firefighting performance and resilience over a wide range of nominal and fault scenarios encountered in firefighting response operations. Results suggest decreased communications lag and increased surveillance result in less fireline breaches and injuries across both nominal and faulty conditions. While the system is resilient to external faults and faults introduced by the surveillance aircraft with negligible impact on performance, large-scale communications outages pose a threat. The next sections provide background on wildfire response operations and resilience assessment (Section II), introduce the SMARt-STEReO model (Section III), present the assessment approach and results (Section IV), and summarize the conclusions and limitations of the study (Section V).

II. Background

To contextualize the development of the model, the next sections present the related background, concepts, and prior work in resilience assessment and wildfire response literature that informed this work.

A. Wildfire Response Operations

Wildfire response involves containing a fire by constructing areas of nonflammable material known as firelines in the path of the fire. Personnel form firelines by removing flammable material in the path of the fire, thus preventing the fire from spreading further. A fire is considered contained when firelines are constructed along the entire perimeter. The response is comprised of ground and aerial assets that cooperate to achieve this goal, while adjusting to changing fire conditions [36]. In this context, response planning is managed by an incident commander on the ground who identifies key strategic areas and assigns assets to targets [37]. These targets are relayed to the aerial supervisor, who is effectively an airborne air traffic controller positioned at the top of the fire traffic area (FTA) [38], managing the mitigating actions of individual pilots [38]. For large fires, aircraft coordinate with and support ground operations by performing reconnaissance, aerial ignition, crew and supply transport, and water and retardant drops [39], while ground crews construct the firelines. Wildfire response's inherent system-of-systems architecture means that ground and aerial operators have to communicate frequently to relay information and communicate objectives, a process which can consume a significant amount of attention in large operations [36].

Wildfire suppression requires understanding the inherent risks involved in operations to best protect operators while effectively containing the fire. While the safety of fire fighters is considered to be a major priority, firefighters are subject to hazards from a variety of sources [40], including environmental conditions, human factors, mission-specific aircraft and machinery configurations [41], and operational conditions [38]. Fire fighting difficulty has been quantified using the Suppression Difficulty Index (SDI) [42], which can be used for risk-informed decision-making [43] and has been applied in real operations in both the United States and Spain [44]. While each wildfire incident presents unique challenges, general factors which effect suppression difficulty include ignition and dynamics of the fire (e.g., wind speed, slope, flammability) and the ability of the response to take effective mitigating actions (e.g., ground crew mobility, area accessibility, availability of aerial resources) [42]. Suppression operations are particularly dangerous, with the 2020 fire season resulting in fifteen entrapment incidents, seven hit-by-tree incidents, six vehicle rollovers, six instances of vehicle fires, and fifteen fatalities, 60% of which were due to aerial accidents [45]. To manage the complex nature of risk in wildfire operations, there are both real-time[46] and predictive [47] spacial-temporal risk-informed analytic tools to aid in decision-making. While existing tools are useful, there are major knowledge gaps in risk-informed decision making for wildfire response: there are little data about how management decisions and actions can lead to specific firefighting outcomes [48]. Advances in real-time state-awareness technology, data collection, storage, and distribution systems, as well as system analysis methodologies, could help close these gaps and improve fire response decision making [49].

The availability of new technologies provides several opportunities to improve wildfire response [11], [36]. UAS are currently used in wildfire response to collect data and increase ground crew situational awareness [50], however, these applications are limited. For instance, currently, portions of the airspace are cordoned off with a temporary flight restriction (TFR) prior to UAS use, rather than UAS directly coordinating with other aerial assets [50]. UAS Traffic Management (UTM) [51] has the potential to enable new and more integrated ways of leveraging UAS [11], [36]. The Scalable Traffic Management for Emergency Response Operations, or STEReO project, envisions both autonomous UAS and UTM being integrated in the response [11] to increase communications bandwidth and enable new UAS missions such as logistics delivery and aerial ignition [11], [36]. Increased communications and situational awareness are of particular interest to stakeholders [52]. However, response personnel are hesitant to adopt new technology without proven benefits, safety, and robustness/resilience [52]. The SMARt-STEReO model presented here was developed to enable the evaluation of these benefits.

B. Resilience Assessment

Resilience is a broad topic which has different meanings in different fields of study. For the purpose of this paper, there are two major types of resilience of interest: disaster resilience–the resilience of a community to a catastrophic event–and engineering resilience–the resilience of a system to hazardous scenarios. Disaster resilience research generally focuses on the ability of a community (i.e., a city) to mitigate and recover from the consequences of a defined disaster of interest, such as an earthquake, hurricane, or wildfire [53]. In general, disasters like this have wide-ranging effects to infrastructure [54], [55], health and safety [56], social and psychological behavior [57], governance and institutions [58], and economic activity [59]. Because of the complex socio-technical interactions that happen post-event, a complete assessment of community resilience often requires a holistic approach encompassing all of these attributes [60]. However, the infrastructure and engineering perspective toward disaster resilience–which is more relevant to this work–is much more limited to the direct protection and restoration of physical assets and processes (e.g., infrastructure, safety, etc.) [61].

Aside from disaster preparation resilience can further be an important property to maintain a system's overall function in the face of disruptions. While many different definitions of resilience have been forward [62], [63], and there is an ongoing discussion about the relationship between risk and resilience [64], [65], the underlying concepts behind different resilience frameworks are similar. Broadly, *engineering resilience* is a system's ability to prevent and mitigate hazards, which can include reliability, robustness, recovery, and reconfigurability [66]. This resilience can be conceptualized readily using the resilience triangle shown on the right side of Figure 1, which visualizes how the system performance degrades and recovers from a disruption [67]. Because resilience is a property of the system which mitigates hazards, in many cases the resilience of the system can be measured in an overall risk framework, which yields a precise measure of improvement [68] and enables trade-offs in decision-making [69] (though a risk framework is not required to perform these trades, see: [70], [71], [72]). However, the resilience perspective extends traditional risk quantification approaches to deliberately consider the system's dynamic hazard response so that one can develop the inherent properties (see:[73]) necessary to mitigate unknown hazards [64], [74].

To enable one to conduct this engineering resilience-informed risk assessment, previous work developed the fmdtools toolkit and methodologies, which enable the simulation of a system under nominal and faulty scenarios [75]. The fmdtools toolkit is an object-oriented open-source python package for building resilience simulation models. While fmdtools has previously been used to model systems such as water pumps, multi-rotor aircraft, and power systems, until now it has not been used for complex system-of-systems simulations like wildfire response. Models in fmdtools are made of two main classes: functions, which define the components and their respective behaviors, and flows, which represent attributes passed between or shared by functions. Simulating a model thus runs the methods defining behaviors over a set of time-steps or until a specified end-condition is met. To quantify a system's resilience, sets of fault modes are injected in the model at specified times to simulate the dynamic response of the system to these potential hazardous scenarios, as shown in the lower-left part of Figure 1.

