Development and Testing of a Targeting System for Localized Suppression:
Extended Abstract

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Abstract

Localized suppression of a fire can be advantageous, limiting the fire spread and reducing fire damage. However, the ability to apply a suppression agent to a localized area comes with challenges such as the need for early detection without false positives, bounding of the fire area, and ability to quickly apply agent to the specified area. A student start-up out of the University of Illinois Urbana-Champaign (FireStrike Industries) has designed a suppression system around an advanced infra-red tracking system that effectively targets and delivers the onboard dry chemical suppressant to a nearby fire. Currently the technology is in an advanced prototype validation stage (TRL 7). The paper and presentation will describe the development of the detection capabilities including localization, delivery of the suppression agent, and development of a gimbal used to apply the agent to a targeted area. The detection capabilities are a combination of smoke detection, rate-of-rise heat detection, and absolute heat detection, reducing the chance of false activation while at the same time offering rapid activation time. The targeting system is based around a commercially available infra-red (IR) sensor mounted on the gimbal end effector; this combination allows the IR sensor to scan the entire coverage area, avoiding the need for a wide angle, high resolution IR camera. During one test, the system detected and extinguished a fire 26 seconds after ignition of the smoke source, while the ceiling temperatures remained below 80 °F. The paper will provide test data including detection and suppression times for various fire sizes and growth rates, system coverage area, and challenges with scaling and agent selection for specific applications.

Keywords

Localized Suppression, Thermal Imaging, Combination Detection, Suppression Agents, Targeted Suppression

Introduction

This system is a self-contained fire suppression device that provides localized suppression by utilizing infra-red (IR) targeting to locate a fire's exact location and extinguish it. Compared to many fire suppression systems, this system operates electronically. This provides many benefits beyond the IR targeting, for example, as everything is accomplished through software, it is extremely customizable for any applicable. Any parameters, such as what baseline levels of IR to ignore or when the IR scanning is started can easily be tuned to meet various needs.

Background

Conceptual design of this localized fire suppression system started out with a group of four engineering students at the University of Illinois Urbana-Champaign. Several iterations of prototyping and testing lead from the original non-targeting version to a simple targeting system based on a grid of thermistors and ultimately to the final advanced IR targeting used on the current system. While the system was progressing, the team was growing with the addition of two career firefighters and a software developer. Networking at the NFPA's 2015 Expo led to the association with Fire Risk Alliance which ultimately led to the collaboration for this paper.

System Design

As the system is designed to be a localized suppression system, it is completely self-contained except for the necessary power input which could either be from a 115 VAC 60 Hz or 12 VDC source. **Error! Reference source not found.** below shows the entire

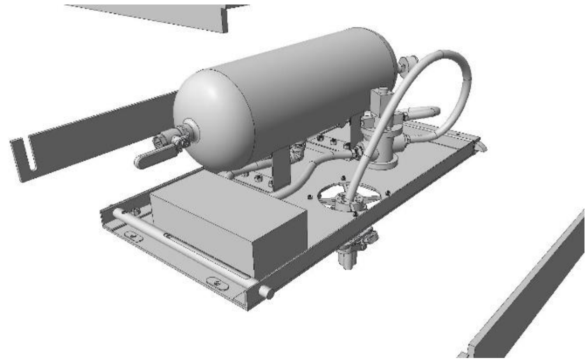

Figure 1. System Overivew: the system is entirely self-contained fire suppression system that offers localized suppression through infra-red targeting. Not shown is the removable cover.

system with the major components which consist of the targeting gimbal, suppressant tank, electronic valve, and microprocessor/electronics. The overall dimensions of the system are 24 in. by 12 in. by 10 in.; the weight of the system is approximately 50 lbs. which includes 20 lbs. of suppressant.

Targeting Gimbal

The targeting gimbal allows the system to direct where the suppressant is sprayed as well as positions the IR sensor to view any area in the coverage area.

