Project Report

Project Update for RBE 595 - Swarm Intelligence (Spring 2023)

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***Abstract*—This paper proposes to design an algorithm to tackle forest fires using swarm robotics. The paper also aims to tune the system parameters to test the system with different parameters and assess the swarm behavior. The data found using these simulations will be studied and an optimal set of parameters are discussed.**

***Index Terms*—Fire fighting, swarm optimization, parameter tuning, task allocation, algorithm design, path planning**

I. Introduction and Background

Wildfires are currently a major problem the world is facing with the latest environment changes going on. The fire spread makes it extremely difficult for people to navigate through forests and go on extinguishing the flames. But if a swarm of coordinated robots are able to do the task it would make the job easier and safer. Also having robots which have higher mobility can do the task faster.

The problem is how to design the swarm algorithm and parameters of the robot swarm to have the most optimized solution to this problem. Current research has not yet delved deeper into the optimization of the swarm parameters for optimal extinguishing of the fires.

We plan to deploy a swarm of robots in a finite forest simulated environment. The robots will initially perform a random walk around the forest until one of them find a fire and then it communicates the fire to the neighboring robots. The robots then move to the fire site and fight the fire under the set parameters which we will be tuning to optimize the fire fighting scenario. The findings of each parameter tuning are then analyzed and compared. The grid is designed to be a 100x100 array where there are different agents of the forest. The system parameters which we will be tuning for swarm synchronization for the most optimal fire spread reduction are:

- Number of robots
- Forest density
- Number of water reservoirs (refill stations)
- Fire detection threshold
- Robot fill radius
- Fire spread rate
- Fire detection rate

II. Related Work

Previous works in this area have not covered how tuning the swarm parameters will affect the swarm behavior. They are more focused on task allocation. This paper aims to compare all the data from the test simulation runs for different values of parameters done on multiple runs of the simulation and taking its averages. This paper will try to find the most optimal set of values for which the fire spread is minimal and how the swarm will most effectively fight the fire.

Robotic technology has been increasingly applied in fire-fighting operations, including forest surveillance, building fire risk maps, forest fire detection and monitoring [1], post-fire recovery monitoring, bushfire hotspot detection, and supporting disaster relief operations. While research and development on robotic-based fire suppression is still limited [2], using robots in place of humans for firefighting activities is gaining interest due to the dangerous nature of the work.

Some works in the field have had more focus on how different drones will be allocated the task of dousing the fires but very little have studied the effect of how once a task is allocated how other factors of the real world will affect this swarm behavior.[4]

III. Methodology

A. Environment

As shown in Figure 1, the environment will be simulated as a 100 x 100 grid system. Within the grid, there will be reservoirs, clusters of trees, and empty areas. The reservoirs are pools of water that the robots can travel in order to refill their water supply. The location of the reservoirs will always be known to them. There will be clusters of trees that will be able to become on fire. The clusters of trees are scattered across the environment. These trees will be considered obstacles by the robots. The empty area is where the robots are able to travel past.

B. Trees and Fires

Initially in the simulation, there will be no fires. The trees will follow the SIRS model. While the tree is alive and green, it is in the susceptible state. Once the tree is on fire and yellow, it is considered to be in the infected state. While a tree is on fire, susceptible trees that are in close vicinity to the infected

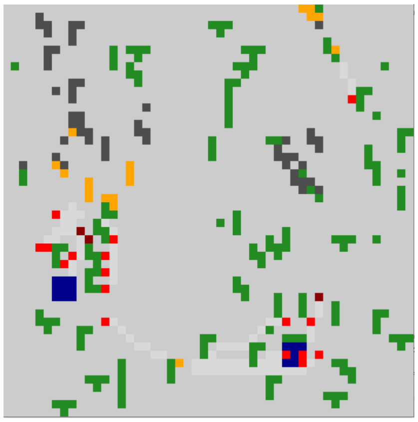


Fig. 1: Example of the environment in the middle of a simulation. The blue is the reservoirs, the green is the trees, the yellow is the fire, the gray is the ash, bright red is robots with water, and dark red is robots without water.

tree will have a probability S of becoming on fire or infected. A susceptible tree will have S chance of becoming on fire for each close tree meaning that the more fires around a tree, the greater chance it will become fire. To ensure that some trees in the environment will be on fire, after 10 steps, a random tree will become on fire. If a tree has been on fire for 60 time steps, it will become ash or the removed state. Ash will be represented as a gray tile. When a fire has gotten B buckets of water from the robots, it will return to being a susceptible tree. Shown in figure 3, is an example of how the trees will act.