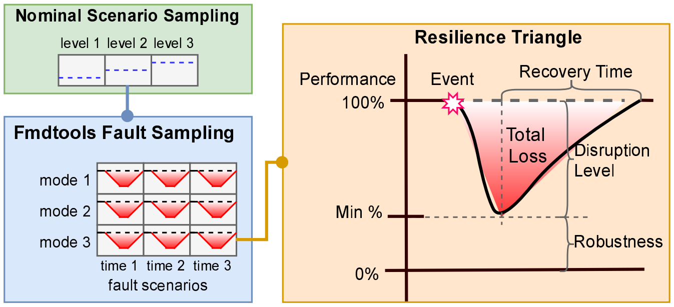


Fig. 1: Resilience sampling approach developed in this work. Faults are sampled to determine resilience while operational scenarios are sampled to determine performance generality.

One limitation of this approach has been that it considers the main source of hazards to be from individual defined faults. While this is applicable to systems where the operational situation is controlled, it is less applicable to the disaster response model presented in this paper, where the nominal (but stochastic) behavior of the disaster itself may lead to hazards. This situation is analogous to Type 1 Robust Design (see: Ref [76]), where the goal is to design the system so that the performance is robust to noise factors (e.g., choosing the technologies which will most consistently contain a wide set of different wildfires). To better consider hazards inherent to a wildfire response mission, this work extends the fmdtools simulation methodology by nesting the simulation of faults within operational scenarios, as shown in Figure 1. Instead of simulating a single nominal scenario, a set of nominal scenarios across levels are simulated to assess the system's resilience to a range of wildfires. In this work, we examine different levels of containment difficulty as levels of nominal scenarios, where difficulty is defined by the average rate of fire spread. Doing so in this emergency response model combines the notions of engineering disaster resilience (the response of a system to a disaster situation like a flood or wildfire) with engineering fault resilience (the response of the system to fault modes). Hence, this research both utilizes the existing fmdtools toolkit to build a novel wildfire response model while extending fmdtools' resilience analysis framework to consider internal (fault-induced) and external (situation-induced) hazards.

III. The SMARt-STEReO Model

The System Modelling and Analysis of Resiliency in Scalable Traffic management for Emergency Response Operations (SMARt-STEReO) model was developed to better understand the complex behavioral dynamics involved in wildfire suppression [77], [36]. For simplicity of demonstration, the overall mission was chosen to model a basic firefighting training exercise, with a 2000x2000 meter grid environment with flat grass/shrubland fuel properties. Based on the known times for the single-timestep operations (grid surveillance and communications, fireline construction, water drops, etc.) modeled this environment, the model time-step was determined to correspond to eight minutes of firefighting time. To ensure model

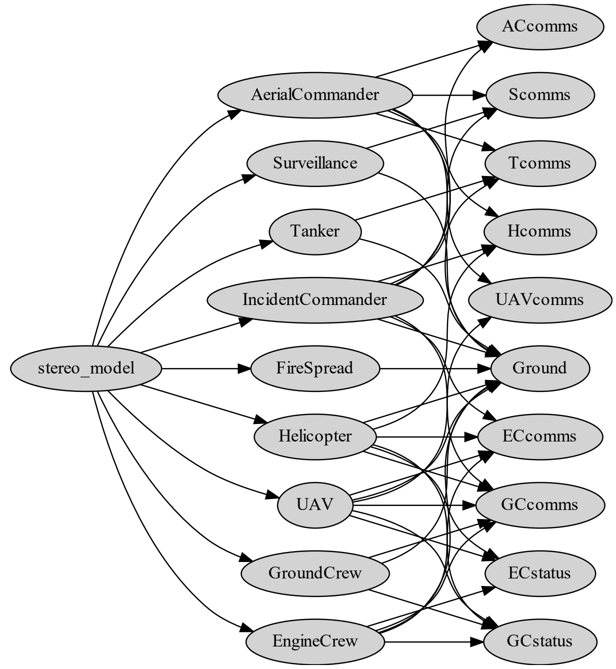
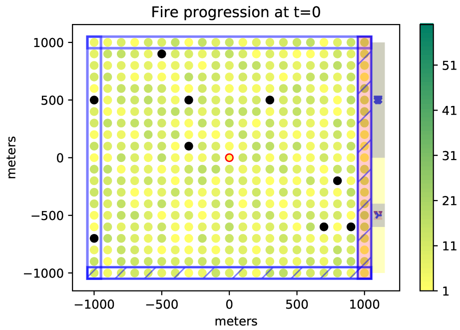


Fig. 2: SMARt-STEReO model classes defining functions (second column) and flows (third column)

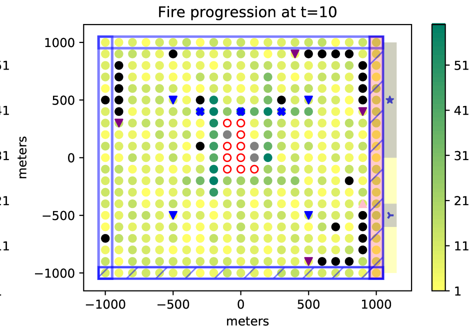
validity, the corresponding assumptions for these operations (and fire propagation) were tuned to match existing data, literature (when available), and external subject matter expert consultation, and the model was tested for software flaws.

The SMARt-STEReO model captures three major parts of wildfire response–the propagation of the fire over time, the planning of firelines and other response efforts, and the actions of ground and air-based assets which execute these efforts. These assets and their behaviors were implemented as functions and flows in fmdtools, as shown in Figure 2. Among the model functions shown in the middle column, the response assets include the incident commander, aerial commander, tanker aircraft, helicopters, ground crews, engine crews, UAVs, and surveillance UAVs. Communication lines are shown in the right column of Figure 2 and connect different assets to each other to carry information about current locations and operational modes.

