Sensor-Driven Inverse Zone Fire Mode

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Abstract

As sensor use in buildings becomes more wide spread, it is possible to use this information as input to an inverse fire model in order to enhance the value of the information available from sensors in both fire and non-fire conditions. Typical fire models use the heat release rate (HRR) of the fire as an input and sensor outputs are calculated. An inverse fire model uses sensor signals as inputs in order to estimate the HRR of the fire.

An inverse zone fire model is being developed at NIST to be used in conjunction with the NIST Virtual Cybernetic Building Testbed to investigate the feasibility of such a model. Version 1.1 of this model uses ceiling jet algorithms for temperature and smoke concentration to convert the signals from heat and smoke detectors to HRR. A version of CFAST is then used to obtain layer temperatures and depths for the room of fire origin as well as surrounding rooms. Details of the ceiling jet algorithms for smoke concentration and temperature will be discussed and an example of the predictive capabilities of the inverse zone fire model will be demonstrated.

Introduction

A sensor-driven inverse zone fire model makes use of signals from a variety of sensors such as smoke, heat, gas, etc. to detect and predict the evolution of a fire in a building. In order to accomplish this task, the fire model must be able to discriminate between fire and non-fire conditions, must be able to recognize detector failure in both fire and non-fire scenarios, and must be able to determine the size, location, and potential hazards associated with a growing fire.

The fire model must be flexible in that it needs to have the capability to handle fire scenarios in rooms where there may be anywhere from a suite of detectors to no detectors. In the no detector case, detectors in adjacent rooms would provide the necessary sensor input to the model. For the suite of detectors, the model must be able to take advantage of the increased amount of information in order to provide earlier and more reliable detection. The model must also be able to accommodate sensor failures due to a growing fire and still continue to provide estimations of fire growth and location. Finally, the model must be able to handle a large number of rooms and must complete its calculation cycle in a time interval that is shorter than real time.

The inverse fire model described in this paper is at an early stage of development with only a subset of the above features present. In the next sections of this paper, the model will be described and an example of its capabilities demonstrated.

Sensor-Driven Inverse Fire Model

Version 1.1 of the sensor-driven inverse fire model, SDIFM, is designed to predict the heat release rate, HRR, of the fire based on signals from either smoke or heat sensors positioned below the ceiling and sampling the ceiling jet produced by the fire. The estimated HRR is the used by a variant of the zone model CFAST[1] to predict layer temperature and heights in the fire room and the surrounding rooms in the building. Based on the predicted layer temperature and height, room conditions such as limited visibility and flashover potential can be deduced.

In non-fire situations, the SDIFM is designed to look for sensor failure, to discriminate between nuisance signals and fire induced signals, and to monitor the condition of detectors that degrade over time.

The structure of the fire model is as follows:

1. The user enters building information that includes the number, location, size, type of vents, and connectivity of the rooms, corridors and other spaces.
2. The user enters the location, type, calibration constants, and set point for each sensor.
3. The model initializes itself and begins to learn about the building environment.
4. The model routinely cycles through all the building sensors checking for signs of sensor failure or possible hazardous/fire conditions.
5. The user will be notified of the location and sensor type for each sensor identified as having failed or otherwise needs replacement.
6. If the model identifies a possible fire signal, a false alarm protocol will be used to verify that the sensor signal is responding to a real fire.
7. If the possible fire signal verifies as a real fire, then the model will estimate fire size and location, predict fire growth and spread, and identify possible fire associated hazards in rooms with or without fire.

No Fire Mode

The model will spend virtually all its time performing item 4. In this mode, the signal received from each sensor will be compared with the historic record to identify any deviation from normal operation. Sensor failure modes will be checked for the sensor type and manufacturer, and sensor signals that fall into these modes will result in a sensor failure signal being sent to the appropriate monitoring station.

Version 1.1 of the inverse fire model has only a simple checking algorithm available that detects sensor failure based on either no signal or a saturated signal from the sensor. As this section of the model is expanded, it is planned to allow a user to enter failure modes that are particular to a specific sensor.

Fire Mode

When the model receives a sensor signal that indicates a HRR increasing with time that has reached a target threshold, the model will try to verify that it is a true fire by assessing the signals received by other available sensors in the area. Such sensors might include CO or CO_2 sensors as well as heat or smoke sensors. If other sensors do not support the fire signal, a trouble signal will be issued and the program will revert to its normal sensor polling. If no other sensors are available in the room or if other sensors also support the presence of a fire, a fire alarm will be issued.

The target threshold for the model to start checking for a fire is based on two alternative methods of defining a fire signal. The first method used by the model is to compare the sensor signal with a user prescribed signal. This signal would be one that has been developed by observing the response of the sensor to small test fires. The second method would be based on looking at the time history of the sensor signal once an estimated HRR based on the sensor signal has been reached. If the sensor signal indicates a time growing hazard that has reached a particular HRR, a fire alarm will be issued.