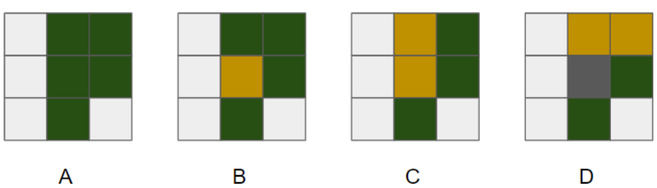


Fig. 2: (A) Initially the trees are alive and healthy. (B) One of the trees combusts into a fire after 10 time steps. (C) The fire spreads to the top tree because it has a higher chance of being adjacent to an already-on-fire tree. (D) Another tree becomes on fire. The original tree has not been put out so it becomes ash. It should be noted that these figures are not one time step away from each other but after many timesteps.

C. Robot Actions

Robots are depicted as a bright red color when containing water. The robots will initially be placed in random locations in the environment and will have water. The robots know the location of all of the reservoirs and will travel to the closest one when they are without water. The robots are fully connected meaning the information they find in the environment they will share with the other robots. The information they are looking for is the location of the fires. The location of found fires is known to all of the robots.

In the scenario when there are no known fires, the robots will pick a random location to walk to. This would allow for the exploration of the environment. If a robot detects a fire that is D tiles away, it will broadcast it to the list of known fires. Once at least one fire has been detected, all robots will choose the closest fire to them and move toward that direction. If the robot does not contain water then it will instead travel towards the nearest reservoir.

Each robot can only carry 1 bucket of water. When it is within dumping range, it will dump its water into the fire. After the water has been dumped it will change to a dark red color.

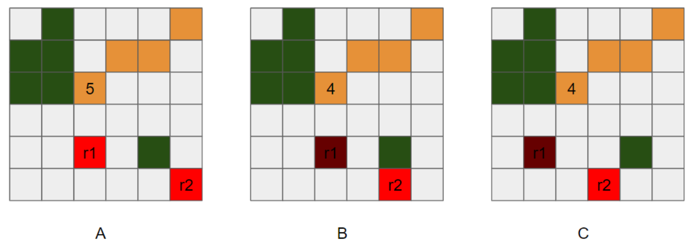


Fig. 3: (A) Robot 1 (r1) in blue is able to see the fire marked 5. This fire is the closest fire to Robot 1 and is within range to extinguish. R1 will broadcast the location of this fire and will attempt to put out the fire. (B) Robot 1 has used its water to extinguish the fire and has changed to a gray color. The fire also changed from a 5 to a 4 indicating it needs 4 more extinguishes before it can become ash. Robot 2 (r2) has received the broadcast on the location of the fire. Since there is no location on fire closer to r2, it will approach the fire broadcasted from r1. (C) R1 doesn't contain any water so it will head towards the hub (not shown in this figure) R2 will look for a fire and notices that there is no fire closer than what it has in memory so it will continue to head towards the fire marked 4.

IV. Proposed Experiments and Expected Outcomes

In order to assess the performance of our forest fire simulation, we will modify various parameters of the experiment and observe the results. Some of the parameters we plan to test and their intuitive outcomes are as follows:

A. Number of Robots in the Swarm (N)

Increasing the number of robots in the swarm would help fight the fire, but having too many robots will be detrimental as they will obstruct one another in reaching their destinations. Having too few robots would mean that the robots would be unable to compete with the forest fires.

B. Changing the rate of spread of a fire that is already burning (S)

This is a probability that when a susceptible tree is next to an infected fire, it will become on fire. The purpose of this variable is to determine whether a fire is able to be saved even when the rate is high.

C. Number of Robots required to douse a block of fire (B)

Each fire will contain the same value in how many buckets it would take to put out the fire. With fewer buckets, the fire would not be able to spread as quickly. The higher number of buckets would result in robots tending to the same fire. We want to see if the swarm will show behaviors of coordinating putting out the same fire before it spreads.

D. Number of Reservoirs (R)

Reservoirs are the only location where robots are able to refill their water. Changing this parameter can show locations where the trees are able to be saved. The reservoir locations are also random in every scenario in order to see how reservoir placement will affect the fire fighting.

E. Fire Detection Radius (D)

This is how many tiles away from the robot that the robot can see if there are any fires. If a fire is within one of the robot's detection radius then it is broadcasted to all of the robots. The variable is a measure of how global knowledge versus local knowledge there is.

