SolarFlare

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In recent years, wildfires in British Columbia have been increasing in both severity and frequency. In 2023, 2245 wildfires burned 2 840 545 hectares, making it the worst wildfire season on record. Wildfires destroy ecosystems, force evacuations, and cause several health problems; these impacts are only growing, along with wildfire frequency. The main cause of wildfires is lightning, which happens mostly in remote regions, so early detection relies on chance observation or delayed satellite detection.[1][3]

Climate change is the biggest culprit for the growing wildfire problem. Climate change causes droughts, heatwaves, and higher temperatures, creating favourable conditions for wildfires. The hotter, drier conditions make the ignition-to-growth time much shorter; now more than ever, early detection is essential to stopping wildfire escalation.[4]

The core issue is not our fire response capacity; it's fast responses and coverage.[2]

My project addresses this problem using both a physical robot and a simulation. The robot is a proof of concept for an autonomous, self-charging wildfire detector. In addition, the simulation is used to simulate communication between detectors in the case of a wildfire.

Literature Review

Human detection methods, such as lookout towers, 911 reports, and aerial patrols, have important limits for early wildfire detection. British Columbia has about 60 million hectares of forest land, making full human coverage unrealistic across such a large and remote area. Studies of fire lookout towers also show that their visibility is often limited: in one analysis, tower visibility ranged from 41.18% upward, and when smoke was assumed to remain at ground level, no towers exceeded 70% visibility. This matters because early detection depends on seeing a fire quickly, and in remote forests, that is difficult to guarantee with human observation alone.[5]

Satellite-based detection is useful for monitoring large wildfires over broad areas, but it is less effective for detecting very small fires early. One reason is resolution: the thermal bands used by MODIS have 1 km spatial resolution, so a very small fire may occupy only a tiny fraction of a pixel and be hard to detect. Satellite detection can also be limited by clouds, smoke, and terrain or canopy effects, which can delay or weaken detection, especially for sub-canopy or smouldering fires. In addition, satellites do not observe every location continuously, so detection depends on overpass timing and data latency rather than constant monitoring.[6]

Environmental sensor networks are a promising step toward earlier wildfire detection, but their biggest limitation is often power and maintenance. Many wireless sensor nodes are battery-powered, and research repeatedly notes that battery replacement in remote or inaccessible areas is impractical. Wired power is expensive and unrealistic in remote forests, while solar-powered systems can also struggle under low-light forest canopy conditions, where shading reduces photovoltaic performance. Because of this, even accurate sensor systems can be limited by how long they can operate reliably without human intervention.[7]

Hardware Proof-of-Concept

Design Considerations

Based on the limitations observed from existing detection methods, there are multiple requirements for a new sensor to be effective. To solve the issue of coverage and power, the robot needs to be able to traverse the forest terrain, including loose rocks, mud, roots, and branches. In addition, the robot needs to be fully self-sufficient; that can be achieved through a light-seeking algorithm. When the robot detects that it is not charging, it will look around for the largest light source, the sun, and orient itself towards it, moving out of the shade. When charging, just like other sensors, it will stay still, looking for any signs of wildfires.

To solve the issue of accuracy, the robot needs to have sensors onboard to detect signs of wildfires. Wildfires can be detected in multiple ways: smoke, an increase in temperature, and humidity. Gas sensors will be able to detect the presence of smoke caused by a wildfire, temperature sensors can detect unnatural increases in temperature, and humidity sensors will be able to tell when a fire is likely to happen.

In addition, the system needs to have environmental durability. The system should be able to resist rain, snow, and extreme temperatures. This can be achieved through a strong frame as well as a durable case to protect it.

Hardware Prototype

These findings led to the creation of my hardware proof-of-concept. The project is a fully autonomous, self-charging wildfire detection system designed to operate in remote wilderness. For the project, I used Arduino parts, a metal frame, and a solar panel. Through research, I found the optimal solar angle in British Columbia is 35.2°, adjustable for each region.[8] I also added a gas sensor to detect wildfire smoke and a radio frequency module to send alerts. I use Arduino for lower energy usage, reduced environmental impact, and software familiarity. The robot uses a light-seeking algorithm to find areas with visible sunlight to charge. If it detects obstacles using its distance sensor, the robot will be able to move around them. The robot also uses treads instead of wheels for optimal weight distribution and all-terrain mobility.

Prototype Limitations

This prototype still has its limitations, though; the radio modules have a limited range, meaning that robots stationed deep within the forest won't be able to communicate possible wildfires to base stations if too far away. However, this problem can be solved using inter-robot communication: rather than communicating directly to a human, the robots can relay the signal to each other, eventually sending a signal to a human.

