Fire-Aware Planning of Aerial Trajectories and Ignitions

Evan Beachly,[1] Carrick Detweiler,[1] Sebastian Elbaum,[1] Brittany Duncan,[1]
Carl Hildebrandt,[1] Dirac Twidwell,[2] and Craig Allen[3]

***Abstract*— Prescribed fires can lessen wildfire severity and control invasive species, but they can also be risky and costly. Unmanned aerial systems can reduce those drawbacks by, for example, dropping ignition spheres to ignite the most hazardous areas. Existing systems, however, lack awareness of the fire vectors to operate autonomously, safely, and efficiently. In this work we address that limitation, introducing an approach that integrates a lightweight fire simulator and a planner for trajectories and ignition sphere drop waypoints. Both components are unique in that they are amenable to input from the system's sensors and the fire crew to increase fire awareness. We conducted a preliminary study that confirms that such inputs improve the accuracy of the fire simulation to counter the unpredictability of the target environment. The field study of the system showed that the fire-aware planner generated safe trajectories with effective ignitions leveraging the fire simulator predictions.**

I. Introduction

Prescribed fires can reduce wildfire severity [1], control invasive species [2], and improve rangelands for livestock and grazing [3]. In our previous work [4], we developed an Unmanned Aerial System for prescribed fires (UAS-Rx). The UAS-Rx, shown in Figure 1, is capable of priming and dropping delayed aerial ignition spheres, which can be used to ignite fires in the interior of the prescribed burn area. This allows an operator to ignite difficult-to-reach areas safely and is more affordable than conventional aerial ignition from a helicopter.

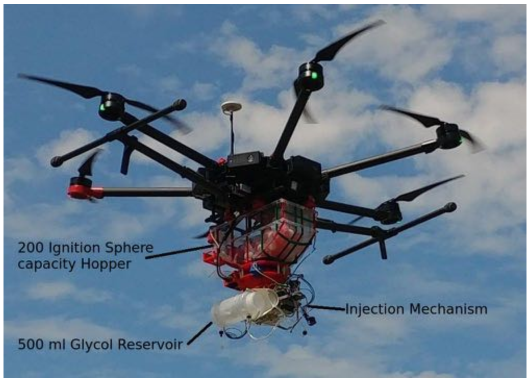


Fig. 1: UAS-Rx in flight.

Despite its potential, the UAS-Rx lacked the fire-awareness to operate autonomously and efficiently. Being aware of the location, direction, and general evolution of the fire is crucial not just to optimize the effect of the ignitions, but also to keep the vehicle and personnel safe. The UAS-Rx must avoid hot, dangerous areas and it must be able to drop ignition spheres in specific locations to assist in managing the fire direction and intensity. Even if additional sensors can be added at the expense of flight time and maneuverability, sensors alone cannot anticipate fire conditions, which is what the UAS-Rx needs to achieve its objectives.

Conceptually, the solution seems deceptively simple: integrate a fire simulation with a path planner. However, existing fire simulators like FARSITE [5] and FSPro [6] are intended to be run off-line, with intensive simulations of various fire scenarios to help the burn crew prepare before the fire. Yet, fires can be unpredictable in nature, especially when there are different types of vegetation, terrains, and changes in wind speed and direction. This is problematic for these fire simulators that work in batch-mode, that is, not allowing for frequent user adjustments as the fire progresses.

To address these challenges, we designed and implemented an approach that includes a specialized fire simulator and a planner that builds on it, both amenable to input from the system's sensors and the fire crew. The simplified fire simulator is unique in that it can provide quick estimates of fire evolution and can be corrected by sensor and user input to counter the unpredictability of the environment. The ignition line planner is novel in that it generates a set of ignition sphere drop points and a path to reach them. It does this using the fire simulation to avoid hot areas while dropping ignition spheres to perform, for example, the common grid ignition technique shown in Figure 2. With this particular technique, the burn crew ignites a grid of spot fires inside the burn area. The spot fires' spacing and timing are used to regulate the fire intensity. Our UAS-Rx replaces the interior ignition personnel carrying the drip-torches, removing them from close proximity to the fire. The UAS-Rx also allows the technique to be executed over difficult terrain with greater precision.

In summary, our contributions are:

- A light-weight fire simulation that can be corrected with real-time observations of the fire.
- An algorithm that uses the fire simulation to plan safe trajectories and effective ignitions for the UAS-Rx automatically.
- A field study assessing the safety and effectiveness of the trajectories generated by the fire-aware planner.
- A study on the accuracy and usability of our fire simulation using fire observations input by a human.

This work was supported in part by NSF-1638099 and USDA-NIFA-2017-67021-25924.

[1] Computer Science and Engineering Department, University of Nebraska
[2] Department of Agronomy and Horticulture, University of Nebraska
[3] U.S. Geological Survey, Nebraska Cooperative Fish and Wildlife Unit

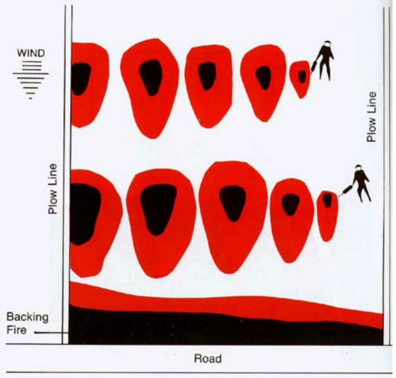


Fig. 2: Grid Ignition Technique [7].