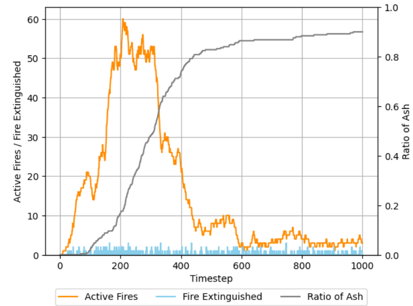
Parameter	Values
Number of Robots	[5, 10, 20]
Fire Spread Rate	[0.005, 0.01, 0.02]
Buckets To Put Out Fire	[1, 3, 5]
Number of Reservoirs	[1, 2, 5]
Fire Detection Radius	[5, 10, 20]

F. Running the simulation

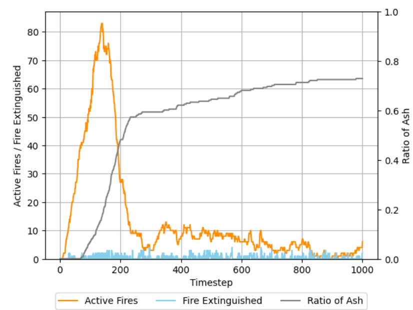
The simulation besides the variables mentioned above will be constant to ensure the fairness of the results. We will keep a constant simulation for all of the experiments. The default configuration is 10 robots, 0.01 rate of spread, 3 buckets, 2 reservoirs, and 10 radius. The only exception is when changing the fire detection radius we will be using 20 robots for each experiment. Each experiment will run for 1000 time steps. The robots will be able to refill their water if they are at least 3 tiles away from the reservoir. They can also fight fires if they are 3 tiles away from the fire. A new fire will appear every 10-time steps. An on-fire tree will become ash after 60-time steps.

V. Results

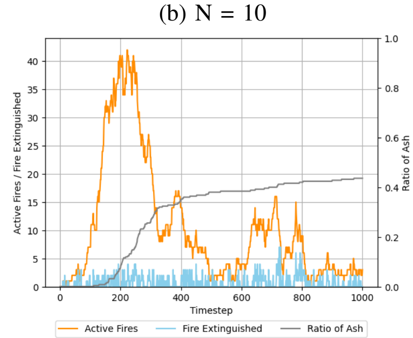
To determine whether the swarm is able to prevent forest fires, we would need to compare how much of the forest lives. The main metric is what percentage of the trees become ash after 1000 time steps. The lower this percentage, the better the parameters were at preventing the fire. We also measured the number of active fires to see when the active fires occur. We also measured the total number of fires extinguished at one time step. If this value is high it means that multiple fires were able to be extinguished at once. This value would be capped at the number of robots there are.



(a) N = 5



(b) N = 10



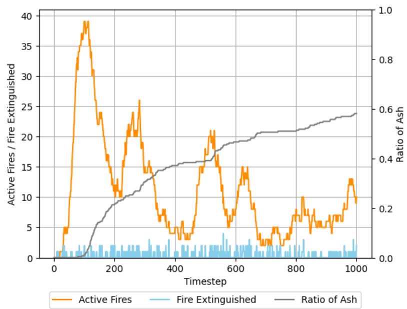
(c) N = 20

Fig. 4: Comparison between the number of robots in the simulation

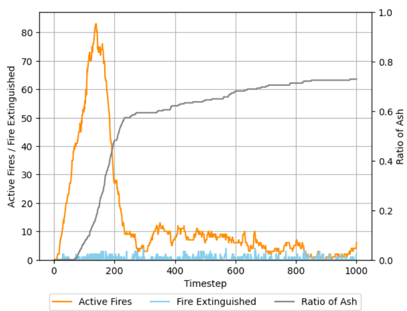
A. Number of Robots

From the results of changing the number of robots as shown in figure 4, it is easy to determine that increasing the number of robots decreases the amount of ash that is in the environment. Having more robots means that more water is being distributed across the environment. The robots are able to reach farther from the reservoirs. When a fire was detected all of the robots would head to the same fire. Once the fire is taken out then the robots would return to their random walk. This mass pivot towards the fire was useful because if there was one fire then there was a higher likelihood that another fire was nearby. This secondary fire can be put out by the robots who were still traveling to the original fire but were not early enough to take out the fire. From all of the scenarios, we can see that there was a large number of fires near the beginning of the simulation but dropped. Only 20 robots had the drop of active fires because it was returned to trees. This is shown by the resurgence of active fires between 600 and 800-time steps. From these parameters, we can see that increasing the number of robots can help reduce ash.

