DAI Abstraction Phase - Wildfire Response

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I. Abstraction Representation

A. Abstraction Depiction

Fundamental to the abstraction of a national wildfire response as a SoS is the presence of a wildfire object to be contained. Wildfires will be generated semi-stochastically in the model, with prevalence varying according to season, location, and prior investment in wildfire education and prevention efforts. Wildfire objects will have properties defining their severity, spread rate, and location. The severity property will determine the amount of resources needed to contain the fire and the likeliness to spread will decide the probability of adding an additional wildfire object across a discrete time step.

Equally critical to the abstraction is the firefighting response. This takes the role of an intelligent set of actors with limited information. Firefighting units will have properties of resource quantities, location, size, and technology level. Resource quantities determine how much the unit can commit to wildfire containment efforts (personnel, vehicles, funding), location determines the time it will take for committed resources to act in containing a wildfire (relative to wildfire location), size determines the initial resource quantities and the resource quantity maximums, and technology determines the error bounds on the unit's assessment of the wildfire's properties. This can take a more transient form, such as modeling the addition of aerial or satellite monitoring technologies as a periodic update of the unit's property assessment. In practice, this would close the error gap and lead to the unit responding more efficiently.

The mechanics of the model are determined by the firefighting response's actions. The first priority of a given firefighting unit is to dedicate resources to containing nearby wildfires. Units will prioritize specific wildfires based on their location, size, and spread rate; however, with potentially erroneous information on any given wildfire, firefighting units can over- or under-commit resources, causing a waste of resources or a delay in containment during which a fire may spread. This can also cause an inaccurate prioritization of wildfires near a given unit, meaning that a rapidly spreading wildfire is left to burn while a mostly stagnant one is contained. When all fires local to a given unit are contained, that unit can send resources to other units in need; this "supply chain" will be managed by a separate stochastic fire evaluation, representing a regional or national authority's directive.

B. ROPE/SoS Discussion

To draw a direct connection between the ROPE table developed in the Definition Phase and the paper model, the Resources identified are spread throughout the firefighting response. [1] Individual units, treated as actors in the paper model, are primarily treated as a β-level resource, and the resources they can send to contain a fire (vehicles, personnel crews, etc.) are on the α level. Technology can be considered at multiple levels, depending on where the information generated goes to. The "supply chain" between response units is considered a regional resource. Operations are determined by response actions, on the α level (resources dispatched to a fire taking the action of containing the fire), the β level (firefighting units taking the action of dispatching resources or sending them to other units as needed), or the γ level (widespread regional distribution of resources to contain major disasters). Policy takes into account the encoded "self-preservation" safety threshold on resource sharing as well as the larger pattern of resource sharing between individual units, and economics come into play within the resource property of the units as well as the technology levels. The wildfire objects and their spread serve as the primary SoS driver; the wildfire property information error is then the main disruptor, leading to variance in ideal response strategies.

C. Behavior, Knowledge, Intention Paper Model of Fire Station Agent

Behavior:
- Send resources to put out fire
- Prioritizes Larger fires nearby
- Send resources to another fire station agent and mobilize resources according to budget
- Collaboration with other stations to form a resource supply chain

Knowledge:
- Fire information for the entire simulated region from satellites.
- Real-time information on resource levels of all fire station agents.
- Information regarding the limits of resources that all existing fire stations can hold
- Real-time information on fires within the same grid location

Intention:
- Put out close-by fires in order of severity
- Backup stations that have a serious fire nearby
- Reinforce stations low on resources
- Minimize times and costs of transferring resources to other stations

The simulation will be conducted on a grid mesh, with each block on the grid set to contain either fire station agents or fire objects. The mesh will be updated at discrete time steps likely ranging from an hour to a day depending on the intended model fidelity. Fire station agents will be generated at set locations on the grid and can monitor the same grid-block fires in real time. To minimize the costs of time and economic value from sending resources, fire stations form supply chains via calculated shortest geodesic paths, under the assumption that there are no obstructions between fire stations.

Overall, the model will simulate the interaction between command centers, firefighting resources, and wildfires. The wildfires act as disruptors, with intrinsic intensity, size, growth rate, and cost values that can change over time. They are generated stochastically and require the intervention of firefighting units to contain them. The national firefighting system acts as the main driver in the system as it establishes the command centers and budgets. These budgets allow for the establishment of firefighting resources, command centers, and satellite resources. The firefighting resources each have an internal effectiveness and speed that allows them to travel to each fire and contain it. They are directed by the command centers which can choose to send resources to a fire, send resources to help other command centers, or mobilize and create resources using some cost. The last major resource simulated is the satellites which have an intrinsic accuracy that provides information on each of the fires to the command center. As mentioned earlier though, the total firefighting resources are constrained by the budget and thus cannot exceed that value and need to efficiently allocate resources to each fire. This all serves the main interest of reducing fire damage and cost throughout the full system. The interactions described above make up the main interdependencies of the system.

II. Design Variables

A. Composition

The firefighting SoS is composed of four main systems. The lowest level is the direct firefighting systems. In this case, there are two systems: on-ground units and aerial units. These units can travel to the fire, work to contain it, and share information. These two systems each have their own speed value, which determines how fast they can move to the fire. They each have a target fire, which determines their travel direction. They each have an effectiveness value that determines how well they fight fires. Finally, they have a cost variable that determines how expensive they are to create and move. The next part of the composition is the command centers. These have a location in the environment, and they operate as the main base for the ground and aerial systems. Each base has a certain amount of resources that they can control. They have the ability to direct, share, and mobilize resources. The final systems in the composition are the satellites that provide wildfire monitoring services. These satellites scan the area and collect information about each of the wildfires. Depending on the number of satellites, they will travel over the environment at different times to scan the area. These four systems: ground units, aerial units, command centers, and satellites make up the composition for this system of systems.