II. Related Work

UASs are increasingly used to support fire management, especially with monitoring and fire measurement [8], [9], [10]. UASs are also incorporated into simulations to facilitate fire tracking [11], [12]. The UAS-Rx is the first unmanned aerial system to provide support for fire ignitions [4], [13], and this effort provides support towards autonomous ignition planning.

Although this is a first step towards fire simulations that can take real-time observations as input to support fire ignitions, we are not alone in pushing for the incorporation of human input into fire models. Recently Gollner et al. expressed the need for such operational wildfire spread models that can take real observations [14]. From a robotics perspective, using human input to update the robot's model of the environment is a common technique to improve the robot's understanding of the environment (e.g., [15], [16]). In order to do that, the environment model built by the robot needs to be conveyed to the human so the human can understand the decisions made by the robot and provide adjustments [17]. Building, conveying, and updating a robot's environment model can be a non-trivial endeavor as the model may not fully map to reality due to limitations of the robot's sensors, resources, and algorithms. Another factor to consider when updating the robot's environment is that human participation, although valuable, may be challenging to obtain and incorporate cost-effectively.

In this work, we tackle each of these challenges in the context of the fire environment with input from fire personnel.

III. System Overview

Our previous work describes a mechanism for puncturing, injecting, and dropping ignition spheres [4]. It also demonstrates how it can be used by a micro unmanned aerial system to ignite prescribed fires. We have since scaled up this mechanism to carry up to 200 ignition spheres (from 12 in the last system) and integrated it with a DJI Matrice 600 (Figure 1). This allows us to fly and drop ignition spheres for up to 30 minutes per flight. The increased mission capabilities of this UAS-Rx drove the need for additional autonomy in terms of path and ignition planning.

Flying
Signal: 100%
GPS: 18 satellites
Battery: 12.8 min
51% 55% 54%
52% 52% 52%

Wind Heading: 22
Line Spacing (m): 40
Drop Spacing (m): 40
Stagger ☐

Fig. 3: UAS-Rx Android application for planning ignition lines. The UAS-Rx is represented as a red and white hexacopter on the satellite map. A pop-up menu over the map has inputs for the ignition planner. The grey line and blue dots are the planned path and ignition locations. The yellow slider serves to project the fire simulation into the future (set at 6 minutes in the future in the figure) and shows how the planned ignitions would connect to the previous ignitions.

The UAS-Rx is controlled by a dual-joystick RC transmitter that also mounts an Android tablet. This tablet runs an Android application we created to control the UAS-Rx and the injection mechanism. This application has many of the features expected of a UAS-flying app, such as live video, avionics displays, satellite imagery, and waypoints, in addition to controls for dropping ignition spheres [18].

The fire simulator and ignition line planning algorithms later described also run on this application and take advantage of the touchscreen interface, shown in Figure 3. The fire simulation darkens the areas of the map that have been burned, and the user can touch the screen to make corrections to the simulation. The ignition line planning algorithm will display the planned line for the user to decide whether to accept it or adjust it. The simulator can also render what the fire will look like in the future, which can help the user preview the effects of the planned ignition line before they decide to execute it. We will discuss this portion of the application interface in detail in Section V.

IV. Correctable Fire Simulation

The fire simulator's goal is to predict how fire spreads from ignition sources (ignition spheres or burn crew). Two requirements drove the design of our fire simulator. First, it must be available continually and usable in the field on a tablet computer. This meant that we needed to simplify existing fire models to quickly update the model while running on a platform with limited resources. Second, fire can rapidly and unexpectedly change speed and direction. This meant that to provide accurate feedback the model needed to be able to incorporate additional input from users or sensors.

With those requirements and implications in mind, we designed the fire simulator with two key components shown in Figure 4. The first component is a simplified fire simulator for how fire spreads outward from point and line ignitions. This component treats lines as a series of points and can

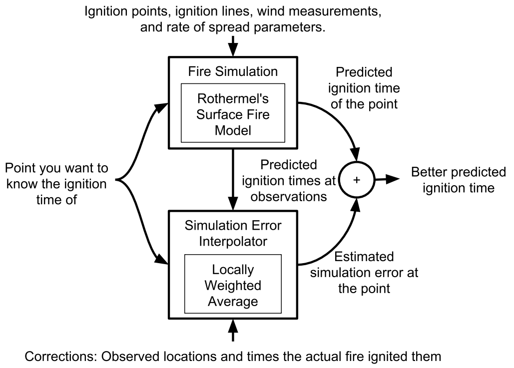


Fig. 4: Dataflow diagram of the correctable fire simulation, showing the inputs and outputs of the two key modules.

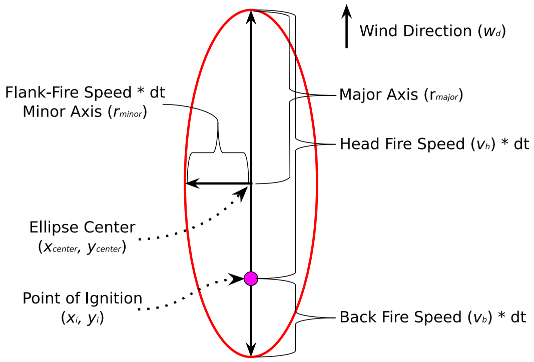


Fig. 5: Fire spread from an ignition point.

compute at what time a point will ignite. The second component takes observations of a fire front location at a given time as input corrections. It then calculates the error of the simulation at that location and time. These errors get interpolated to estimate the error at any particular point and are used to improve the prediction of the fire simulation.