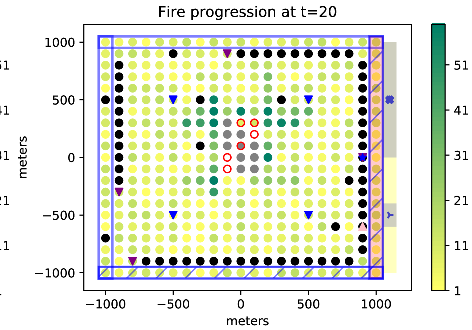
The incident commander uses ground information (Ground in Figure 2) sent from the aerial supervisor (ACcomms) and surveillance aircraft (Scomms) [11], [12] to identify high-priority gaps in the fireline based on the proximity of the fire to valued locations, such as a city. Then, the incident commander assigns ground (GCcomms) and engine crews (ECcomms) to these gaps. Gap locations are also used to determine threats communicated to the aerial supervisor (ACcomms), who then relays drop locations to tankers (Tcomms) and helicopters (Hcomms). Ground crews and engine crews are assigned logistics deliveries by UAVs (UAVcomms) [11] when their supply levels (GC/ECstatus) drop below a critical threshold, or transitioned to a rest mode when fatigue levels (GC/ECstatus) rise above critical threshold. Depending on the scope of the analysis, the SMARt-STEReO model can be run



(a) t=0



(b) t=10



(c) t=20

Fig. 3: Grid flammability (time-to-ignition) at progressive simulation times. Each time-step is eight minutes.

in different configurations specifying the type of scenario, the characteristics of the fire, the type of response, and the faults to be used. Both the characteristics of the fire (e.g., map property distributions, wind speed, place locations, sides to protect) and the response (e.g., communication delays, the degree of state awareness, the quantity of each asset, the size of tanker drops, etc.) can be adjusted as parameters prior to simulation.

As shown in Figure 3, fire propagation is modeled using a grid of points, where each point has numerical properties for *flammability*, *fuel*, *fuel type*, and *altitude* which dictate quickly how the fire spreads over time. A point ignites after adjacent points are on fire for $t = time$ number of evaluations (4 per time-step), where a low $time$ (i.e., high flammability) results in a fast-spreading fire, and a high $time$ (i.e., low flammability) results in a slow-spreading fire. Different maps with varying characteristics (i.e., *time, fuel*) may be generated with uniform, random, and other procedurally-generated property distributions. These property distributions can further be specified by changing their parameters–in the case of this study, for example, `ave_time` is used to specify the average sampled *time* value for the map. In the simulation in Figure 3, all four sides are designated to be protected (grey boxes), with priority (red) given to the right side, and engine crew accessible-sides on the right and bottom edges (blue diagonal lines). In this simulation, the fire begins at $t = 0$ at the center of the grid and is marked by point with a red outline. As the fire progresses at $t = 10$ in Figure 3b and $t = 20$ in Figure 3c, suppression efforts are visible, including fireline construction (black dots with ground/engine crews as purple/pink triangles, respectively) at the edge of the grid, surveillance aircraft in place in the four quadrants of the grid (blue triangles), tanker drops (bright green dots around the fire) and tanker/helicopter aircraft (blue "X"s). Later in the simulation, parts of the fire have burned out (grey dots in the middle of the fire). This illustrates a suppression effort that will be completed successfully, since the fire has not advanced close to the firelines, and a significant amount of construction has been completed. When the firelines are completed or breached, the simulation is terminated. If the simulation runs for the entire time limit (60 in this work) the simulation is terminated and the results are classified as a breach or completion based on the progression of the fire and status of response assets. Injury occurs if ground or engine crews get too close to the fire (after taking evasive action).

A. Experimental Approach

Simulating the model in different configurations until the mission is completed or failed forms the basis of the experiment. To evaluate the performance and resilience of possible responses simultaneously, it is desirable to compare them over a wide range of performance-affecting parameters to ensure that the comparison generalizes. This is accomplished using the nested test approach shown in Figure 1, in a test that involves multiple design factors, which are the types of responses being compared, difficulty factors, which specify the type of scenario (e.g., flammability), and replicates, which are scenarios (i.e., maps) generated for sets of given design and difficulty factor levels. The resulting experiment used to evaluate the performance of the system has $c{*}d{*}r$ simulations, where c is the number of designs to compare, d is the number of difficulty levels, and r is the number of procedurally-generated map replicates. When the simulations are completed, the average performance P over the set of operational scenarios O can thus be calculated as

$$P = \underset{O}{\mathbb{E}}\{M\} \tag{1}$$

the expected value of these performance metrics of interest over the set of simulations. In this simulation, the metrics of interest M are fireline breaches, breach/completion time, injuries, and number of injuries.

Resilience quantification further extends this approach by simulating each replicate over a set of hazardous scenarios S defined by faults F injected at potential fault times T. This results in an experimental size of $c * d * r * f * t$, where f is the size of the set of fault modes F and t is the corresponding number of fault-injection times T, which results in a much more computationally-expensive experiment than the performance evaluation. The resulting average performance defining the resilience R to fault scenarios is

$$R = \underset{O,S}{\mathbb{E}}\{M\} = \underset{O}{\mathbb{E}}\{\underset{S}{\mathbb{E}}\{M\}\} \tag{2}$$

where M is the response metric (in this case, fireline completion and injury variables). Note that in the literature, resilience metrics are often calculated in terms of the nominal performance–instead, in this work we provide the operational