Simulation Design and Intent

The simulation was built to compare four wildfire detection methods: watchtowers, satellite, robot sensors, and drones. Because real-world testing of these methods would be impractical and expensive, and hard to test fairly, I designed a software simulation to compare these different detection methods over hundreds of trials.

The simulation models a forest as a field of randomly placed trees across a map. Fires start randomly and have a chance to spread to nearby trees. Each detection method is then tested on how quickly it can identify a fire and alert home base.

The robot sensors in the simulation represent the physical robot built in my project. Like the real robot, each simulated sensor unit has a short detection range and uses a mesh communication network to pass alerts between units and back to the home base. This mirrors the robot's wireless alert system and its dependence on proximity to other units for reliable communication.

An important design choice for the simulation was to measure time in simulation steps rather than real-world time. This decision was made because it would have been hard to translate simulation time to real-world time. As a result, the results of the simulation cannot be directly applied to real life. Rather, the simulation can be used to compare simulation methods relative to others. Fire ignition locations are also randomized to prevent any detection methods from having an advantage.

The simulation was also designed to run automatically across hundreds of trials without manual input, producing results including median and mean detection time, standard deviation, and spatial coverage. This makes it much easier to find the fastest methods as well as the most consistent methods.

	Watchtower	Satellite	Robot sensor	Drone
Number in the environment	4	1	12	8
Location in the environment	On the forest edge(fixed positions)	N/A	Throughout forest(random)	Sweeping motions over the forest(random)
Fixed or moving	Fixed	Fixed	Fixed	Moving
Frequency of taking measurements	Continuous	Every 60 simulation steps, 10-15 min real time	Continuous	Continuous
Range	45 pixels	Full coverage	10 pixels	25 pixels
Communication	To grid	To grid	To each other	To grid
Detectable size of fire	Any size	30 fire pixels	Any size	Any size
Cost per unit	Varies widely (~$60,000)	Data is free, satellites are extremely expensive	~$120	~$10,000
Detection method	Human observers or cameras	Thermal imaging	Sensors(gas,heat, humidity, cameras)	Visual or infrared cameras
Visibility	Fog/rain, terrain	Clouds, smaller fires, tree cover	Little impact	Clouds, fog, tree cover

Sources: [9][10]

Simulation Experiments and Results

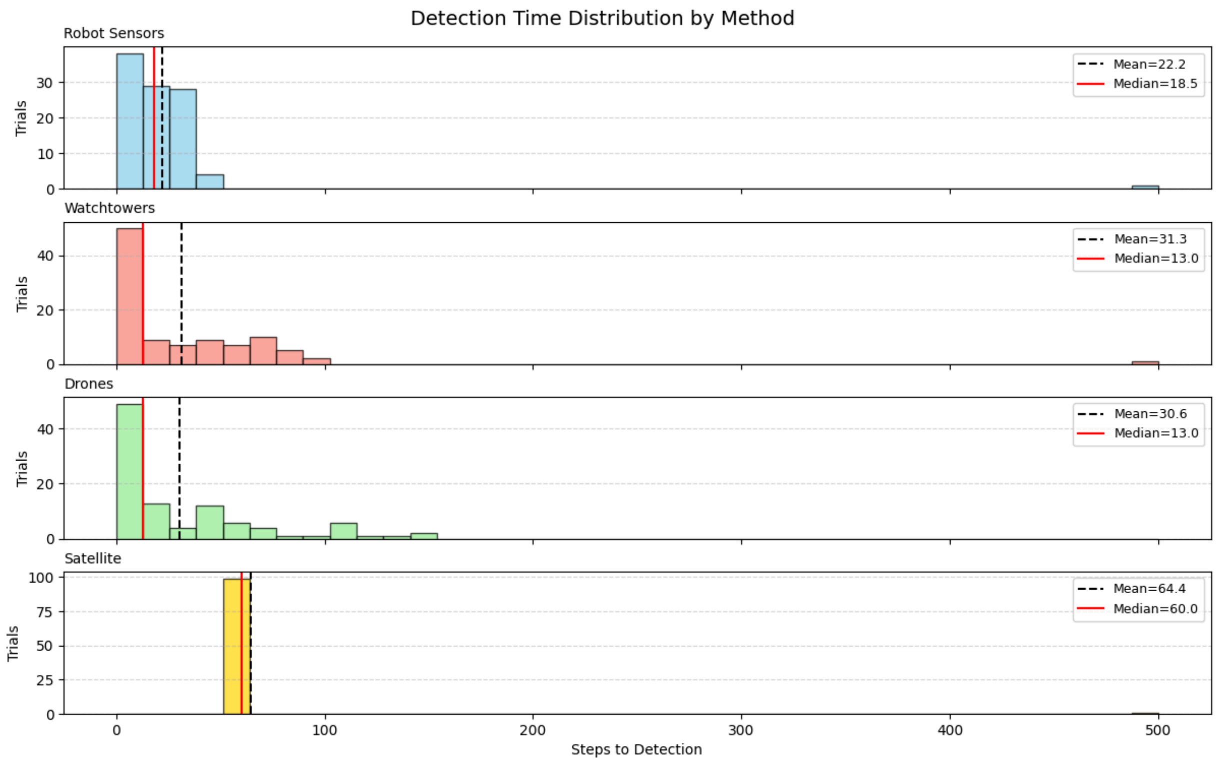
To compare the 4 different detection methods, the simulation was used to run 100 trials for each one, finding their average, median, and maximum detection steps. Totalling 400 trials, each one had randomly spawned fires, which all progressed step by step until a fire was detected or until the simulation reached 500 steps.