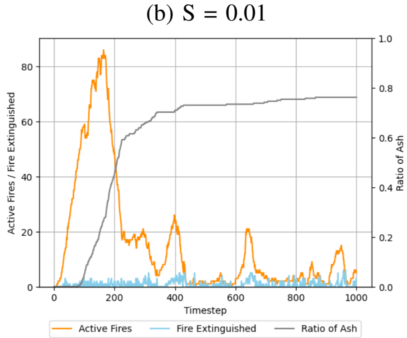
B. Fire Spread Rate



(a) S = 0.005



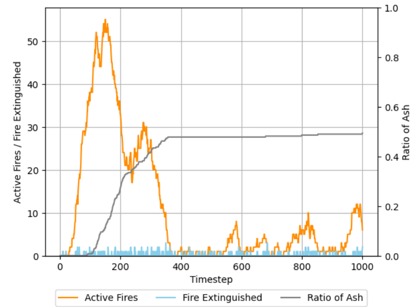
(b) S = 0.01



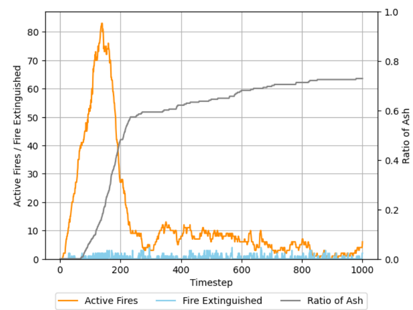
(c) S = 0.02

Fig. 5: Comparison between the spread rate of fire in the simulation

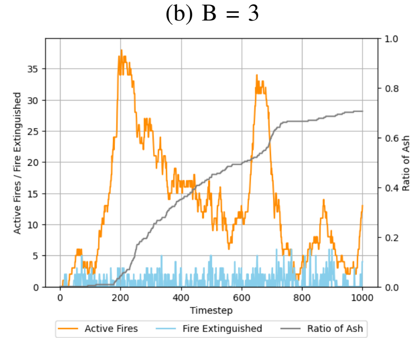
As shown in Figure 5, increasing the fire spread does increase the amount of ash build-up. The fire rate of 0.005 had interesting properties with the number of active fires. A large number of active fires does seem to occur at the beginning but there is a trend of large amount of fires returning. This trend is explained that the fires will become ash before they are able to spread. The amount of high spikes in fires are more caused by the random spawning of fires in the environment. But from this that the robots are still unable to keep the ash ratio below 0.5. In the spread rate of 0.02 we can see less frequent spikes. This is because the fire spread rapidly however the fire was not able to spread to trees that were far away.



(a) B = 1



(b) B = 3

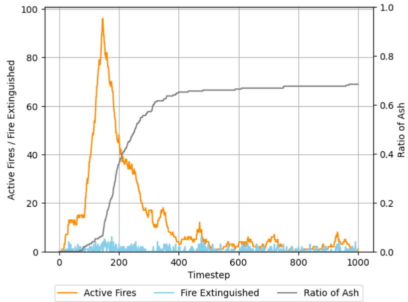


(c) B = 5

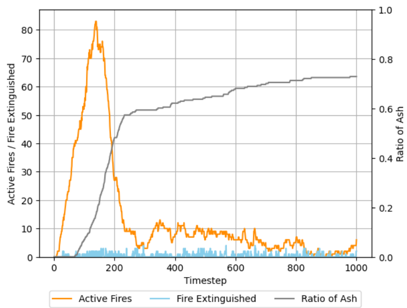
Fig. 6: Comparison between the number of buckets per fire in the simulation

C. Buckets to Put Out Fire

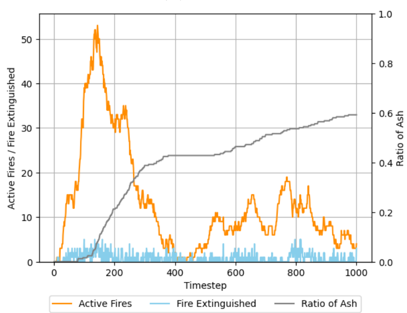
Figure 6 is a comparison between how many buckets it takes to put out a fire. Since a robot is only able to carry one bucket, multiple robots would need to put out the same fire for it to be taken out. Three and five buckets had nearly identical ash ratio. In these scenarios, the robots would only put out fires near the reservoirs and not go farther out. The remaining trees were always the ones closest to the reservoirs so they wouldn't turn to ash. One bucket allowed the robots to quickly resolve the fires near the reservoir so they could explore more. The spike in the number of active fires with five buckets is due to the robots leaving one of the reservoirs to help with the other one. The number of fires extinguished in one time step is much greater because multiple robots are needed to extinguish the same fire.