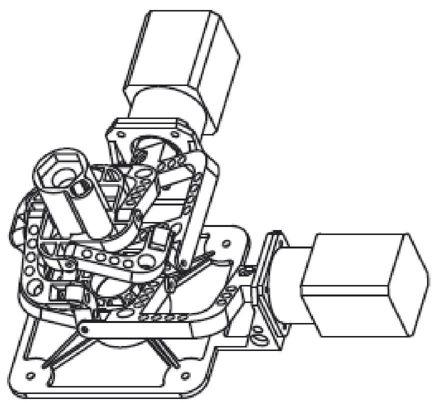

Figure 2. Targeting Gimbal: the target gimbal allows the IR sensor to be scan the environment and positions the extinguishing nozzle.

This gimbal allows for two rotational degrees of freedom, so when positions are referred to, they are based on the angle of the nozzle from the two planes of the motors. This makes the targeting algorithm independent of the height of the ceiling and in fact independent of the orientation of the system itself. This is of course if the effect of gravity is ignored; at some point the suppressant would divert from the straight path the algorithm assumes. The possibility of correcting for distance has been considered but as of yet as not been tested.

The current targeting gimbal is manufactured by 3D printing each part and using metal pins to connect the links. However, the design is well suited for injection molding or machining. The motors are commercially available stepper motors with a gearbox attached to achieve the desired torque output.

Suppressant and Tank

The current system is based on a standard ABC dry chemical suppressant which is contained and pressurized in a 20 lbs. tank. Other configurations of tank size or even connecting to a supply network such as a pre-existing sprinkler system are feasible with minimum effort. Alternative suppressants could also be used, the only requirement would be that they be a streaming agent and not a flooding agent. The pressure required would have to be taken into consideration and a different tank, tubing, and valve might be required but the overall system design and targeting would be unchanged.

Electronic Valve

The valve in use is a solenoid air pilot poppet valve. The poppet style valve provides tight sealing as the tank's pressure helps keep the valve shut and this style of valve was found to work repeatedly without issues where other types of valves kept clogging because of the nature of the dry powder. This poppet style valve is similar to the valves found in ABC dry chemical fire extinguishers. A disposable C02 cartridge is used to provide the force to open the poppet valve, the flow of C02 is controlled electronically by a solenoid valve. This CO2 cartridge has enough pressure for dozens of valve cycles; however, in principle it would be replaced after every activation event.

The benefit of this style of value is that it provides extremely fast response around the order of 50 milliseconds. Electronic ball valves were also tried which worked without issues but had much slower response times which became important as the total time to locate and extinguish a fire kept on reducing.

Microcontroller/Electronics

The device is run by a 16 MHz 8-bit microcontroller which interfaces with and controls all the peripherals with consists of the stepper motors and their associated drivers for the targeting gimbal, the IR sensor, smoke detector, electronic valve, and thermistors.

IR Sensor

The infra-red sensor is a commercially available 16 by 4 pixel array with a 60° by 15° field of view (FOV), corresponding to a 3.75° by 3.75° FOV per pixel. The refresh rate is programmable up to 512 Hz, which exceeds the maximum scanning speed; meaning the motors are the limiting factor in determining how fast a fire can be targeted.

Thermistors and Smoke Detector

Three standard thermistors are used to monitor the ceiling temperature and rate of ceiling temperature increase. A commercially available smoke detector is used to provide a Boolean input of the presence of smoke.

System States

The system operates in one of two modes, monitor mode or active mode. In monitor mode, the system does not actively search for a fire using the infra-red sensor. Once appropriate conditions are detected, the system switches to active mode where it actively searches for the fire. While it is possible to continuously search for a fire, doing so would draw significantly more power than waiting till a fire is probably started and would lead to increased wear on the motors and targeting gimbal.

Monitor mode

Monitoring mode is the state in which the system waits for a fire to occur; as such, much of the time will be spent in this mode. The goal of monitoring mode is to determine when a fire is most likely present. As such, in this state the system behaves similar to a standard fire sensing device. However, the system does not need to be as confident in detecting a fire as a fire sensing device as it will rely on the infra-red data to actually determine if a fire is presence.