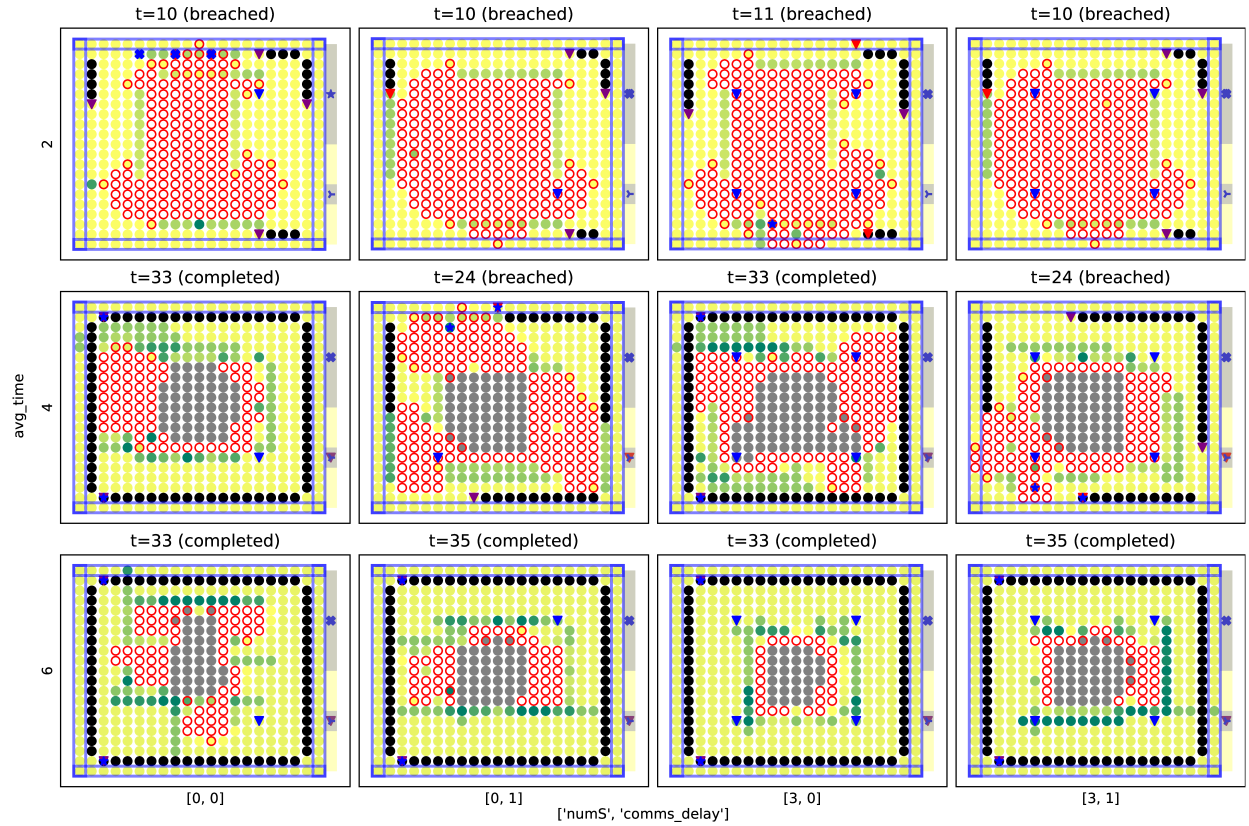


Fig. 4: Final frame of encircling simulations over a range of difficulties and interventions

and faulty performance separately to better represent the comparison of design factors in the nested approach. Additionally, while the underlying distribution of fault rates are unknown in this work, this expected performance metric gives one a distribution-free idea of how the system performs, i.e., the average resilience of the system to the set of faults.

IV. Computational Experiment

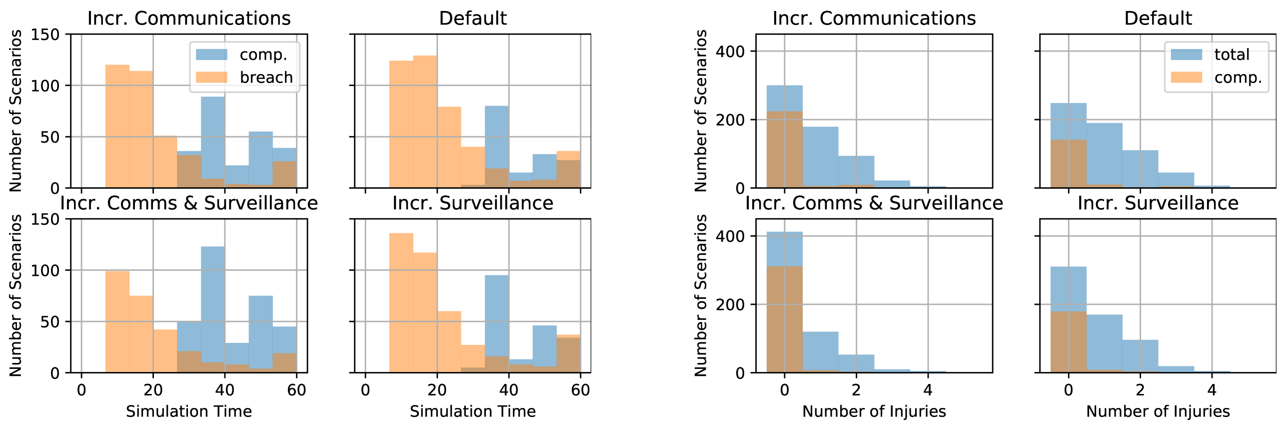
The goal of this experiment is to better understand how improved communications and surveillance can improve the performance and resilience of aerial and ground wildfire response operations. This section uses the firefighting model and experimental approach developed in Section III to quantify and visualize the effect of these changes over a variety of operational circumstances and fault scenarios. Of particular interest is the ability of increased communications and surveillance to affect operational performance (the ability of the SoS to complete firelines) and ground crew safety (injuries), how these effects are influenced by difficulty, and how these effects are further affected by fault scenarios. These changes are represented as four different designs in the experiment which are constructed by changing the `numS` (number of surveillance UAVs) and `comms delay` (lag in communicating fire position):

- Default (0,1): The "present state." There are no surveillance UAVs (meaning only the quadrant of the map that the aerial supervisor covers is communicated) and there is lag due to information being relayed manually between the aerial commander and the incident commander.
- Increased Surveillance (3,1): The number of UAV surveillance planes is increased to three, giving the incident commander more constant information about the map and position of the fire. To achieve this, three UAVs are instantiated in the model that send the remaining quadrants to the incident commander.
- Increased Communications (0,0): The lag due to manual information relay is removed, meaning that the map information relayed to the incident commander by the aerial supervisor and other surveillance assets is always current. This is implemented in the model by making the surveillance assets send updated map information to the incident commander at each (instead of every other) time-step.
- Increased Surveillance and Communications (3,0): The number of surveillance planes is increased to three while the communications lag is reduced, meaning that the incident commander always has a current view of the grid (i.e., implementing both (3,1) and (0,0) model changes.

To examine the general performance and resilience of these designs, they are compared over differing fire spread rates (`ave_time`) and procedurally-generated maps.

A. Effect of Fire Spread Rate on Performance

Prior to evaluating performance, it is important to first understand how the spread rate of the fire (a set difficulty factor in the experimental approach) effects the containment of the fire. To do this, the model is run over a range of



(a) Performance effect (b) Effect on injuries

Fig. 5: Effects of design factors in tested nominal scenarios. Each time-step in the simulation is eight minutes.

spread rates to examine how the simulation unfolds. For the purposes of this visualization, the uniformly-distributed map at the different average flammability levels is used to provide a consistent comparison of the different designs factors. The final frame of these simulations over a uniformly-distributed map is shown in Figure 4. As shown, there is very little difference in the response of the designs to high-difficulty fires at `ave_time`= 2–while the responses with less communications lag enable firecrews to start their firelines earlier, this does not result in a completed fireline because the fire spreads too quickly. On the other hand, in the low-difficulty scenario where `ave_time`= 6, all responses are able to capably complete the firelines and contain the fire. In these cases, the fires spreads slowly enough that improved surveillance and communications do not make a marginal difference, other than completion time (less communications lag means that the firelines are constructed two time-steps quicker).

In contrast, consequential differences in fireline construction and fire spread are readily observed when there is a moderate fire difficulty (`ave_time`= 4). In these scenarios, the reduction of communications lag results in completed firelines which contain the fire, while the other responses are not able to complete the firelines before the fire escapes. This helps one understand the effects of technology improvements in the complex, dynamic system-of-systems scenario of wildfire hazard response: a technology may not improve fire containment in every possible scenario, but it will change the distribution of fire containment over the set of scenarios by making some fires containable which would not be otherwise. Thus, the next sections will study how these designs affect performance and resilience by evaluating how they change the distribution of successful fireline completions.