B. Configuration

The configuration of the model depends on the interactions between each of the systems. The aerial and ground units mostly interact with the command centers. When not deployed, they will stay at the bases and will return to the bases after a fire is contained. They also can share information and take orders from the command centers. These units also depend on each other since they will work together to contain different fires. As mentioned, the command centers will interact heavily with the firefighting units. They can send, receive, and mobilize these units. Additionally, the centers can interact with other centers. They can share information, share firefighting resources, and request resources from other stations. Several stations can also work together in a single geographic area to fight a fire. This group of centers interacting would make up a higher level on the ROPE table as a Geographical Area Coordination Center (GACC). Multiple GACCs would then form the national fire response. Finally, these centers collect information from the satellites. The satellites can also interact with other satellites by spacing themselves out to have a more consistent information rate.

C. Control

The hierarchy of control in the system is centered around the command centers. They directly command the individual units and can tell them where to go and who to help. They don't have direct control over the other centers, but they have the capability to request and share resources. Further models could include a center base that has control over the GACC and, thus, multiple other centers as well. The satellites and GACC interactions are controlled by the national fire system. This controls the satellite spacing, budget, and priority policy for the centers and satellites. This is the highest level of control in this model.

III. Performance Metrics and Hypotheses

A. Performance Metrics

1) Resource Saturation (%): Resource saturation is the percent of total resources being used to fight fires at any given time. This can be a value for both the aerial and ground resources. A high resource saturation indicates that most of the resources are used and may leave the system vulnerable to major disasters. However, a very low resource saturation may indicate that some of the resources are not being used and may be in excess.

2) Estimated Cost ($): The estimated cost comes from the cost of launching satellites, operating satellites, and expending resources to fight fires. The goal is to minimize the total costs of the system while also ensuring other system parameters are fulfilled. The costs can be estimated from historical values for the operation of large scale fire equipment and also launching and monitoring satellites. Another factor would be the budget of the firefighting corps which can be found through historical values.

3) Average Fire Containment Time (Time steps): The average fire containment time is the average number of time increments that are needed to fully contain a fire. At this point, no more resources would have to be sent to the fire, and the current resources already invested could be recovered. Essentially, this measures the time from fire inception to it being fully managed. This will likely be a function of fire intensity along with the number of resources allocated to each fire. The goal would be to minimize this value.

4) Fire Knowledge (% error): The Fire Knowledge metric determines how accurate the global knowledge over a fire is. Each fire will have intrinsic intensity, size, and growth values, and subsequent measurements will have resulting noise that will reduce the accuracy of the fire information. Having more observations and more accurate ones will increase the information accuracy. Overall, this metric measures the average amount of error in information at any time. Multiple satellite observations will increase accuracy.

5) Total Firefighting Capability (Total Fire Area): The total firefighting capability is determined by the total number of fires the entire system would be capable of containing. A higher capability means that more fires could be contained by the full system. This is dependent on the number of resources and effective coordination of each of the agents along with the types of fires being presented. This metric is useful for measuring the total potential of the system compared to previous configurations.

6) Total Fire Cost ($): The total fire cost determines the amount of damage caused by the various fires across the land. Some land areas will have a higher intrinsic value, such as a city, and some will have less. As fires start and spread in this area, they will cause damage. Thus, the goal of the firefighting systems would be to minimize these costs.

B. Hypotheses

Since the research questions from the definition phase focused mainly on the effect of adding satellites to the overall efficiency of the firefighting network, several hypotheses were generated predicting the effect of these satellites. The first was that increasing the number of satellites would decrease the network resource saturation as the information provided by satellites would allow better resource allocation to each fire. This would allow fire centers to send the optimal number of resources to a fire, minimizing waste and leading to a lower saturation value. However, it is also hypothesized that there is a lower bound of resource saturation where an infinite number of satellites can not lower the value further. Thus, saturation will become limited through total resource amount. This is similarly hypothesized for the knowledge metric. Since each active satellite will increase the operating costs of the system, a second hypothesis was that there would be an optimal number of satellites that balance total cost and system performance. This is because the addition of more satellites will likely have a diminishing return for firefighting capabilities. Thus, there is a level where the costs and risks of an additional satellite will outweigh the benefit it provides to firefighting. The third hypothesis was that satellites would lower the average fire containment time. This is because the satellites would ensure that resource centers do not underestimate fire size as much, leading to insufficient resources. Thus, all fires would have the correct amount of resources. And would be able to be contained quickly without the fire spreading.

IV. Modeling Approach

This project team's intention is to write a MATLAB *agent-based discrete time simulation* for the wildfire response scenario. This will use a grid-based stochastic wildfire domain with spatially disparate response units to model the interactions between units; varying parameters over repeated trials will allow conclusions to be drawn on the effects of different technologies and strategies to wildfire response. The MATLAB program will have three main parts. The first part simulates the land grid with important topography. It then simulates the creation and spread of wildfires. The second part of the program will simulate the resource control centers that can react to the environment, fight fires, share resources, and use information. This makes up the essential part of the firefighting aspect. The final part is the satellite program that works to scan the environment with a certain time delay to simulate the satellite's orbit. The satellites should then send information to the resource centers. These three factors should interact with each other to create a firefighting network capable of detecting, responding to, and containing multiple fires throughout a year.

REFERENCES

[1] Renda Yang Calvin Chang, Max Lantz. AAE 56800 Spring 2025 Team 18 Definition Phase, March 2025.