Towards Predicting High Sensitivity Smoke Detector Operational Performance in Building Environments

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Abstract

A scalable approach to very early warning fire detection systems is needed to address a diverse set of building environments. In this paper, an integrated model was developed to evaluate detector performance in the building environment. The approach evaluated the early fire detection performance of fixed and adaptive sensing aspirating smoke detectors. The validated modeling results showed adaptive sensing provides reduced false alarm rates in a number of scenarios. This approach can provide decision makers critical information on a detector's performance in the context of the building environment.

Keywords: Aspirating Smoke Detector (ASD), ROC Analysis, Building Environment

Introduction

High sensitivity smoke detection systems offer a very early warning to a fire hazard, typically by employing laser scattering measurements that provide sensitivity that is orders of magnitude greater than conventional detectors. With high sensitivity, the risk of false or nuisance alarms is inherently higher but such risk is typically reduced by proper design, installation and commissioning that incorporates an understanding of the specific installation environment. However, achieving such a tailored design, installation and commissioning process (within a quantitative framework) is not straightforward.

In commercial buildings for example, while the number of small (less than 25,000 sqft) commercial buildings is substantial; by floor space, large (greater than 25,000 sqft) commercial buildings dominate with over 60 % of the build space [1]. Given that fire detection systems are deployed over a diverse set of building environments, a scalable approach to solutions is required.

High sensitivity smoke detection design philosophies for commercial buildings have been developed heuristically, which if not certified by outside agencies, cannot assure desired performance. A key gap is the design knowledge to relate point detection performance to the overall smoke detection system performance for long term exposures to a dynamic building environment. There is growing interest for modelling and optimizing the performance of the building's services at early stages of the construction project. This leads building engineers and owners to demand fire detection system performance tied to building operations and events.

Closing this gap would enable designers and building owners to better understand the impact of sensitivity, latency and detector false alarm rates (FAR) in the context of a given building environment. This would enable more informed and consistent smoke detection system setting selection, including the threshold selection or the use of adaptive algorithms.

Background

Significant advances have been made recently on developing methodologies for predicting the performance of smoke detectors. In 2008, the NFPA published a report on a validated engineering methodology to calculate and accurately predict the response time of spot-type and aspirated smoke detection systems exposed to specific cases of incipient fires and growing fires [2]. In addition, experiments conducted by Dinaburg and Gottuk (2012) demonstrated a method and apparatus for controlling smoke concentration levels to measure the drift and sensitivity of air sampling detectors (ASDs) during exposure to small levels of smoke [3]. Utilizing the 2012 results, James Milke, John Vythoulkas and Yun Jiang demonstrated a method to simulating response time and sensitivity impact on ASDs with respect to low ambient smoke levels [4].

These findings provide a basis for understanding the detector model's sensitivity in particular situations, such as after a pre-exposure to a background level of smoke. These studies are first steps towards addressing the need for methodologies that evaluate the impact of sensitivity, latency and detector FAR in the context of the building operation.

While the sensitivity of a detector has been reliably predicted with methods as previously mentioned, modelling the probability of nuisance alarms during the detector's lifetime involves the creation of more complex models of the building's environment and its long term evolution.

Objective

To develop a methodology for calculating and visualizing the operational performance of aspirating smoke detectors during long term exposures to characteristic building environments.

The key metrics of the classic ROC analysis are true positive rate (TPR) (which, in our case, characterizes the probability of the detector providing an *early* fire detection) and FAR. The joint representation of these metrics for a representative operation time will allow evaluating the reliability of a detector to detect smoke and minimize disruptions due to nuisance and false alarms.

Model Development

The model developed focuses on linking building operations to ASD operation by calculation of the receiver operator characteristics (ROC). This approach provides a graphical means to measuring a smoke detector performance [5]. Ultimately, such a model is intended to support the evaluation of detector performance over days and years (with environmental variability) and to determine the impact to alarm decisions made every second. Towards this goal, separate models were created to simulate building operations, smoke and nuisance events, detector performance and algorithms. The building operation, events and detector models were experimentally derived while the algorithm models were developed in C-code and run on Matlab and Visual Studio.

The decision to experimentally derive versus simulate components of the model is based on the estimated accuracy gained from each approach. Historical data and known relationships for detectors in specific building environment are substantial and likely of higher fidelity than a standalone simulation. Given a specific building environment, there remains a vast range of potential nuisance or fire events which can vary significantly, with any one test not being representative of the potential range of scenarios. Simulation of such events can cover a broad array of conditions beyond what is possible with experiments alone. Finally, the algorithm performance is simulated using the actual algorithm embedded within the detector to provide true representations of the response.

The integration of each model is achieved by providing a common input and output enabling the output from the building operation and events models to be inserted into each detector model. The output of the detector model then flows to the algorithm model. The final output, the alarm decision, is then tied back to the building operation and event inputs.