B. Performance Evaluation

To compare the performance of the designs, the corresponding models are simulated over a range of difficulties (`ave_time` of 2-6), with 100 procedurally-generated maps at each level to ensure adequate statistical power while minimizing computational cost. The resulting distribution of fireline breach and completion times is shown in Figure 5a, with a quantitative description in Table I. As shown, the decrease in communications time leads to substantial decreases in breached fire-lines (19%), with a more modest decrease when adding in increased surveillance (8%). When both surveillance is increased and communications time decreased, 27% fewer scenarios result in fireline breaches when compared to the default design. To evaluate if observed differences in the distribution of fireline completions and breaches between the design factors are due to noise or statistically significant, we first use a χ^2 independence test. The χ^2 test evaluates the likelihood of independence of two categorical variables, in this case design scenario (default, increased surveillance, increased communications, both increased communications and increased surveillance), and fireline end result (breach or completion), by analyzing the difference in expected and observed frequencies of each class. If the two variables are independent, then the differences should follow a χ^2 distribution for the given degrees of freedom (df). The test indicates there is a significant difference in the number of completions and breaches across the design factor levels ($\chi^2 = 106.9$, $p < 0.00001$, $df = 3$), and thus the design impacts the frequency of fireline completions and breaches.

The statistical merit of individual effects can further be evaluated using the confidence intervals in Table I constructed using the bootstraping method. In general, the effects on fireline completion for each of the designs (and the combination) appear to be significant at the 95% confidence level. However, while increasing surveillance and decreasing communications time appears to lead to a marginally faster average fireline completion time, the margin is negligible. Between designs, the distributions of times do not have equal variances, equal sample sizes, nor share a normal distribution, thus the conventional ANOVA is not appropriate. Instead, a non-parametric Welch ANOVA test, which uses weights to counter-act unequal variances, was conducted, and found no significant difference in average fireline completion time between the designs ($F = 2.13, p = 0.09$). Thus increasing surveillance and communications decreases the number of fireline breaches, but does not decrease completion time.

Similar effects are seen for injuries in Table I and Figure 5b,

TABLE I: Descriptive statistics across design factors.

Value	Statistic	Incr. Comms & Surveillance	Incr. Communications	Incr. Surveillance	Default
Injuries	% of Scenarios w/ Injuries 95% C.I.	31.403 (27.667,35.167)	50.013 (46.0,54.167)	48.351 (44.333,52.333)	58.722 (54.833,62.667)
	Total Injuries 95% C.I.	0.46 (0.346, 0.573)	0.755 (0.653, 0.857)	0.732 (0.629, 0.835)	0.955 (0.851, 1.059)
Breaches	% of Scenarios w/ Breach 95% C.I.	46.383 (42.5,50.333)	59.816 (56.0,63.671)	67.81 (64.333,71.5)	73.668 (70.163,77.0)
	Completion Time 95% C.I.	42.009 (41.014, 43.004)	42.622 (41.425, 43.819)	43.839 (42.605, 45.073)	43.677 (42.266, 45.088)

which show the number of firecrew injuries across the full range of simulations. To determine whether the injury effects are significant in a way that is robust to the underlying distributions, we again use a Welch ANOVA test. This test finds a significant difference in the mean number of injuries between the four designs ($F = 32.3, p < 0.00001$). Post-hoc analysis shows that increasing both surveillance and communications results in a significantly lower mean number of injuries when compared to the default design ($T = 9.50, p < 0.001$). Increasing communications speed or surveillance alone had a modest effect on the distribution of injuries. When compared to the default design, there is a slight decrease (18%) in injuries due to increased surveillance alone. Decreased communications lag alone results in slightly fewer (15%) injuries than the default design and increased surveillance alone, since firecrews are given more recent information about when to escape an approaching fire. However, when both communications speed and surveillance are increased, the distribution changes considerably, with a much larger decrease (46%) in simulations with injuries. This is for two reasons: First, the decreased lag enables crews to complete their firelines more frequently, making them less likely to get close to the fire–this is reflected in the number of times the zero-injury scenarios are also full fireline completion scenarios. Second, the reduced lag combined with the increased surveillance give the crews more accurate and timely information about when the fire is approaching, allowing crews to more easily escape in time.

C. Resilience Evaluation

There are two major resilience-related considerations of interest in this study–the impact of possible faults introduced or removed by new technology, and the technology's effect on external fault scenarios (e.g., mechanical faults in helicopter or tanker aircraft, necessary delivery to ground crew) which the system must encounter and respond to. To understand the engineering resilience of the studied technologies, the following section evaluates three main considerations for each design over the same set of operational scenarios (difficulty levels and maps) considered in the performance evaluation: fault scenarios introduced by the surveillance asset, the potential for introduced high-severity communications failures, and the impact of the new response on existing fault scenarios. Based on this evaluation, one can then decide whether the performance and resilience improvements given by these technologies are worth the potential risks associated with their introduction.

1) Introduced Surveillance Faults: To first evaluate the resilience of the system to faults introduced by surveillance aircraft, four main faults were identified for simulation: minor mechanical failures, tracking position faults, degraded navigation faults, and major mechanical failures. The overall effect of major mechanical failures is to take the asset out of commission for the duration of the simulation, while the other faults take the asset out of commission for two time-steps. To evaluate these faults efficiently, the single-fault scenarios were simulated in the surveillance aircraft in three fault injection times evenly-spaced in the nominal simulation interval. The results of this evaluation are shown in Figure 6 and summarized in Table II, for both design levels where the surveillance planes are added. As shown in the effect on fireline completion, there is no change over any fault, indicating that there is enough redundancy in surveillance planes that taking one out of service for any period of time does not have a substantial impact. This is additionally true with injuries, where the changes in proportion of scenarios with injuries are well within the confidence interval for the nominal scenario. In summary, neither major nor minor surveillance single-fault scenarios have a substantial impact on fire containment or injuries and thus the risk posed by these faults is minor compared to the overall performance effects. These effects (like all studied here) may change given a different firefighting situation where there are fewer UAVs, a larger map, or lower overall visibility.