The determination of a HRR from a sensor signal requires knowledge about the characteristics of the sensor and its position with respect to the fire. Sensor characteristics include the calibration curve for the analog/digital signal generated by the sensor as a function of temperature, optical, or smoke/gas concentration and the delay time introduced either by thermal lag or flow conditions into the sensing element. NIST is presently testing smoke detectors to provide the necessary data for a subset of this type of sensor.

Once the sensor characteristics have been defined, the HRR may be estimated using modeling correlations coupled with a zone fire model. In the following discussion, it will be assumed that only one sensor is present in each room. The sensor will be located close to the ceiling where it can be considered in the ceiling jet. Presently, the SDIFM contains algorithms to estimate HRR from either the excess temperature or the smoke concentration in the ceiling jet. Both algorithms will require substantial testing and may not be the final algorithms used in the model.

HRR from ceiling jet temperature

The present algorithm that is used to determine the HRR from the ceiling jet temperature was developed by Davis, et. al.[2] The model gives the ceiling jet temperature as a function of radial distance from the plume centerline as a function of HRR, layer depth and temperature, and the location of the fire. In the application of this algorithm to heat detectors, it is assumed that a layer has developed that modifies the radial dependence of the temperature of the ceiling jet but that the layer temperature is not sufficiently higher than ambient such that the ceiling jet temperature is increased by the presence of the layer. With the above assumptions, the HRR can be determined from

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$$Q_c = 0.172 H^{5/2} \left(\frac{r}{0.18H} \right)^{0.345} \left(\frac{\Delta T_{cj}^{3/2}}{T_\infty^{1/2}} \right) \qquad \textbf{(1)}$$

where Q_c is the convective heat release rate, H is the ceiling height above the fire surface, r is the radial distance from the plume centerline, ΔT_{cj} is the excess ceiling jet temperature, and T_∞ is the ambient temperature. To get the total heat release rate, the radiative fraction of the fuel, χ_r, must be estimated. For large fires, the radiative fraction will be relatively small, perhaps on the order of 0.2[3]. The total heat release rate, Q, would then be given by

$$Q = \frac{Q_c}{(1 - \chi_r)} \qquad \textbf{(2)}$$

Equations 1 and 2 contain four unknowns, H, χ_r, r, and ΔT_{cj}. In situations where a hot upper layer is believed to have formed, the convective heat release rate calculated in equation 1 will be assumed to equal the total heat release rate. This approximation attempts to correct partially for the impact of the hot upper layer on the temperature of the ceiling jet. In a subsequent version of the SDIFM, a zone model estimate of the layer temperature and depth in the space may be incorporated to correct the ceiling jet temperature for layer effects. With this information, the entire model for the ceiling jet in reference 1 can be used to deduce a more accurate HRR.

In situations where only one heat detector is available in the room of fire origin, the values of H and r must be assumed in order to obtain a crude estimate of the HRR. A reasonable estimate for enclosures of normal room height would be that the ceiling height above the fire surface, H, is approximately 0.25 H_r, where H_r is the floor to ceiling height. For rooms where high rack storage exists, a larger value may be warranted. The value for r could be estimated as equal to 0.5 times the minimum room dimension. Since the radial dependence is not strong, this value is not nearly as important to the calculation as the estimate for H.

For two or more detectors present in the room, the estimate for H still needs to be made unless the detectors are at varying heights from the ceiling. Assuming that this is not the case, an estimate for H of 0.25 H_r is still appropriate but the radial distance to the fire can now be estimated if the detector spacing in the room is known.

HRR from ceiling jet smoke concentration

An algorithm has been developed which provides an estimate of the maximum smoke mass concentration in the ceiling jet as a function of position and HRR[4]. The maximum smoke mass concentration in the ceiling jet is given by

$$C_{s0}(r) = \frac{7.94 Y_s Q^{2/3} \left(\frac{H}{r} \right)^{0.57}}{h_c (1 - \chi_r)^{1/3} \left(1 + \frac{0.0853 (1 - \chi_r)^{2/3} Q^{2/3}}{(H - z_0)^{5/3}} \right) (H - z_0)^{5/3}} \tag{3}$$

where C_{s0} is the maximum smoke mass concentration in the ceiling jet, r is the distance from the plume centerline, H is the distance from the fire surface to the ceiling, h_c is the heat of combustion, Y_s is the smoke yield fraction, χ_r is the radiative fraction, Q is the total heat release rate, z_0 is the virtual point source. This equation is inverted in the SDIFM such that the HRR is calculated from the measured smoke mass concentration. This correlation was developed for the unconfined ceiling situation and must be modified once a smoke layer develops. NIST is developing a set of experiments to test this algorithm for several fire sources.

Estimating extent of fire hazards

Once a HRR has been obtained for one or more of the identified fire sources, this information will be passed to a version of CFAST in order to calculate layer heights and temperatures in each room of the structure. From this information, hazards such as limited sight, high temperatures and potential for flashover may be identified on a room by room basis for the current fire conditions.