The simulator models how the fires spread from an ignition point using a time-varying ellipse [19] as shown in Figure 5. From the ignition point (x_i, y_i), the center of the ellipse can be calculated using Equation 1, where ω_d is the heading of the wind, v_h is the head fire velocity, v_b is the back fire velocity and t_d is the time delta. Where $t_d = t - t_i$, with t being the time of interest and t_i being the time of ignition.

$$\begin{aligned} x_{center} &= x_i + \frac{2t_d \times cos(\omega_d)\,(v_h - v_b)}{2} \\ y_{center} &= y_i + \frac{2t_d \times cos(\omega_d)\,(v_h - v_b)}{2} \end{aligned} \tag{1}$$

The ellipse's major and minor radii can then be calculated using Equations 2:

$$r_{major} = \frac{v_h - v_b}{2 + v_b} \times t_d \text{ and } r_{minor} = v_b \times t_d \tag{2}$$

The rate of fire spread is based on Rothermel's surface fire model [20], which provides equations that relate factors like wind speed, slope, and fuel moisture to the head fire's rate of spread across the ground. We simplify the model by making two assumptions about those factors. First, we assume that the non-wind parameters are estimated and configured before the burn and that they are constant for every point on the terrain. Second, we assume the back fire rate of spread is equal to the head fire rate of spread at 0 wind [19] and that the flank fire rate of spread is equal to back fire rate of spread at low wind conditions [19], [21].

This implementation can quickly compute the time the fire front will reach any location (x, y) by finding the value of t for which the ellipse will intersect that location. Furthermore, corrections can be made to the fire simulation. Correction inputs, recorded as a location at a given time, are used by the simulator to compute the error between the predicted and the observed time a point ignited. This error is then interpolated using a squared exponential function of the distance to the queried point to effectively update the simulation state.

V. IGNITION LINE PLANNING

The ignition line planner determines the line of ignition sphere drop locations and is initiated when the user presses the plan button in Figure 3. It leverages the fire model to predict where the fire will be to ensure that the UAS-Rx maintains a specified distance from a fire front. The fire model and ignition line planner incorporate environmental conditions such as wind when specifying a distance from the fire front, thus allowing safe flight in high wind conditions. The ignition line planner also incorporates feedback from users to ensure that the plan is appropriate given the current conditions and personnel locations.

The approach used is based on the grid ignition technique shown in Figure 2. A line of spot ignitions is placed orthogonal to the wind and offset from the backfire. The spacing between the lines and ignition spots can be configured to regulate the intensity of the fire and time to complete the burn [7]. The menu in Figure 3 has three main controls for the user to regulate the fire intensity and duration of the burn: ω_d the wind heading, ls the line spacing, and ds the drop spacing.

Algorithm 1 shows the pseudocode of the ignition planner. Each call to this algorithm plans the next line of ignitions ($plan$), represented as a list of waypoints to fly to and a set of locations to trigger ignition sphere drops. Each ignition line is meant to burn off the downwind portion of the unburnt area, so the UAS-Rx uses a polygon ($area$) to track the remaining burn area between calls to the algorithm. This polygon initially starts as the bounding perimeter. To align the planned fires with the previously started fire lines, a list of previous drop points on the perimeter of the unburnt area ($prev\_drps$) is also managed by the algorithm. Additionally, the planner takes the fire simulation ($fsim$) and location of the UAS-Rx (uas) as input.

Line 1 of the algorithm finds the vertex of the unburnt area polygon that is most downwind. Then, it moves upwind a distance equal to the line spacing to find the potential line the ignition spheres will be dropped along, orthogonal to the wind. At Lines 2 and 3, if the potential ignition line is outside of the control perimeter, then the prescribed fire is completed, and no more lines can be planned.

Algorithm 1: Plan Next Ignitions

```
Input  : Unburnt Area $area$, Previous Drop Points
         $prev\_drps$, Wind Heading $wh$, Line Spacing
         $ls$, Drop Spacing $ds$, Fire Simulation $fsim$,
         UAS Location $uas$
Output: Waypoints and Drop Points $plan$
1  $iline \leftarrow$ findNextIgnitionLine($area$, $wh$, $ls$);
2  if $iline$ is outside $area$ then
3      return No Plan // Burn Complete;
4  end
5  $dap \leftarrow$ findDropAlignmentPoint($iline$, $prev\_drps$);
6  $pot\_drps \leftarrow$ generateDropPoints($iline$, $dap$, $ds$);
7  $pot\_drps \leftarrow$ removeOutsidePoints($pot\_drps$,$area$);
8  $str\_path \leftarrow$ planPath($pot\_drps$, $uas$);
9  for each $str\_path$ do
10     $path \leftarrow$ checkPathSafety($str\_path$, $fsim$)
11 end
12 $plan \leftarrow$ selectFastest($path$);
13 if $plan.numSafeDropPoints > 0$ then
14     return $plan$
15 else
16     $area \leftarrow iline$.cutOff($area$, $prev\_drps$);
17     Goto 1;
18 end
```

Line 5 finds a point on the potential ignition line, dap, to align the drops. This point is selected so that it is directly upwind of a previous drop location that is close to the center. This way the fire, from the current drop location, will meet up with the fire from the previous drop location. If the drop spacing or orientation of the planned line differs from the previous line, then the fires started at the previous drop locations might not line up. We, therefore, minimize the alignment error by ensuring a central drop is aligned.