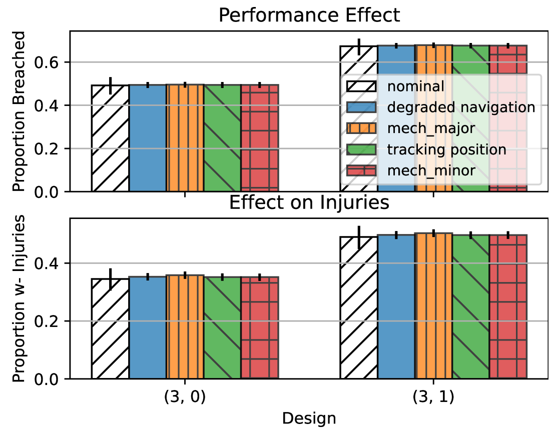
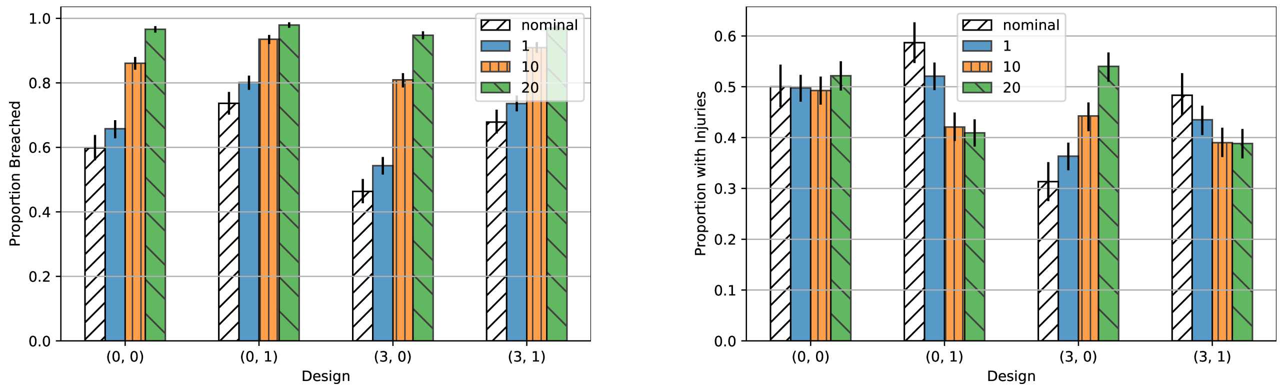


Fig. 6: Resilience of responses to introduced surveillance faults

2) Introduced Communications Faults: One important consideration in changing firefighting communications technology is the possibility of it increasing the susceptibility of the system to large-scale communications outages. Currently, since communications are mostly handled directly between each asset via self-powered radios, there is very little risk of a total loss of communications for all assets. However, switching to new communications technology could change this if the overall architecture changes from a direct, peer-to-peer communications model to an indirect, client-server communications model. In this case, a failure in the server could result in loss of communications for all assets. In this section, this risk is evaluated by testing the design factors to a total loss of communications for all assets, at different



(a) Performance effect

(b) Effect on injuries

Fig. 7: Resilience of responses to total communications disruption

levels of disruption: 1-time-step, 10 time-steps, and 20 time-steps. While it is unexpected that current operations (without increased communications) will be susceptible to this type of fault scenario, they are also evaluated here for reference. This is done by simulating each disruption at three different evenly-spaced times in the nominal simulation interval.

The resilience of the responses to this type of fault is shown in Figure 7 and summarized in Table II. As shown, increasing the amount of disruption time increases the effect that the faults have on the response, with longer disruptions resulting in a breach of the fireline in every case. As shown, in a minor disruption case (where the disruption is resolved in one time-step), the improvements in the nominal scenario from the increased surveillance design (i.e., (3,1)) compared to the default design (i.e., (0,1)) are erased, while the benefit of improved communications (i.e., (0,0)) is made more modest. Similarly, the performance reduction for the combined improvements (i.e., (3,0)) in a low-severity disruption still outperforms the default design in the nominal scenario, an improvement which disappears for longer disruptions. The injury trends are less clear. Interestingly, all designs except the increased communications and surveillance design have fewer injuries in fault scenarios than the nominal scenarios. Upon examination of the breach data, this is likely because the communications failure interrupts deployment of ground crews to firelines (putting them in less danger) and makes early fireline breaches (where the simulation may end before a ground crew is put in danger) more likely. However, the same general trend holds for the designs with increased communications–injury improvements are reduced in these fault scenarios but not fully erased. Thus, while the introduced technological improvements would offer no improvement on the basis of fireline construction or injuries if they resulted in these high-severity failures occurring often, they could still decrease ground crew injuries.

3) External Fault Impact: Finally, it is important to also consider how the design factors are affected by externally-driven failure scenarios–that is, scenarios which are not related to the change in communications or surveillance technology. Three main types of faults are considered here:

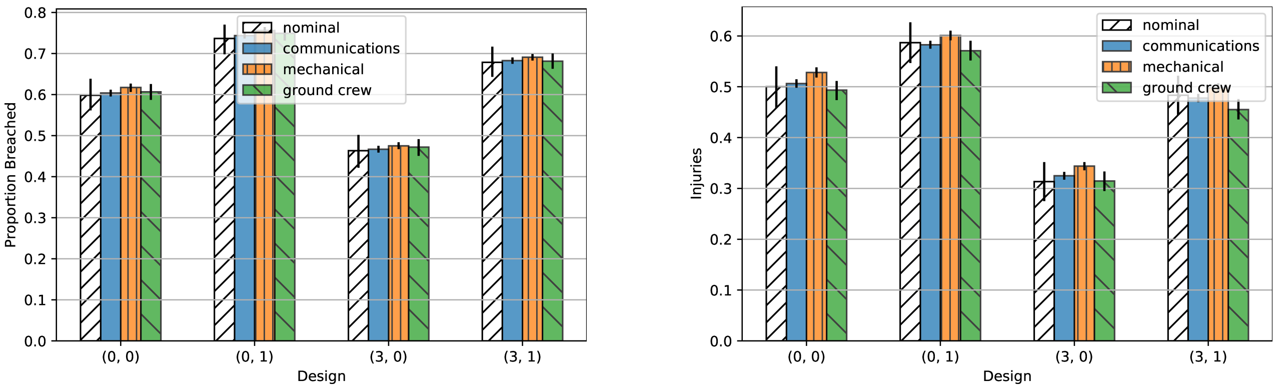
- Communications faults, which result in a disruption of communications to and from an individual asset;
- Mechanical faults, which result in an asset being taken out of commission for 5 time-steps (minor) to the entire simulation (major); and
- Ground crew faults, which slow individual ground or engine crews or cause them to return to base to recover.

Because the number of unique fault scenarios is high, only the single-fault scenarios were simulated at a single injection time to reduce computational expense. As shown in Figure 8 and Table II, these faults generally have a low impact. While there is a small increase in the distribution of breaches for communications and mechanical faults, it is dwarfed by the nominal performance effect. This is also the case for injuries, with small increases in each design factor that are within the pre-existing range of performance variability in the nominal scenarios. In summary, the performance effects of the technologies generalize over single-fault scenarios, meaning that a more effective response also results in response that is more resilient to known faults.