In addition, with a known HRR history, projections can be made using CFAST to estimate fire growth and spread. The present version of SDIFM does not have this capability and it can be included only after the algorithms for estimating the HRR have been verified experimentally.

Model verification

Since the SDIFM is designed to operate in a space with a large number of rooms, verification of the algorithms becomes a major problem. One way to do verification will be to use the results of multiple room fire experiments and test the predictions of the SDIFM against these experiments. The number of these fire experiments is quite limited, so an additional method of verification is being used. The Virtual Cybernetic Building Testbed at NIST is a computer platform where the building ventilation, heating and cooling, and sensor activities in a multiple room building can be simulated. The present structure modeled in the testbed contains three rooms and will be upgraded to six rooms. Using CFAST or FDS[5], a fire scenario can be generated for the testbed and the resulting sensor signals coming from the testbed can be used as the model input for the SDIFM. In this way, the SDIFM can be tested using a virtual fire source and receive signals which are representative of what may happen in an actual fire scenario.

An example of a simulation of a fire scenario using the three-room test bed using the visualization software, NIST Smokeview[6], is shown in figure 1. A fire starts in room 1 and grows rapidly with the SDIFM issuing warnings of a growing fire and showing the present room conditions as far as the need for protective clothing, limited sight, or flashover. As fires start in the other rooms, the SDIFM identifies the fire condition and ends up following a multiple room, multiple fire scenario.

The SDIFM has been tested with scenarios that had as many as fourteen rooms with four of the rooms containing fires. The calculation cycle for the model has been significantly faster than real time. The portion of CFAST used for SDIFM has significantly faster execution times compared to the release version of CFAST, 3.1.4.

A number of issues arise when sensor data is used to determine fire spread. The predictive accuracy of this type of model will decrease as the fire scenario being tracked begins to differ from the physical and geometrical assumptions used in the model. Phenomena such as wind, window breakage and wall collapse all have substantial impacts in the ability of the model to predict fire growth and spread. Since the model depends on sensor data, there is a feed-back mechanism to accommodate some of these effects. Substantial testing will be required to evaluate the predictive accuracy of this type of fire model.

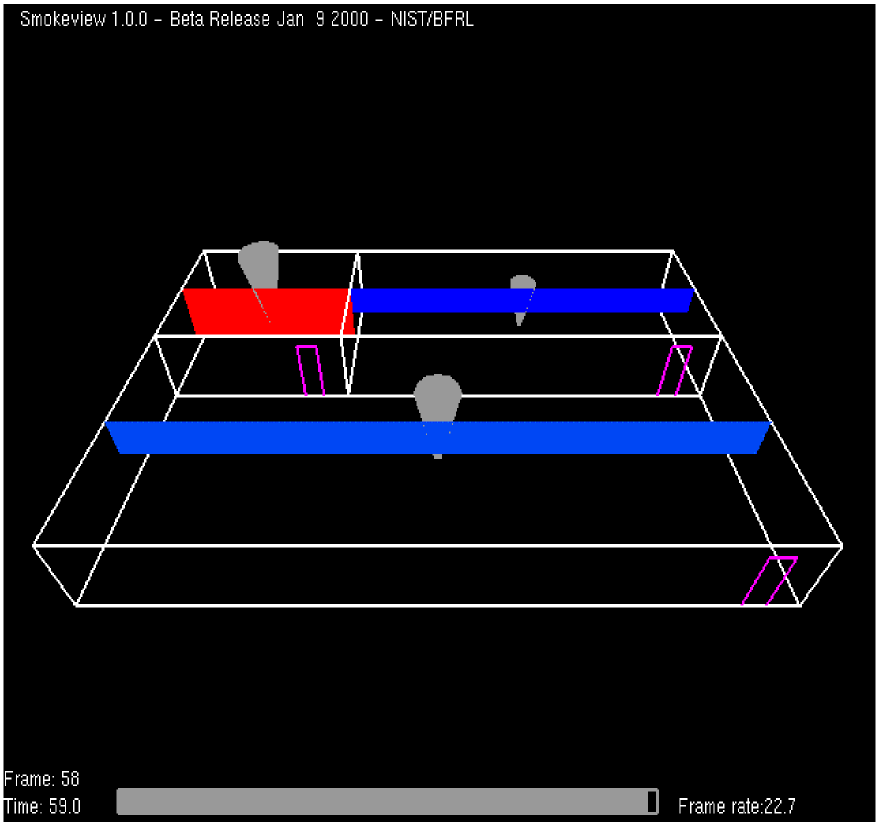

Figure 1 Three room simulation of a fire which started in the small room. The colored slices represent the layer depth with the red color indicating flashover conditions and the inverted grey cones showing the presence and size of fires in the rooms. The visualization is done using NIST Smokeview.

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