(a) R = 1



(b) R = 2



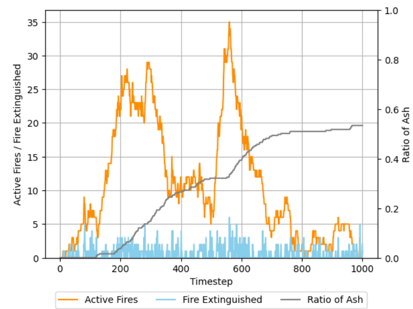
(c) R = 5

Fig. 7: Comparison between the number of reservoirs in the simulation

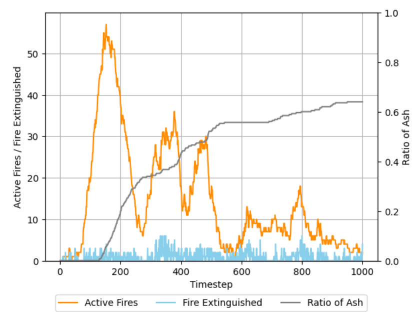
D. Number of Reservoirs

Figure 8 shows the difference in the number of reservoirs. Reservoirs are the only location where the robots are able to refill their water tank. This meant that the trees that are closer to the reservoirs would be more likely to stay as trees. The difference between one and two reservoirs was not that much in the number of ash. The only time it made a difference is when the reservoirs were placed on opposite sides of the environment. However, if they were further away, two swarms would emerge and would treat one reservoir as their own. But since these swarms were smaller they wouldn't be as effective in fighting the fires. Having 5 reservoirs changed a lot. With more access to water, the robot would find a fire and then move to a reservoir close to that fire without having to travel back to the reservoir it came from. The fires that were extinguished were always close to the reservoirs so increasing this value had a much better effect on lowering the ash. The number of active fires was much less in the beginning because of this which is why more fires would appear later in the simulation.

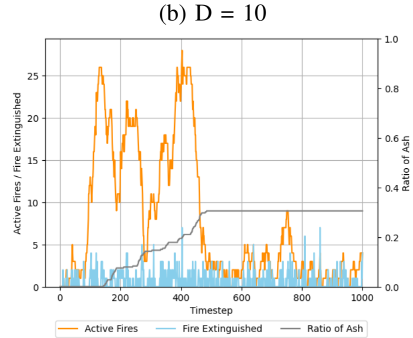
E. Fire Detection Radius



(a) D = 5



(b) D = 10



(c) D = 20

Fig. 8: Comparison between the detection radius in the simulation

For these simulations, we used 20 robots to see if we can develop mini swarms. As shown from the number of reservoirs, if there aren't enough robots at one reservoir then they would travel to the other one to make one large group which is the reason to use 20 instead of 10 robots. Unexpectedly we saw that having the default radius of 10 was worse than having a larger and smaller radius. With the smaller radius, the robots created small pacts because they wouldn't clump together in the beginning with the first fire. When the first fire normally occurs all of the robots would migrate towards it but since it took longer to find the fire, the robots were much more spread out. In the opposite case with a radius of 20, there was a significant improvement in reducing the ash. The robots would immediately find all of the fires and take them out before they have the chance to spread. The number of active fires fluctuated many times because the robots were able to handle fires so there wasn't a huge transformation into ash.

VI. Overall Behaviors

After running all of the simulations, robot behaviors to better explain how effective they are at forest fighting. The reservoir placement was random but their positions greatly affected how the robots performed. Reservoirs farther apart created a diverse area where two sections of the environment could combat the fires. The fires would mainly be fought around the reservoirs because, the time it took for the robots to take out one fire and head back to the reservoir to refill and come back, a new fire would emerge. The random fire starting would cause all of the scenarios to have an initial spike of active fires. The random fires were too frequent that the robots were not able to keep up with the fires far away from the reservoirs. Since the swarm was fully connected, all of the robots tended to stay together. The only times that they split was if the reservoirs were far away and the first fire was handled before it became one large group. The robots were able to handle a part of the forest but until then the fires would take over.