The monitoring state consisting of reading thermistor data every 0.5 seconds. On the current model, three thermistors are used. Simple error correcting consisting of computing the average and standard deviation of the three values and ignoring a thermistor value if it is too far from the average is used. The three thermistor readings (possibly two if the error correcting detects a bad thermistor) are averaged to compute a single temperature level at a given time instant. After computing this average, a linear least squares equation is fit to the last 20 temperature readings, covering a time period of 10 seconds. From the least squares equation, a time averaged temperature and time averaged rate of temperature increase are extracted.

If we let T_i be the temperature value at time t_i, where in this case $i = 1,2 \ldots 20$ which can be generalized to $i = 1,2 \ldots n$, a linear equation through all these points would consist of the form

$$T = At + b \tag{1}$$

where constants A and b are given by

$$\begin{bmatrix} t_1 & 1 \\ t_2 & 1 \\ \vdots & \vdots \\ t_n & 1 \end{bmatrix} \begin{bmatrix} A \\ b \end{bmatrix} = \begin{bmatrix} T_1 \\ T_2 \\ \vdots \\ 1 \\ T_n \end{bmatrix} \tag{2}$$

In practice, this equation cannot be solved exactly as there are more equations than unknowns. However, constructing the least squares line through the points gives the best fit. Applying least squares gives the equation

$$\begin{bmatrix} t_1 & t_2 & \cdots & t_n \\ 1 & 1 & \cdots & 1 \end{bmatrix} \begin{bmatrix} t_1 & 1 \\ t_2 & 1 \\ \vdots & \vdots \\ t_n & 1 \end{bmatrix} \begin{bmatrix} A \\ b \end{bmatrix} = \begin{bmatrix} t_1 & t_2 & \cdots & t_n \\ 1 & 1 & \cdots & 1 \end{bmatrix} \begin{bmatrix} T_1 \\ T_2 \\ \vdots \\ 1 \\ T_n \end{bmatrix} \tag{3}$$

Multiplying out and solving the resulting equations for A and b (skipping multiple steps for the sake of conciseness), gives the results

$$A = \frac{n(\sum_1^n t_i T_i) - (\sum_1^n t_i)(\sum_1^n T_i)}{n(\sum_1^n t_i t_i) - (\sum_1^n t_i)(\sum_1^n t_i)}$$
$$b = \frac{-(\sum_1^n t_i)(\sum_1^n t_i T_i) - (\sum_1^n t_i t_i)(\sum_1^n T_i)}{n(\sum_1^n t_i t_i) - (\sum_1^n t_i)(\sum_1^n t_i)} \tag{4}$$

Letting $t_{max} = \max(t_1, t_2 \ldots t_n)$, the time averaged temperate and time average rate of temperature increase are given by

$$aver.temp. = At_{max} + b$$
$$aver.rate = A \tag{5}$$

Other equations could be fit to these data points as well, such as a quadratic or cubic polynomials. The idea would be the same, but the resulting equations would change.

In addition to these two values, the system also utilizes a smoke detector connected to a hardware interrupt on the microcontroller. No sampling interval is required as the interrupt will let the microcontroller know when the smoke detector senses the appropriate level of smoke.

Based on these three criteria: time averaged temperature, time averaged rate of temperature increase, and the presence of smoke; the system decides whether or not to switch to active mode. The current criteria is if any of the three are met.

As all these are software based criteria, the awakening criteria can be modified to suit various applications by changing the limits or by changing the criteria itself, such as requiring the presence of smoke and either the average temperature or average rate to be greater than their respective limits.

Active mode

Once the criteria for switching from monitor mode to active mode is met; the system switches to active mode. Active mode consists of two steps: locating the fire and extinguishing the fire. Of course, both these steps do not have to be accomplished if the locating step determines that no fire is present.

Targeting

Targeting consists of locating the hottest location in the environment. This is accomplished by scanning the environment using the infra-red sensor. The infra-red sensor has a 60° by 15° field of view (FOV). The targeting nozzle can pivot 38° in any direction from vertical, giving a coverage area of 76° by 76°. The actual coverage area in square feet is dependent on the height of the system. As the coverage FOV is larger than the IR sensor FOV, multiple IR images from multiple locations are required to view the entire coverage area.