Once the alignment point is found, a drop location is placed at the alignment point and others are placed along the line every drop spacing, ds. If $area$ is concave, this may result in placing potential drop points outside of the unburnt area. Line 7 ensures these are removed.

Line 8 takes the potential ignition points pot_drps and creates two paths. The first path is a straight line from the UAS to the leftmost ignition point. The second path is a straight line from the UAS to the rightmost ignition point. The paths then go from the current ignition point to the next closest in a straight line.

Once two straight lines, str_path, from the UAS to all ignition points have been created, the algorithm checks how safe they are using the fire simulation, as per lines 9 and 10. It does this by assuming that the UAS will fly at a constant velocity, specified by the user, along the entire straight line. It then samples the fire simulation along the line between waypoints and requests its ignition time. If the point along the line would ignite within a certain small threshold of the UAS getting there, the line is considered unsafe.

If the path is not safe, it instead considers ascending to a predetermined safe altitude (configured to 60m in our study given the landscape, vegetation, and prevalent winds) before flying to and descending at the drop location. If the drop location is not safe when it would be reached, the planner skips that ignition and instead tries to reach the next ignition from the current location.

Line 12 then selects the faster of the two paths. Line 13 checks whether there were any safe drop locations in the planned line. If there were, then it returns the plan line. If not, perhaps the fire has already encroached to that point. Lines 16 and 17 cut that section off of the unburnt area and tries planning again by returning to line 1.

VI. TRAJECTORY ASSESSMENT

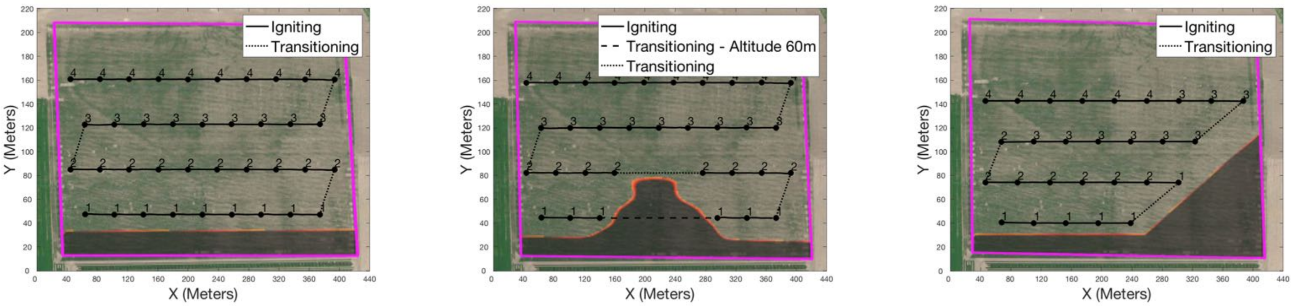
We conducted a field study to assess the UAS-Rx's ability to plan ignition lines. Specifically, we wanted to validate three features of the ignition line planning algorithm, that it: 1) suggested lines that were consistent with those of a typical burn crew performing a grid ignition technique as shown in Figure 2, 2) generated safe trajectories while still effectively setting a fire line, and 3) was able to dynamically adjust to changes in the fire as represented in the fire model.

A. Scenarios

The studies were conducted in a 20 acre field in south-east Nebraska. Since the purpose of the study was to evaluate the ignition line planning algorithm, UAS-Rx's flight trajectory, and not the direct ability for the drone to ignite fires (discussed in [4]) we set up four distinct simulated fire scenarios and fed them to the ignition line planner. The planner then suggested a fire line to be executed by the UAS-Rx, which was the target of our assessment.

The four scenarios represent conditions that are likely to appear in prescribed burning practices. All scenarios were initialized with the same burn perimeter and wind of approximately 2m/s in the southerly direction. The first scenario, depicted in Figure 6a, consists of a single backing fire which started from the most southern line of the burn perimeter. This backing fire then spread uniformly against the wind in a northerly direction. In the second scenario, shown in Figure 6b, the backing fire again originated from the most southern line of the burn perimeter but did not spread uniformly. The fire in the center of the burn perimeter spread faster than that along the edges. Ununiform spread was simulated to test having a terrain with different vegetation, moisture, or slope. The third scenario (Figure 6c) shows two converging fire fronts. The first fire front was started in the same manner as that of the first scenario, while the second fire started along a 45° angle from the burn perimeters southern line. The fourth scenario is similar to the third except that the ignition line planner was not initially aware of the second fire front, running 45° angle from the burn perimeter's southern line (shown in Figure 7). This second fire front was added to the model mid-flight to assess the effect of users' updates to the fire front on flight trajectories.

