Midterm Report - Team HELlo

Emerald (Nai-Syuan) Chang, Hunter Caslin, Lanea Rohan

Introduction

Wildfires have the power to majorly disrupt both a farmers livelihood as well as the overall crop production. In 2024 the US lost an estimated 20.4 billion dollars in crops and rangeland from natural disasters [1]. Just over half of that came from drought, wildfires and heat, accounting for roughly 11 billion dollars of lost revenue. With an increasingly volatile climate, weather predictions from top meteorological bodies show an increased risk of wildfires up to 50% by 2100, with even historically unaffected regions coming under threat [2,3]. The increasing number and strength of wildfires will only exacerbate wildfire damage to crops, resulting in more pressure on farmers.

Unfortunately, organized governmental response to wildfires on cropland is limited. With limitations on both water and manpower, many farmers are forced to watch as their fields burn or risk their lives and machinery to create rudimentary fire breaks with tillage machines. For farmers who try to save parts of their fields, they are confronted with a variety of challenges, including poor visibility from wildfire smoke, heat exhaustion in vehicles not meant for these types of situations and high risk of machine damage to both tilling components and tractor cabs.

We propose to mitigate these harms to both farmers and equipment by implementing a real-time path algorithm that can respond to an active cropland wildfire. Using bolt-on heat sensors, we plan to use real-time data collection to drive the path of an autonomous tiller to create a firebreak. Firebreaks are a time and true tested method for slowing and potentially stopping wildfires [4]. This research connects to digital agriculture as we are utilizing technologies such as sensors, autonomous machinery, and real-time data analytics to improve disaster mitigation for farms. These technologies allow farmers to have continuous monitoring of environmental conditions that will help with faster responses to emerging threats. By leveraging autonomous tillers and introducing firebreaks to stop cropland wildfires, we hope to help farmers minimize the impact of climate-induced challenges and make farm management more sustainable.

Related Work

There is little to no prior research on real-time path planning with dynamic barriers for agricultural machines thus far. Therefore, we draw mostly on several papers that discuss dynamic path planning for autonomous agricultural vehicles as well as several papers on dynamic obstacle avoidance in autonomous automobiles.

Several recent papers suggest using deep learning and reinforcement learning for intelligent and real-time path planning in autonomous agricultural vehicles [8,9] while other papers focus on dynamic path planning and object avoidance for robots more generally [5,6,7]. While the combination of real-time path planning and dynamic object avoidance has been trivial for agriculture technologists thus far, we find it to be one of the main challenges with real-time path planning for fire breaks. We are forced to dynamically adjust our path as the fire line advances. Although we can draw from path planning and prediction models for autonomous cars, they rely on a set of sensors and depth perception that are not reliable in smoke and dust kicked up by tilling fire breaks. Other relevant research that focuses on real-time agricultural planning either relies on additional farm-specific reinforcement [8], which is unfeasible due to the nature of crop fires, or relies on specific target/way points as goals [9], which we cannot guarantee based on fire progression.

Goals and Evaluation Metrics

Our goal is to build an interactive visualization software, which simulates fire spreading on a soybean farm, with a tractor that computes the best and safe path to create a fire break using simulated camera and heat sensors.

MVP Features

- A basic fire spreading simulation.
- A tractor node that can drive on a simulated farm.
- A path planner that takes fire into account and computes the best safe firebreak path.
- Visualization that shows the fire spreading and tractor moving.

Success Criteria

- Fire spread, sensor input, and tractor motion must all update without crashes for ≥ 95 % of runs.
- The simulated tractor should successfully avoid being consumed by fire in ≥ 80 % of test runs.
- The algorithm should reduce ≥ 30 % of farm area burned compared to a baseline (no-tractor case).

Technical Specifications

Simulation[1]

We first simulated fire spread and tractor movement using Python, with visualization step-by-step through Matplotlib. The farm environment is represented as a two-dimensional grid, where each cell corresponds to a one-square-foot area containing values that define its elevation, fuel type (heat content, mineral, dirt, moisture), and burning state (unburned, burning). We currently generate the map with Gaussian-filtered random noise to produce a smooth terrain that mimics realistic topography. The next step we are going to take is to import actual DEM map data of farmlands to fit the existing grid data type. The fire spreading algorithm is modeled using the implementation of the Rothermel Fire Spread Model [10] by SimFire [11]. This model predicts the rate of fire spreading (ft/min) based on the characteristics of the grid, like wind and elevation, with a correction factor originally developed by the US Forest Service.

In addition to implementing an operational fire simulation with SimFire, we also were able to add a tractor and fire break to the simulation. To mimic the tilled fire-break soil as unburnable, we add a new fuel type to the SimFire list. The fire break fuel type preserves many of the attributes from the soybean fuel type with certain exceptions: it is unburnable ($w_0 = 0$), emits no heat ($h=0$) and does not spread ($S_T = 0$ and $S_e = 0$). The path of the tractor's past movement creates the fire break - we update cells on the path to have the fire break fuel type and change their color to purple to help visualize what areas have been tilled. With our basic testing setup one pass of the tractor creates a wide enough fire break to halt wildfire progression, as can be seen in Figure 1b. In this figure, the tractor is represented by a gold-color cell that updates at each time step, mimicking real-world movement in comparison to fire spread.

[1] Our project code base can be found here: https://github.com/athaichi/HELlo_fire

Presently, the tractor can be controlled to move in the four basic directions with either WASD or arrow key commands. We also include an ending condition: if the cell with the tractor on it is on fire then the path is considered a failure. At this point we stop the simulation and report which cell the tractor and fire intersect on to the terminal and print a note on the simulation.