Comparing the ash ratios between all of the fires as shown in Figure 9, we can see that the best scenario is when there were 20 robots with a fire detection radius of 20. In second place is still 20 robots but a radius of 10 and in third place is using 1 bucket to get rid of the fire. It is clear that increasing the number of robots in the same limited space would be effective at removing fires because there is just more water available. Having a larger radius means that having nearly global information is better for the swarm at recognizing fires early. Using only one bucket just meant that fewer robots had to travel back to the reservoir to refuel so there was more exploration. The worst scenario is having 5 robots which makes sense because there isn't enough water to deal with any of the fires. An important observation is that all of the ratios almost plateau. This means that the robots are consistent enough to save a part of the forest. However, they all seem to get to this point relatively early in the simulation so most of the forest is a lost cause.

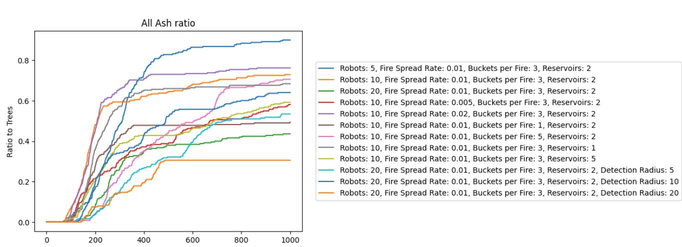


Fig. 9: All of the different scenarios and their ash ratio.

Looking at the number of active fires in figure 10, all of the scenarios have a spike in the beginning. This is caused by the random fires being generated more than the actual spread of the fires themselves. If another analysis is done, this number of creating a random fire every 10 time steps should increase. The number of fires would always decrease because there were just fewer susceptible trees around. The scenarios with the most active fires were having one reservoir and an increased spread rate of 0.02. Having just one reservoir caused the fire to spread more quickly away from the reservoir. Having more reservoirs gave less time to travel from the reservoir to the fire. The increased spread rate was because the fire just spread almost immediately.

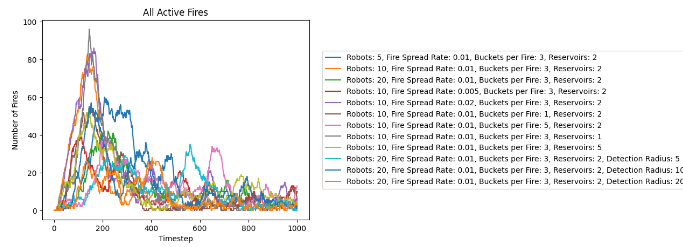


Fig. 10: All of the different scenarios with their number of active fires.

Figure 11 shows the total number of fires extinguished in each scenario. The best scenario was there there were 20 robots with a radius of 10. Simply having more robots made it easier to take out fires. The next best was actually needing 5 buckets to put out a fire. This is because the only fires being put out were next to the reservoirs. While the rest of the environment burned the swarm was effective at keeping the trees next to the reservoirs alive. The third best was having 5 reservoirs because the time to travel between the reservoirs and the closest fire was far less.

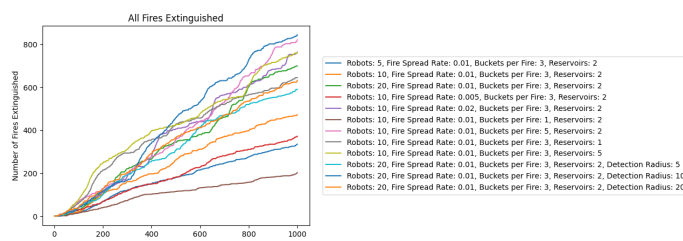


Fig. 11: All of the different scenarios and their total number of fires extinguished.

VII. Conclusion

We created an algorithm that uses a fully connected swarm to combat forest fires. We found some behaviors that the swarm prefers to be near reservoirs and the safest trees are those near reservoirs. The amount of ash created would mostly be around 60 percent of the forest. Increasing the number of robots and their detection radius would be able to drop this number. Since increasing the detection radius would give near-global information about the environment it could have been better to have a centralized system. The robots would clump together in all of the scenarios leaving parts of the environment unprotected if there was no reservoir. A centralized or better algorithm could have had the swarm split up more to cover more area. We were able to create this algorithm but it wouldn't be the best at preventing most of the trees from turning ash.

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