D. Discussion

The approach taken here examined how better communications and surveillance capabilities can improve wildfire response while highlighting technological challenges. Unlike typical missions envisioned for UAS and UTM technologies (e.g., mapping, delivery service, etc.), the "nominal" mission in aerial firefighting is inherently hazardous: communities and firefighters are both put in danger if a fire unexpectedly changes direction. Since the operational context is highly variable, the impacts of these technologies are best understood not in terms of their performance improvements in any single context (which may not generalize), but in terms of the improvement of the outcome distribution. A resilient wildfire response strategy in this setting requires considering both the resilience to fault scenarios (i.e., engineering resilience) and to the dynamics of the fire (i.e., disaster resilience).

The case for technological improvement in aerial fire response is premised on improving fire containment and operator safety. As shown in Figure 5a, increased surveillance and reduced communications lag can increase the performance of wildfire response over a range of fire scenarios, with the best improvement coming from the combination. In general,



(a) Performance effect

(b) Effect on injuries

Fig. 8: Resilience of responses to external fault scenarios

TABLE II: Resilience of the design factors to the three tested types of faults.

Type	Fault	Incr. Comms		Incr. Comms & Surv.		Default		Incr. Surveillance	
		Breach	Injury	Breach	Injury	Breach	Injury	Breach	Injury
Nom.		0.61 (0.59,0.63)	0.49 (0.47,0.51)	0.47 (0.45,0.49)	0.31 (0.3,0.33)	0.75 (0.73,0.77)	0.57 (0.55,0.59)	0.68 (0.66,0.7)	0.46 (0.44,0.48)
Surv.	Major	N/A	N/A	0.46 (0.45,0.47)	0.33 (0.32,0.34)	N/A	N/A	0.68 (0.67,0.69)	0.50 (0.45,0.52)
	Minor	N/A	N/A	0.46 (0.45,0.47)	0.33 (0.31,0.34)	N/A	N/A	0.68 (0.67,0.70)	0.50 (0.49,0.52)
Outage	t=1	0.66 (0.63,0.68)	0.5 (0.47,0.52)	0.54 (0.52,0.57)	0.36 (0.34,0.39)	0.8 (0.78,0.82)	0.52 (0.49,0.55)	0.74 (0.71,0.76)	0.43 (0.4,0.46)
	t=10	0.86 (0.84,0.88)	0.49 (0.46,0.52)	0.81 (0.79,0.83)	0.44 (0.41,0.47)	0.94 (0.92,0.95)	0.42 (0.39,0.45)	0.91 (0.89,0.93)	0.39 (0.36,0.42)
	t=20	0.97 (0.96,0.98)	0.52 (0.49,0.55)	0.95 (0.94,0.96)	0.54 (0.51,0.57)	0.98 (0.97,0.99)	0.41 (0.38,0.44)	0.97 (0.96,0.98)	0.39 (0.36,0.42)
Ext.	Tool	0.62 (0.61,0.63)	0.53 (0.52,0.54)	0.48 (0.47,0.48)	0.34 (0.34,0.35)	0.76 (0.75,0.76)	0.6 (0.59,0.61)	0.69 (0.68,0.7)	0.5 (0.49,0.51)
	Mech.	0.6 (0.6,0.61)	0.51 (0.5,0.51)	0.47 (0.46,0.48)	0.32 (0.32,0.33)	0.74 (0.74,0.75)	0.58 (0.57,0.59)	0.68 (0.67,0.69)	0.48 (0.47,0.49)
	Comms	0.6 (0.56,0.64)	0.5 (0.46,0.54)	0.46 (0.42,0.5)	0.31 (0.27,0.35)	0.74 (0.7,0.77)	0.59 (0.55,0.63)	0.68 (0.64,0.72)	0.48 (0.44,0.52)

reduced lag and increased surveillance improve the response by giving the incident commander more current information, while reduced lag additionally enables fire crews to start building firelines quicker. These improvements not only increase the number of fires that the response can contain, but decrease the number of scenarios with ground crew injuries. This shows the potential performance benefit of surveillance UAVs combined with a real-time high-throughput data link between the operators, supporting the notion that the proposed improvements could increase disaster resilience and firefighting capability by enabling a faster and more informed response.

However, if technological improvements to fire response contribute risk to performance or operator safety, pursuing them may not be justifiable. As shown in Figure 6, while surveillance UAVs add additional fault modes, the overall modeled response was resilient to these modes, since the faults only created minor disruptions and because multiple surveillance aircraft. However, changing the communication technology used by responders has potential risks *if* it becomes possible for the entire communications network to be inoperable as shown in Figure 7. Thus, this technology needs to have a low probability of communications faults during response operations and provide redundant communication paths so that no individual communications fault can stop communications through the chain of command. Finally, technological changes can make a response more or less prone to existing failure scenarios. As shown in Figure 8, this was not the case for increased surveillance or communications, which saw little change in performance under externally-driven fault scenarios. In general, changes that improve the operational performance of the system by making the fire easier to fight also help in fault scenarios. If the SoS is more prepared to fight a fire, faults are easier to mitigate because there is more slack to be taken up before the fireline or ground crews are put at risk. As a result, despite potentially introducing fault scenarios, a SoS with better communications and surveillance technology can be more resilient because the performance improvement generalizes to fault scenarios.

V. Conclusions

This paper studied the potential performance and resilience effects of UAS and UTM for wildfire response using a high-level dynamic simulation of the wildfire propagation, surveillance, fireline planning, and fireline construction. In this approach, the performance of the system was measured as the ability to contain the fire over a wide range of scenarios with different inherent difficulties. Results indicated that decreasing communications lag and increasing surveillance yields significant improvements in the distribution of fireline completions because fire crews and tankers were able to respond earlier and the response in general could be planned with more accurate and timely information. In general, the impact of externally-driven faults and faults introduced by the surveillance aircraft was low enough that it was more than compensated for (in those scenarios) by the performance improvements. The biggest modelled threat to the resilience of these improvements is the potential for large-scale communications outages. If these outages occur often or at a high severity, they can negate the benefits of increased communications and surveillance. Thus, future UTM data link systems for aerial firefighting need to be designed to prevent single points of failure, even for minor faults which can be resolved quickly. In summary, UAVs and high-throughput data links have the potential to transform wildfire response and increase operational effectiveness so that firefighters can respond to a broader range of fires and fault scenarios, however, this performance increase is contingent on dependable communications infrastructure.