Sensors Research

For this project, the goal was to find a sensor capable of detecting wildfires thermally from a safe distance that could be mounted on a tractor. Thermal infrared sensors were selected because they can detect heat signatures through smoke and work effectively both day and night. Among the options considered, the Hadron 640+ radiometric thermal camera was chosen for its high sensitivity, moderate field-of-view, and compatibility with moving platforms as it has been used in similar applications to our simulation.

Based on pixel-resolution calculations, the Hadron 640R+ can reliably detect small hotspots up to roughly 0.5–1 km, medium hotspots up to 1–1.2 km, and larger fire areas at distances of 3–5 km under favorable conditions. These ranges depend on environmental factors such as smoke, humidity, and thermal contrast, but they provide a conservative basis for safe monitoring. By selecting this sensor, the project ensures early detection of wildfire hotspots while maintaining a safe operating distance for the tractor.

Next Steps

Our next steps are to implement a real-time, sensor-based feedback loop to automatically adjust the tractor's path. We will scale our field, tractor and movement to real world values. We will then implement the sensor technology as a form of awareness sensing around the tractor. Simultaneously we will implement a path planning algorithm using D* algorithm, which is the dynamic version of A* that can heuristically search for the optimal path and continuously update as new information becomes available. When the tractor encounters fire or blocked areas, it will use the D* algorithm to update its local map and recompute a new path on the fly.

We also want to experiment with DQN, using reinforcement learning to help the tractor learn from repeated fire scenarios. The DQN model will observe local fire and terrain conditions, predict potential risks, and gradually learn strategies that minimize burned area while maintaining tractor safety. From there, we will run simulations until we achieve basic fire avoidance and to preserve as much of the field as we can.

Demo

Below are the two figures referenced in the technical explanation. Figure 1a shows the firespread model without the introduction of a tiller-created firebreak, while Figure 1b shows the change that introducing a firebreak creates. In both figures, the topographical information about the field has the wildfire cell coloration laid over top. The red cells represent actively burning parts of the field, while the black is burnt out cells. The vertical purple line in Figure 1b represents the tiller's path (ie. fire break). However, the tiller ends up running into the fire line, which represents a fail state. Thus, the simulation ends early, and a short message is printed to the screen.

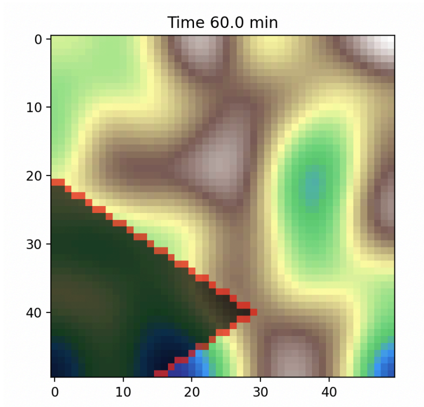

Figure 1a

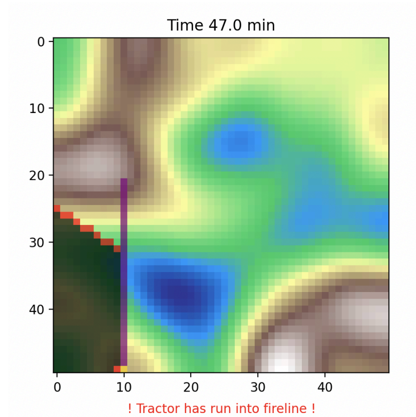

Figure 1b

Timeline

Week 4-6. System setup, fire simulation ✔

Week 7-8. Add tractor and collision logic ✔

Midterm report

Week 9-11. Path simulation and adding sensors to tractor

Week 12-14. Refine path planning

Week 15. Prepare presentation poster, Final presentation

Challenges

Challenges to Date

Challenge	Solution	Owner
Wildfire simulator cell2fire proves difficult to scale for our uses	We pivot to using the more scaled down wildfire simulator SimFire. This proves to be much more functional for our study, and allows for easier integration of the tiller and fire break.	Emerald and Lanea
No average tiller or tractor model	Finding a disk harrow that can take down soybean with popular tractor model with enough HP	Hunter
Adequate thermal sensors to bolt onto the simulated tractor	Using high quality sensor to detect thermal infrared from a distance.	Hunter

Future Challenges/Limitations

Future Risk	Mitigation Plan	Owner
D* Algorithm or DQN cannot keep the tractor safe from fire with a dynamically moving fire	(1) Pivot to different RL models. (2) Simplify fire spreading.	Emerald
Real-life sensor setup is not enough for the algorithm to perform to our goal	Add an aerial view based on information that can be potentially gathered through a drone.	Hunter

Work Distribution

Lanea: Since the project proposal, I worked collaboratively with Emerald on getting the basic simulation up and running. Together we evaluated both the Cell2Fire and SimFire wildfire simulators before ultimately choosing to go with SimFire. Once we settled on a fire simulator, I added in the fire break fuel type and tractor, including movement, fire break fuel type conversion, tractor–fire and fire break-fire interactions. I also helped to write various sections of this midterm report.

Emerald: I mainly worked on setting up the project, including importing the fire spreading algorithm, setting up basic visualization, and generating test maps. I contributed to converting the project idea into an executable plan and coordinating the workload. I also updated part of the midterm report.

Hunter: I worked on finding a tiller, tractor, and sensor to use for the simulation. I also did research on recent wildfires. I helped update a part of the midterm report.

Citations

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