For the purpose of illustrating the utility of such a model, a test case was chosen that could readily be validated with experimental data.

The test case consisted of an elevated and sustained ambient pollution level created by a typical daily event in a given building, represented in our experiments by a paraffin candle lit twice per day and then snuffed. Candles were lit at 9 am and 6 pm and allowed to burn for 15 min before being extinguished.

This experiment is intended to serve as an easily reproducible test case for the purpose of model validation. At the same time, it provides insight into a potential operational scenario a building owner may face: in a warehouse a diesel truck starts every morning in preparation for loading of refrigerated goods for delivery runs, altering the ambient pollution level but not representing an actionable fire or smoke event. Such a scenario can highlight the tradeoffs between fixed vs. adaptive sensitivity approaches with respect to detector true positive and FAR.

The experimentally derived detector model incorporates the detector's front end response (DUT 1's detector readings with respect to smoke concentration shown in figure 1). ASD detectors typically have a large dynamic range with nonlinear responses. Each manufacturer's detector performs a calculation of this response before calculating the sensitivity and alarm levels. This linearization is based in the transfer function of the circuit which needs to be experimentally validated in order to build a simulator. The following steps were followed in our case:

1. In a smoke tunnel, create very slow ramps that increase the smoke density up to 0.2 % obs/m and get the particles density vs the laser head response (the obscuration in this case has to be estimated from the particles concentration).
2. Create in a smoke tunnel slow ramps that increase the smoke density up to 2 % obs/m and get the obscuration vs the laser head response.
3. Create in a smoke tunnel ramps that increase the smoke density up to 20 % obs/m and get the obscuration vs the laser head response.
4. Smoldering fire testing in a fire room and get the obscuration vs the laser head response.

By experimentally validating the transfer function of the detector circuit, Figure 1, the relationship between %LH and smoke concentration can be determined. Characterizing this transfer function for different detectors will allow using the same stimulus model to compare the behavior of different detector models.

For the simulation of our device with adaptive algorithm, the source code of a Detector Under Test (DUT) 1 was used. The hardware dependencies to sensors are emulated in a model-view view model application that provides synthetic inputs. The use of visual studio allowed the algorithm code to be separated from the user interface and hardware. Using this approach, data is fed to the application and the firmware clock is sped up to reduce computation time. The algorithm model environment can simulate the decision making of both fixed and adaptive sensitivity algorithms. The obscuration, laser head value, and alarm threshold is then output in an Excel spread sheet for ROC analysis.

After incorporating the model components described above, evaluation of an ASD during long term operation in building environments can be performed in terms of true positive and FAR. Note that in this paper we maintain the TPR naming used for classic ROC analysis. The TPR is defined as the ASD's identification of the fire event in the incipient stages. The definition relates to the operation of high sensitivity smoke detectors for early warning.

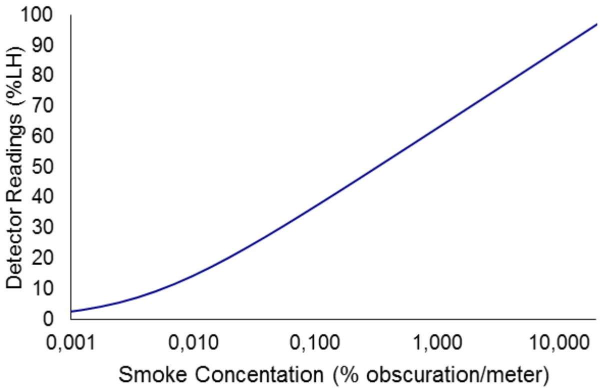

Figure 1. Experimentally derived relationship between the smoke concentration observed in the environment and the detector readings needed for the algorithms.

A measure of a system's ability to balance performance can be represented graphically with an ROC curve as shown in figure 2. In an ROC curve, a given detector performance is plotted as the probability of early detection or TPR as a function of the FAR (Specificity). Each point represents a sensitivity / specificity pair corresponding to the fire detection threshold settings selected in a particular detector. Given that typical building owner/operators expect high rates of detection with low FAR, the measure of performance is then evaluated as the minimum distance from any point in the ROC curve to the ideal goal (100 % fires detected early with 0 false alarms. Goal is represented as a 'star' in figure 2).

The representation of the detector performance with an ROC curve enables understanding and communicating the impact that the alarm threshold has on performance. The choice in alarm threshold for fixed sensitivity systems provides a specific sensitivity / specificity performance. The overall detector performance is fixed. This means that earlier detection is a trade for higher FAR and potentially inferior performance given the false alarm tolerance. In the current study, the DUT 1 and DUT 2 utilize fixed sensitivity to determine the presence of smoke.