Each method was tested using the same forest layout and fire behaviour to ensure fairness. The only thing that changed across experiments was the detection method, which ensured that any differences in performance could be attributed to the detection method rather than any other factors.

In addition, the simulation also showed the coverage of each detection method in terms of the percentage of the forest covered. For the satellite, this is always 100%, which is offset by its periodic scans and minimum fire size for detection. For the robot sensors and the watchtower, coverage is fixed to their set location. For drones, coverage is represented by the combined coverage of all 4 drones at any given time.

The results of the experiment are shown below.

Method	Median (steps)	Mean (steps)	Std Dev	Max (steps)	Coverage
Robot Sensors	18.5	22.2	50.1	500	15.1%
Watchtowers	13.0	31.3	56.0	500	49.0%
Satellite	60.0	64.4	44.0	500	100.0%
Drones	13.0	30.6	38.1	144	27.9%



Watchtower and Drones

Watchtowers and drones both achieved the lowest median detection time of 13 steps. However, they both had high variance, shown by their high standard deviations(56 and 38.1, respectively). This is explained by their coverage: the watchtowers are stationed in the four corners of the map, leaving the middle uncovered. As for the drones, because they are constantly moving, they could be patrolling away from the fire's location in many circumstances. Because of their inconsistencies, both the watchtower and satellite took the longest on average(31.3 and 30.6 steps, respectively).

Satellite

The high median of the satellite is because of its structural limitations: because it can only scan every 60 steps, the minimum detection time is 60 steps. In addition, the satellite requires a minimum of 30 burning trees to be able to detect any fires, so it is difficult for it to detect fires instantly, as the other detection methods can. The standard deviation of 44 shows that while the satellite is more consistent than the watchtowers or drones, fires that spread slowly or stay under the minimum detection size can go undetected for long times. These results align with the findings in the literature review: the low resolution of the satellites means that they have trouble detecting smaller fires, and the time between scans can also allow fires to spread rapidly.

Robot Sensor

The results of the experiment show that the robot sensors achieved the fastest mean detection time of 22.2 steps, making them the fastest detection method despite having the lowest coverage of 15.1%. This is the most important finding of the experiment because it shows that even with low individual detection ranges, 12 distributed sensors are still capable of detecting fires more quickly than other methods. No matter where a fire starts, it will usually spread to one of the 12 sensors. However, the median of 18.5 shows that while most fires are caught early, some fires can take much longer to detect.

These results support the goal of the project, which is to prove that a network of low-cost sensors can outperform much more expensive alternatives in mean detection time. However, the sensors are still inconsistent, as demonstrated by the high standard deviation(50.1).

No single method completely dominates across all metrics. Watchtowers are fast in good conditions but unreliable when fires start away from corners. Drones are mobile but unpredictable. The satellite is the most consistent, but it cannot catch small fires early. The environmental sensors, despite having the lowest coverage, still have the fastest average detection time. This proves that many small-range units spread across a forest can collectively achieve detection performance comparable to more expensive or infrastructure-heavy alternatives.

There are still some limitations to the simulation, though; in real life, drones do not have constant uptime like in the simulation because they need time to charge. In addition, their movement is not as unpredictable as it may be in the simulation. As for the detection range, the range for various types of detection methods can vary widely, so these results can not be directly applied to real life. For example, the range of a watchtower in the simulation may not translate directly to real life. Finally, the simulation can only imitate wildfires at a very basic level; there are many factors that affect wildfire spread that are not included. For example, wind, weather, or humidity.

Conclusion

This project set out to address the growing wildfire problem in BC. My solution was to develop a low-cost, autonomous ground sensor for wildfires. For the project, I developed a physical prototype with most of the robot's basic functions, like fire detection, light-seeking, and all-terrain navigation. To simulate fire detection, I created a simulation to compare different methods; the results of the simulation proved that my idea of multiple, spread-out sensors could perform just as well as the much more expensive alternatives.

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