This is accomplished by the targeting gimbal, see Figure 3. The targeting gimbal allows the IR sensor and the targeting nozzle to be rotated to any area in the 76° by 76° coverage area. On an 8 ft. ceiling, this corresponds to a floor coverage area of 13 ft. by 13 ft. This coverage area increases with the height of the system off the floor.

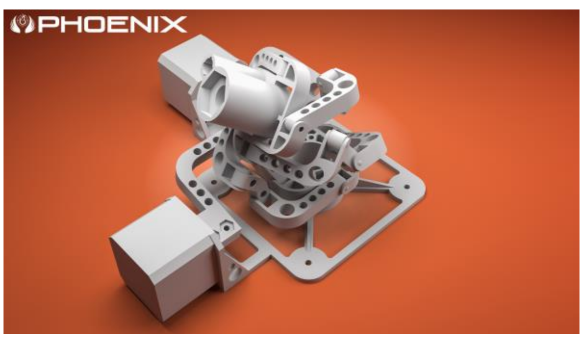

Figure 3. Targeting Gimbal: the target gimbal allows the IR sensor to be scan the environment and positions the extinguishing nozzle.

Upon awakening, the system commences a global scan, where the targeting gimbal positions the IR sensor to view preset locations to effectively cover the entire area. With a coverage area of 76° by 76°, 21 IR images are required giving 48 by 28 individual IR readings for a total of 1,344 data points. This global scan takes on average 4.4 seconds to complete.

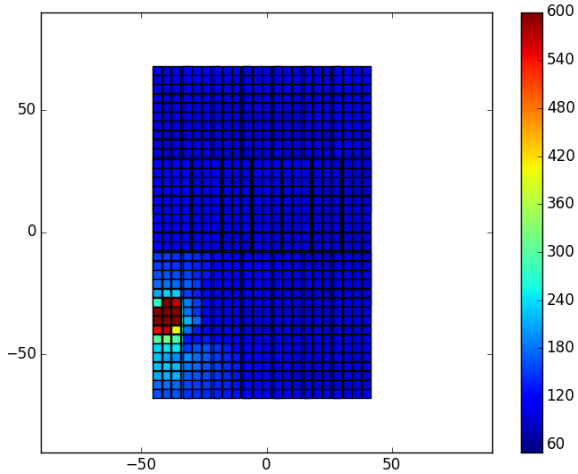

Figure 4: Global Scan: this is an actual infra-red data set of a global scan with a fire in the lower left corner. The color scale is in °F. This scan took 3.81 seconds and consists of 1,344 individual readings.

The algorithm is designed to allow for parallel processing which would reduce this time even further; however, to date this has not been attempted.

Figure 5: Actual Fire: this is the fire that the system saw in Figure 4.

Once the global scan is complete, if the system has located a hot spot, it rescans around that specific area. This is done to make sure that the IR data around the fire is as current as possible. Once this is accomplished, the fire's location is calculated and the system checks its activation criteria.

Activation

Once the scanning mode has targeted the potential fire, the system determines if it should activate or not. The six criteria used to determine activation are the following: absolute ceiling temperature, rate of ceiling temperature increase; temperature of the potential fire, size of the potential fire, rate of growth of the potential fire's temperature, and rate of growth of the potential fire's size.

Absolute Ceiling Temperature

The absolute ceiling temperature is calculated based on the readings of the thermistors. The three thermistors are averaged together using error correcting to make sure all are functioning. Then a time averaged value is computed using the least squares approach discussed earlier. If this time averaged temperature is above a preset limit, currently set at 140 °F, the system will activate.

Rate of Ceiling Temperature

The rate of ceiling temperature increase is based on the time averaged rate of temperature increase recorded by the three thermistors as discussed earlier. If this rate is above a preset value, the system will activate.

Temperature of Potential Fire

As the system utilized IR to locate the fire, a direct reading of the potential fire's temperature is possible.