The UAS-Rx was instructed to take off and fly to a height of 15m above the ground using the navigation Android appli-



(a) Scenario 1: A fire front which runs uniformly parallel to the southern burn perimeter and is burning north against the wind.

(b) Scenario 2: A fire front which runs non-uniformly parallel to the burn perimeter and is burning north against the wind.

(c) Scenario 3: Two fire fronts converging, from the south and at a 45 degree angle, both burning north against the wind.

Fig. 6: Traversed path of the UAV given different fire scenarios.

cation. For each scenario, the corresponding fire model was loaded into the fire simulator application. For the scenario where the fire model changed during flight (Figure 7) only the fire front parallel to the southern burn perimeter (Fire Front 1) was loaded. The ignition line planner was then run, and the suggested trajectory accepted by the user (starting with line 1, following the rest of the lines in numerical order). The UAS-Rx autonomously navigated along a transition line, then autonomously followed the ignition line while dropping ignition spheres at the specified intervals. Once the suggested trajectory was complete, the user would request a new ignition from the ignition line planner. The user would once again accept the trajectory, and the process would repeat.

B. *Results*

In the first scenario, Figure 6a, the UAS-Rx found the fire front and placed an ignition line parallel to it into the wind. The UAS did not fly into any areas which were considered dangerous for the UAS. After the initial ignition lines, marked using 1's, the vehicle transitioned to the second ignition line. While transitioning the UAS-Rx did not drop ignition spheres, meeting our expectations.

For the second scenario, Figure 6b, the vehicle again found the fire front and placed an ignition line parallel to it, into the wind. The ignition line planner recognized that there are unburnt areas on both the left and right-hand side of the fire front. It calculated that the best way to ignite both of these was to transition over the fire front. This was done by stopping before the fire front and autonomously changing altitude from 15m to 60m (dashed line). Ascending prevented the UAS-Rx from being affected by the high temperatures from the fire, and thus avoided a dangerous situation. Once it had transitioned to the other side of the fire front, it reduced its altitude to 15m and continued dropping ignition spheres. These actions show that that the ignition line planner is able to correctly navigate the UAS-Rx safely over fires while igniting unburnt areas. Another interesting point can be seen in ignition line 2. Similar behavior to that of ignition line 1 was exhibited even though the initial fire front as seen in Figure 6b was not directly underneath the ignition line. This was because the UAS-Rx was able to correctly calculate that the fire would have spread such that it was underneath the suggested trajectory line. This shows that that fire model does indeed affect the suggestions made by the ignition line planner.

The third scenario, Figure 6c, further exemplified the ability of the UAS-Rx to place ignition lines optimally while avoiding dangerous fire fronts correctly. The suggested trajectories maximize the area the ignition lines cover of the target burn area. The ignition lines also start at the point furthermost downwind. This allows the fire to spread in a controlled manner.

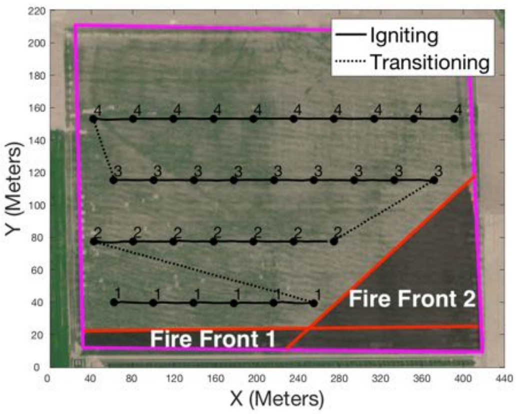


Fig. 7: The traversed path by the UAV-Rx, after adjusting its flight path for an unforeseen fire front coming from a south-east direction in Scenario 4.

The final scenario in which the fire model changed mid-flight is seen in Figure 7. When the ignition line planner first calculated an ignition trajectory, the trajectory was the same as that of ignition line 1 in the first scenario (Figure 6a). This was due to the simulator initially being presented with a fire simulation containing only fire front 1. However, mid-flight, the UAS-Rx was stopped and a second significant fire front, fire front 2, was added into the simulator. The addition of fire front 2 caused the planner to stop ignition line 1 and suggest ignition line 2 to avoid the updated fire fronts.

A sub-optimal transition between ignition line 1 and 2 occurred due to fire front 2 being updated to within the UAS-Rx's safety threshold. The UAS-Rx recalculated two new paths: one to the rightmost ignition point, and one to the left. The transition to the right would first have to ascend to 60m for safety. The ascent and descent added more time (versus a transition to the left), and thus the leftmost path was selected.

Overall, the ignition line planner was able to correctly suggest ignition lines similar to those employed by burn crews using grid ignition. The ignition line planner was able to suggest lines which avoided dangerous situations, including flying the UAS-Rx too close to the fire front or outside of the burn perimeter. The vehicle was able to identify and safely navigate over fires by changing altitude. The ignition line planner correctly integrated with the fire simulation and was able to use the fire simulator's ability to project the fire into the future to suggest lines which would be safe even as the fire spread. Finally, the ignition line planner was able to adapt to users' input on the fly.