Because this study focuses on improvement potential of new technologies, a limited number of factors were studied and the model presented does not represent every potential consideration. In particular, surveillance UAVs will need to be able to coordinate with existing aerial assets without introducing conflict points [52]. While this work showed the need for reliable high-throughput communications systems, developing a reliable solution may be challenging due to highly varying geographic and atmospheric conditions. Additionally, this study was limited in scope to surveillance UAVs and communications throughput. Future work should address these limitations by modeling a wider range of new technologies (e.g., pilot automation) in more detail to better understand their opportunities and pitfalls. Finally, this simulation was limited to a relatively simple training exercise environment (2000x2000 grid of flat grass/shrubland terrain with a corresponding 8-minute time-step). This limitation was in part due to the high-level discrete-time nature of the simulation, where a number of complex model operations take a single time-step. Future work should further develop and adapt the model to simulate a wide variety of firefighting scenarios with different grid sizes and resolutions, property distributions, and corresponding time-steps to show how well these results generalize across types of firefighting scenarios.

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APPENDIX

A. Model Validation and Tuning Efforts

Efforts were undertaken to ensure model validity, including model testing and tuning, verifying assumptions with external data and models, and corroboration with external subject matter experts. One of the key considerations in developing this model was the selection of the overall mission (time-step, grid size, asset response effectiveness, etc), which was chosen to model a basic firefighting training exercise for simplicity and clarity of demonstration. To model this mission, an eight-minute time step was selected, resulting in a total mission duration of eight hours for the 60 time-step simulation. An eight-minute time-step allows consideration of ground crew fireline construction, aerial suppression, and communications impacts in a single timestep, while the 60 time-step duration ensures the model reliably simulates to a given end-state (i.e., breached or completed firelines), rather than terminating before the end-state can be determined. An automated testing approach was further developed using Python's `unittest` module comprising 113 distinct tests, which revealed 13 major bugs which have been resolved in development. While these software tests do not guarantee model validity, they do reduce the possibility of software flaws affecting simulation results. Additionally, the structure of the model and impact of assets was qualitatively evaluated by experts from the STEReO [1] project, who gave feedback during development which affected the overall modeling assumptions.

Because of the discrete-time representation of this model (and relatively low time resolution), many of the operations in the model occur within a single time-step. Because of the hard-coded nature of the model representation of these tasks, it was important to tune these operations (especially single-timestep operations like communications, surveillance, travel, etc) and determine the corresponding time for each model time-step. Operations of the model and their respective times in the model are shown in Table I, along with their assumptions and the relative impact of these assumptions on the simulation. To ensure correct model calibration, these times were corroborated with real-world data and existing literature, when this information was available, to determine how much time a time-step represents. Fire spread rate in the SMARt-STEReO model was compared to three existing physics-based models developed by Fernandes [2], Rothermel [3], and Sauvagnargues-Lesage et al. (Valabre model) [4]. Across wind speeds from zero to ten meters per second with shrub-like fuel, the fire spread rate of the SMARt-STEReO model is within 10% of the range of spread rates from the three physics-based models. Terrain's impact of fire spread rate was also corroborated in the SMARt-STEReO against United States Forest Service research, with thirty degree downhill fires spreading slower by a factor of approximately two,

Asset	Operations	Timesteps	Rationale	Sensitivity
AerialCommander	Surveillance of one grid quadrant and Communications with IC, Tankers, and Surveillance	1	Detailed flight information and drop locations relayed	Moderate
	Flight time before refueling	48	Piloted aircraft requiring 6.5 hours of fuel	Low
Surveillance	Surveillance of one grid quadrant and Communications with IC	1	Prevents overlap with AerialCommander and other surveillance assets	Low
	Flight time before refueling	23	Small aircraft with battery/tank lasting 3 hours	Low
Tanker	Takeoff, travel, and water drop	1	High rate of travel (90m/s) between location and nearby airport	High
	Travel to base, landing, refill	1	High rate of travel (90m/s) between location and nearby airport with active refueling station	High
	Flight time before refueling	38	Heavy aircraft with low flights requiring 5 hours of fuel	Low
IncidentCommander	Communications with Surveillance, Coordination of Aerial and Ground Assets	1	Detailed information relay and planning/coordination.	Med-High
FireSpread	Spread from grid point to adjacent grid point	0.25+	Enables speeds of up to 0.8 m/s (140 ch/hr), enough to cover the range of directly fight-able fires. Tuneable depending on grid flammability, wind, etc.	High
Helicopter	Surveillance of quadrant	1	Low flight and detailed information relay	Low
	Delivery of Crews/Supplies to Fire Break	1	High rate of travel with nearby air base	Low
	Return to Base (with or without crew)	1	High rate of travel with nearby air base	Low
	Flight time before refueling	23	3 hours of flight in heavy, low-flying helicopter	Low
UAV	Takeoff and dropoff of supplies at ground crew	1	Moderate speed and nearby air base	Low
	Charging	9	Electric aircraft with 1.2 hour charge time	Low
GroundCrew	Construction of Firelines over 0-2 grid points	1	Tuneable, depends on fuel distribution. Average rate of 0.2 meters (50 ch/h) per second assumed for light brush	High
	Accumulation of fatigue while working	25	Roughly half a work-day of firefighting	Low
	Recovery of fatigue at base	6	1 hour break	Med-Low
EngineCrew	Construction of Firelines over 0-2 grid points	1	Tuneable, depends on fuel distribution. Average rate of 0.2 meters (50 ch/h) per second assumed for light brush	High
	Travel across 3 gridpoints (300m)	1	Transport of heavy equipment to limited-access location.	Moderate
	Accumulation of fatigue while working	25	Roughly half a work-day of firefighting	Low
	Recovery of fatigue at base	6	50-minute break	Med-Low

TABLE I: Times for various asset behaviors in the SMARt-STEReO model.

and thirty degree uphill fires spreading faster by a factor of approximately two when compared to level terrain [5]. The ground and engine crew construction rate was furthermore tuned to be within the ballpark of approximately 0.2 meters per second (50 ch/h) assuming a Type 3 Dozer, Type 1 Slope class, and light brush fuel [6]. While tanker aircraft exist in a variety of sizes and configurations, with the smallest aircraft capacity of 800 gallons and the largest capacity of 24,000 [6], aircraft assumptions in the SMARt-STEReO were based on the Modular Airborne Fire Fighting System, (MAFFS), which holds a 3000 gallon capacity, resulting in a drop length of approximately 400 meters [6], [7], with refills taking approximately twelve minutes [6]. In the SMARt-STEReO model, for this to correspond to one time-step and permit three drops covering 100 meter by 100 meter pixels per time-step. Based on these rates for tanker, ground crew, and fire operations as well as assumed rates for communications and surveillance times, the time-step was determined to be roughly eight minutes. While this is valid over the given firefighting scenario (grid distribution and resolution, fire location, etc), future work should provide a means to tune the model to new scenarios.

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