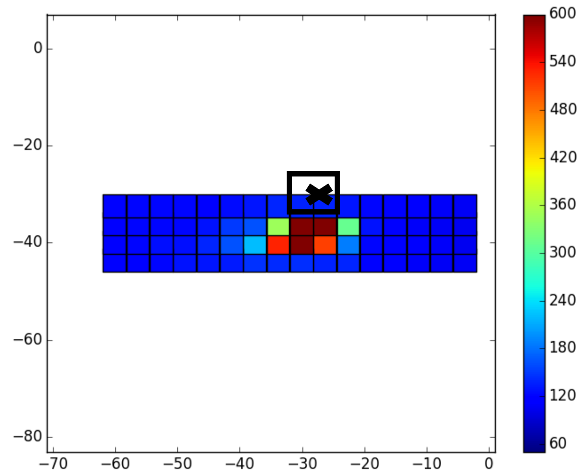

Figure 6. IR Image: this is an actual infra-red image take from a fire. The color scale is in °F. The location of the hottest spot is given by the "**x**". The four pixels surrounded by the black line are the four nearest neighbors. The average of these four pixels is used as the temperature of the fire.

The temperature of the fire consists of the average of the 4 pixels of the IR sensor closest to the potential fire. If this temperature is above a preset limit, the system will activate. This is illustrated in Figure 6.

Size of Potential Fire

This criteria is also based on the readings from the infra-red sensor. The size of the potential fire is based on the number of hot pixels from an infra-red image centered at the potential fire's location. The size of the potential fire is based on the sum of all hot pixels in the current reading. A hot pixel is any pixel above a set temperature. If this sum is too high, the system will activate.

Rate of Growth of Temperature of Potential Fire

The system also tracks the rate of growth of a potential fire. This criteria is only used if the system has located the same potential fire's location before without activating (i.e. the system targeting this location before, but at the time the activation criteria was not met). If the system has targeted the potential's fire location before and the rate of growth of the potential fire's temperature is too large, the system will activate.

Rate of Growth of Size of Potential Fire

This is similar to the rate of growth of size of a potential fire except it is based on the growth of the potential fire's size.

Not activate

If none of these criteria are met, the system does not activate. Instead it scans the immediate area surrounding the location of the potential fire in case the fire is spreading or in case the first location was inaccurate. If the potential fire is still present, the system will retarget it. At this point the rate of growth of both the temperature and size criteria can be used. If any of the activation criteria are now met, the system will active. If not, this step is repeated. A maximum limit is in place to keep the system from getting stuck focusing on a hot but invalid location.

Asleep

If after any scan is complete, all the awakening criteria are not met, the system exits active mode and resumes monitor mode. It will properly enter activation mode if any of the awakening criteria are met again.

Activation mode

Once the fire is located and the activation criteria are met, the system opens the solenoid air pilot poppet valve releasing the suppressant. A minimum and a maximum discharge times are built in. Between these upper and lower limits, active monitoring of the IR data is used to determine when to stop releasing suppressant.

While the suppressant is being released, the IR data is centered at the fire's location (as the nozzle and IR sensor are aligned) and the IR sensor continues to read data. For each image taken from the IR sensor, the fire's location and temperature within that image is computed. If the temperature is above a preset limit, the system repositions the nozzle to this new location to continuously focus on the hottest spot of the fire. If the temperature is below this value, the nozzle is not repositioned.

If at 10 consecutive IR sensor readings, the temperature is still below this limit, the system stops releasing suppressant as the fire is extinguished. This is of course dependent on if the minimum discharge time is met.

After activation is finished, the system will revert back to targeting mode. If the fire rekindles, the system will re-locate and engage. While in scanning mode, if all the awakening criteria are not met, the system exits active mode and resumes monitor mode.

Although the system is designed to and can suppressant multiple fires, this was done to handle re-ignition or a multiple fire scenario. In practice, the system would undergo maintenance after every fire. This would consist of refilling and charging the suppressant, cleaning the valve, and changing out the disposable CO_2 cylinder.

Testing

The system will be tested on three different fire sizes, three distances, and two growth rates. Each test will be run three times for repeatability. The two different growth rates are fast growth fires consisting of flammable liquid isopropyl alcohol pan fires while the slow growing fires will consist of wood cribs. The fast growing fires' sizes will be controlled by adjusting the pan size. The slow growing fires' sizes will be varied by controlling the amount of wood cribs.