VII. PRELIMINARY USER STUDY

We ran a user study to estimate how the accuracy of the fire simulation can be improved with human corrections, and to obtain feedback from users on different aspects of the application interface. This study imitated how the fire simulator would be used during UAS-Rx operation over a prescribed fire. We used the UAS-Rx to capture aerial video recordings of two prescribed fires of 20 to 30 acres in eastern Nebraska. One prescribed fire was used for training the participants, and the other was used for the experiment. The participants watched portions of these recordings while correcting a simulated fire on a tablet to match the fire in the recording. We then assessed whether these corrections improved the simulation's accuracy.

A. *Experiment Procedure*

This study was conducted with five participants who are graduate students of Agronomy, Horticulture, and Applied Ecology. They all had been to prescribed fires, and four have been igniters at prescribed fires. The age of the participants ranges from 25 to 27, and each participant uses touchscreen devices and Google Maps at least weekly. The map on the application interface uses Google Maps imagery and the default touch gestures for moving the map. The participants were contacted by email through a professor in their department, and they were given $15 in compensation for their time.

The study was conducted with each participant in a quiet conference room and proctored by a researcher. A computer monitor was positioned on the table in front of the participant and was used to display the recorded video as shown in Figure 8. The fire simulation was run on an Asus Nexus 7 tablet, which the participant used while sitting in front of the monitor.

Each participant was asked to read a document that described how the correctable fire simulation would help the UAS-Rx perform ignitions at prescribed fires. Next, the participant was asked to fill out a questionnaire about their prescribed fire experience and familiarity with touchscreen devices and Google Maps.

Fig. 8: A frame from the video the participants watched during the experiment.

1) Training and Practice: For training, the participant watched a five-minute video that demonstrated how to use the fire simulation's interface on the touchscreen tablet. The video is a screen captured from the tablet running the fire simulation in the practice scenario with a narrator demonstrating and describing each function of the application interface. Touches on the screen were represented by white circles so that the viewer could see the point of contact. Figure 9 shows a screenshot of the interface that the participants used.

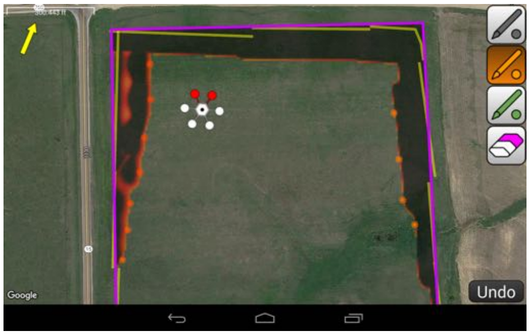


Fig. 9: The application interface the participants used to adjust the fire simulation. The tools for adjusting the fire simulation are on the right side. The black pen tool marks areas as burned, the orange pen tool marks areas as currently burning, the green pen tool marks areas as unburned, and the eraser tool erases marks.

Participants had five tools to interact with the fire simulation. The black, orange and green pen tools were used to make corrections to the simulation by specifying locations ignited in the past, present, or future respectively. A mark appeared at the touched location to remind the user of the correction, and the eraser was used to remove corrections. The undo button undid the last correction or erasure. The training video also demonstrated that small fire features could not be created with the simulation, as corrections get averaged out, and instructed the viewer that it is more important to adjust the main fire front to the correct position. After the video, the participant was handed the tablet with the practice fire scenario running. The proctor asked the participant to try each demonstrated operation, which included touch gestures for moving the map and using the tools.

Next, the proctor led the participant through a training run similar to how the experiment would be conducted. The tablet was reset to the practice fire scenario and then was given to the participant while a synchronized video recording was started on the monitor. The participant was then asked to use the interface to correct the simulated fire to match the fire in the recording. The video ran for 3 minutes.

2) Experiment: After the practice session, each participant was asked to read another document that explained how the experiment would be structured, and also described and showed the burn plan that was distributed to the burn crew before the prescribed fire. To familiarize participants with the terrain and the landmarks in the burn plan, they watched a one minute video recorded by the UAS-Rx taking off and flying over the burn area of the prescribed fire.

For the experiment, five three-minute segments were selected from the recorded video, and the tablet was programmed to be able to start the simulation from the beginning of each of these segments. The participants would view each segment in chronological order and use the tablet to make corrections to the simulated fire. The corrections made in each segment would persist on to the next segment. Each correction, erasure, and undo was logged.

After the experiment, the proctor left the room and another person entered to interview the participant so that the participant wouldn't feel pressured against providing criticism in front of a researcher on the project. The participants were asked questions about how well they thought they did, how difficult it was, if it felt like they were making a lot of corrections, and something they liked about the interface as well as something they would like to change.

B. Results

To assess the accuracy of the fire simulation with and without user corrections, we first needed a ground-truth of where the real fire front was located at any given time. When possible, we directly used the video recordings to determine the real fire location. When the camera only provided partial views of the fire, we used a triangular mesh to interpolate the fire front location for the areas that were not readily visible.

Given the ground-truth fire front location, we then computed the average distance to the closest point on the simulated fire front, using a one-meter grid, at every minute for the duration of the prescribed fire. Figure 11 shows an example of the fronts and their comparison using the interface from the experiment, with the simulated fire (red line) providing a close approximation to the real file (blue line). Figure 10 shows the error distance over time. The thick black line in this graph shows the error of the simulation when no corrections are made, with a rapid error growth early on in the fire and some period of error reduction as the simulation catches up to the fire front progress. The dashed lines show the error of the simulation with each participant's corrections. Over the period between the start of the first video segment and the end of the second video segment, the simulation with no corrections had an average fire front error of 24.8 meters, while the average simulation with participant correction front error was 15.7 meters. This is a *36% improvement over the simulation without corrections*, for minimally trained users operating an interface prototype. Furthermore, given that the burn area was 340 meters wide, the corrected error was only 4.6% of the width of the burn area.

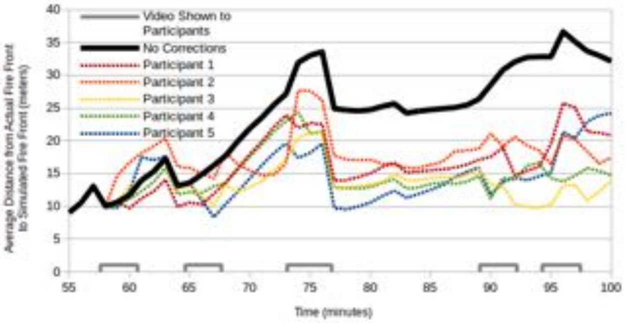


Fig. 10: The error between the actual fire and the simulated fire with each participant's corrections, and with no corrections. The intervals at the bottom show the video segments shown to the participants during the experiment.

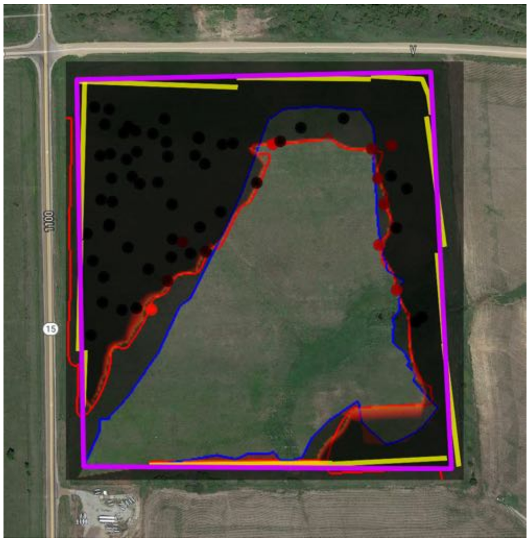


Fig. 11: An example comparing the simulated fire with a participant's corrections (red front) to the actual fire (blue front) at 78 minutes into the burn.

The survey responses, summarized in Table I, also indicate that no participants felt like their corrected simulation was a poor representation of the actual fire. That said, two participants mentioned that the blotchiness and smoothness of the simulation were difficult to work with, and we speculate that may be caused by the resolution of the tablet. One participant noted that it was difficult to represent patchy areas of the fire with the simulation and another noted that the monotony of the grassland made it difficult to match the video to the map, and it was easier to match the shape of the fire than the exact position. Features like roads, creeks, and telephone poles helped, but they were not always in the video. Another participant stated that the fish-eye lens

TABLE I: Summary of Participant Responses.

Question	Participant Responses		
How well did you think that your fire simulation with the corrections matched the fire you saw in the video?	2 Good	3 Neutral	0 Bad
How hard or easy was it to correct the simulation to match the simulated fire to the fire in the video?	1 Easy	2 Neutral	2 Hard
Did it feel like you were making a lot of corrections?	1 Few	1 Neutral	3 Lots

distortion was confusing, but seeing the UAS-Rx on the map helped figure out the location. We will leverage this feedback in our future work.

The participants made from 77 to 175 corrections in total, but the number of corrections did not have a strong correlation with the final accuracy of the model. The effort in providing those corrections, however, weighted on the three participants with the most corrections, who reported that they felt they were making lots of them. Three participants also suggested a pen-like tool to draw a continuous line or curve to mark where the fire front is instead of placing individual dots. This is again something we will consider in future work.

VIII. CONCLUSIONS AND FUTURE WORK

We have presented an integrated approach to make the UAS-Rx more fire-aware through the integration of a fire simulator and a planner for flight paths and ignition-sphere dropping locations. We showed that the fire simulator's limited accuracy could be compensated through the incorporation of user input. Our field tests also showed that the UAS-Rx planned ignitions lines, generated using the fire simulation, were safe and met the desired grid-pattern requirements. Finally, the feedback from the users pinpointed many aspects of the simulator and the system in general that merit extensions including the incorporation of wind, terrain elevation, fuel maps, and more sophisticated fire spread elements to drive the planning in more complex fire environments. We would also like to enable the simulator to take temperature sensing and wind information to improve its accuracy further.

Acknowledgments

We would like to thank the study participants, the Tri County Prescribed Burn Association of Nebraska, A. Bevins for interviewing the participants, and A. Islam for designing the hopper for the UAS-Rx. In accordance with the University of Nebraska Conflict of Interest policy, the authors Detweiler and Elbaum disclose their role as co-founders of and their financial interest in Drone Amplified, Inc.

REFERENCES

[1] M. Baeza, M. De Luıs, J. Raventós, and A. Escarré, "Factors influencing fire behaviour in shrublands of different stand ages and the implications for using prescribed burning to reduce wildfire risk," *Journal of Environmental Management*, vol. 65, no. 2, pp. 199–208, 2002.

[2] J. F. Stritzke and T. G. Bidwell, "Eastern redcedar and its control," *Weeds Today*, vol. 15, no. 3, pp. 7–8, 1984.

[3] J. E. Keeley, "Fire management impacts on invasive plants in the western united states," *Conservation Biology*, vol. 20, no. 2, pp. 375–384, 2006. [Online]. Available: http://dx.doi.org/10.1111/j.1523-1739.2006.00339.x

[4] E. Beachly, J. Higgins, C. Laney, S. Elbaum, C. Detweiler, C. Allen, and D. Twidwell, "A micro-uas to start prescribed fires," in *International Symposium on Experimental Robotics*. Springer, 2016, pp. 12–24.

[5] M. A. Finney, "Farsite: Fire area simulator-model development and evaluation," 2004.

[6] M. A. Finney, I. C. Grenfell, C. W. McHugh, R. C. Seli, D. Trethewey, R. D. Stratton, and S. Brittain, "A method for ensemble wildland fire simulation," *Environmental Modeling & Assessment*, vol. 16, no. 2, pp. 153–167, 2011.

[7] D. Wade and J. Lunsford, "A guide for prescribed fire in southern forests. technical publication r8-tp 11." United States Department of Agriculture, Forest Service Southern Region, Tech. Rep., 1989.

[8] V. Ambrosia, S. Wegener, T. Zajkowski, D. Sullivan, S. Buechel, F. Enomoto, B. Lobitz, S. Johan, J. Brass, and E. Hinkley, "The ikhana unmanned airborne system (uas) western states fire imaging missions: From concept to reality (2006–2010)," *Geocarto International*, vol. 26, no. 2, pp. 85–101, 2011.

[9] L. Merino, F. Caballero, J. R. Martínez-de Dios, I. Maza, and A. Ollero, "An unmanned aircraft system for automatic forest fire monitoring and measurement," *Journal of Intelligent & Robotic Systems*, vol. 65, no. 1-4, pp. 533–548, 2012.

[10] L. Merino, J. R. Martínez-de Dios, and A. Ollero, *Handbook of Unmanned Aerial Vehicles*. Dordrecht: Springer Netherlands, 2015, ch. Cooperative Unmanned Aerial Systems for Fire Detection, Monitoring, and Extinguishing, pp. 2693–2722.

[11] D. W. Casbeer, R. W. Beard, T. W. McLain, S.-M. Li, and R. K. Mehra, "Forest fire monitoring with multiple small UAVs," in *American Control Conference, 2005. Proceedings of the 2005*, vol. 5, Jun. 2005, pp. 3530–3535.

[12] R. C. Skeele and G. A. Hollinger, "Aerial Vehicle Path Planning for Monitoring Wildfire Frontiers," in *Field and Service Robotics*, ser. Springer Tracts in Advanced Robotics, D. S. Wettergreen and T. D. Barfoot, Eds. Springer International Publishing, 2016, pp. 455–467.

[13] D. Twidwell, C. R. Allen, C. Detweiler, J. Higgins, C. Laney, and S. Elbaum, "Smokey comes of age: unmanned aerial systems for fire management," *Frontiers in Ecology and the Environment*, vol. 14, no. 6, pp. 333–339, 2016. [Online]. Available: http://dx.doi.org/10.1002/fee.1299

[14] M. Gollner, A. Trouve, I. Altintas, J. Block, R. de Callafon, C. Clements, A. Cortes, E. Ellicott, J. B. Filippi, M. Finney *et al.*, "Towards data-driven operational wildfire spread modeling: A report of the nsf-funded wifire workshop," Tech. Rep., 2015.

[15] S. Kohlbrecher, A. Romay, A. Stumpf, A. Gupta, O. Von Stryk, F. Bacim, D. A. Bowman, A. Goins, R. Balasubramanian, and D. C. Conner, "Human-robot teaming for rescue missions: Team vigir's approach to the 2013 darpa robotics challenge trials," *Journal of Field Robotics*, vol. 32, no. 3, pp. 352–377, 2015.

[16] T. Somers and G. A. Hollinger, "Human–robot planning and learning for marine data collection," *Autonomous Robots*, vol. 40, no. 7, pp. 1123–1137, Oct 2016. [Online]. Available: https://doi.org/10.1007/s10514-015-9502-8

[17] J. Scholtz, "Theory and evaluation of human robot interactions," in *System Sciences, 2003. Proceedings of the 36th Annual Hawaii International Conference on*. IEEE, 2003, pp. 10–pp.

[18] E. Beachly, C. Detweiler, S. Elbaum, D. Twidwell, and B. Duncan, "Uas-rx interface for mission planning, fire tracking, fire ignition, and real-time updating," in *International Symposium on Safety, Security, and Rescue Robotics*. IEEE, 2017.

[19] M. Alexander *et al.*, "Estimating the length-to-breadth ratio of elliptical forest fire patterns," in *Proceedings of the eighth conference on fire and forest meteorology*, vol. 29, 1985, pp. 85–04.

[20] R. C. Rothermel *et al.*, "A mathematical model for predicting fire spread in wildland fuels," 1972.

[21] R. J. Barney, N. V. Noste, and R. A. Wilson, *Rates of spread of wildfire in Alaskan fuels*. Dept. of Agriculture, Forest Service, Pacific Nothwest Forest and Range Experiment Station, 1978, vol. 311.