However, algorithms and hardware that provide adaptive decision making capability moves the detector performance closer to the goal (figure 2). This enables a detector to provide equivalent or better sensitivity at lower FAR. The adaptive sensing approach studied utilizes the fluctuations in the background particulate levels to adapt the alarm threshold. The DUT 1 studied in this paper has an additional setting that utilizes adaptive sensing to set the alarm threshold. Looking at the detector over an extended period of time, it can be inferred that the sensitivity of the detector to a fire remains constant, as it adapts to the fluctuations caused by the ambient conditions. This enables adaptive sensitivity to keep constant the ratio between true alarm events and probability of nuisance alarms during the detector life. The approach shifts the overall detector performance closer to the goal.

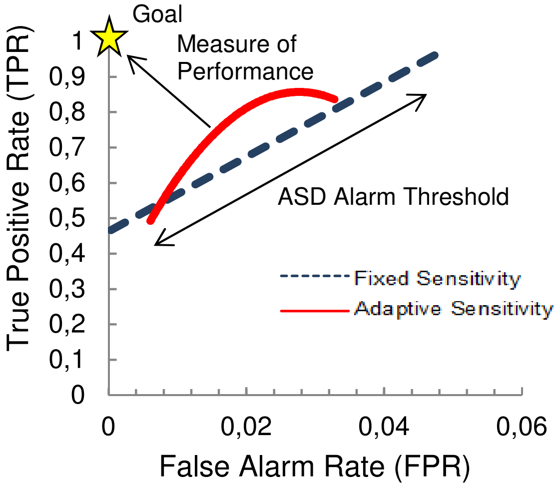

Figure 2. Illustration of an ROC analysis, a given detector performance is plotted as the probability of early detection or TPR as a function of the FAR.

Experimental Validation of Model

A key component of the model development was the validation of the detector simulation. Five detectors were used in the study: Two detectors for study and 3 reference detectors. Four DUT were connected to a smoke distribution box: The two detectors for study were a Kidde Senator 100 and a Vesda-VEU; the two reference detectors are a Kidde Senator 200 and a Vesda-VLP. An additional ASD was used to pump smoke into the distribution box as well as monitor the smoke level input. Sampling air is transported via conventional 27 mm air sampling pipes. The tests have been executed at a stable environmental lab temperature of 22 ºC.

The endcaps and holes of the detectors inlets were been calibrated in order that all DUT aspirate the air at an average speed of 2 m/s to provide a transport time from fire room to detectors of < 30 seconds. The exhaust pipe returns the sampled air into the chamber as well to maintain the equilibrium of differential pressures.

In order to ensure all detectors saw the same levels of smoke at the same time, measurements were conducted in a sealed chamber and connected to a smoke distribution box. Smoke was pumped from the fire room to the distribution box via an ASD Smoke detector to monitor the smoke levels being transferred to the distribution box. This detector provided the basis for the fire test ground truth. The two other reference detectors were placed inside the distribution box to monitor smoke distribution within the distribution box. The homogeneity of the smoke seen by the detectors was then validated using four EN54-20 standard cotton wick fires with permutation of detector positions between tests. The detector responses matched within 0.02 % obs/m and 5 seconds.

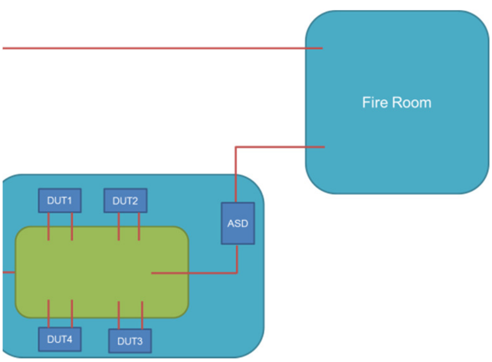

Figure 3. Picture of experimental test rig and schematic showing the test setup.

Alarm conditions and laser head values were recorded for the Kidde Senator100 and Vesda-VEU at a rate of 0.003 Hz. The sample values correspond to the highest value obtained during this period to ensure we capture alarm conditions. The period of time was chosen based on the resolving power needed to describe the smoke conditions and capture performance of the detectors with respect to multiple, slowly evolving, smoke conditions. The sensitivity settings for the Vesda-VEU and the Kidde Senator100 were 0.4 %obs/m and Alarm Factor 2, respectively. These settings were selected to maintain a high degree of fidelity between the detector responses.

The model validation test included a mix of nuisance sources and real smoke events over ten days to simulate a building environment. In the tested scenario, 24 hours of background data was collected. This was followed by a series of nuisance events, in this case elevated background particulate levels, generated by 2 candle burnings per day over 4 consecutive days. A period of 5 days of no nuisance events followed. Finally, the test concluded with a standard BS6266 single wire burn test, representing a real fire event.

Performance Analysis using ROC

ROC analysis was used to compare the performance of fixed and adaptive sensing algorithms for ASD. The comparison requires measurement of performance with respect to a ground truth. In the present case, we categorize the fire ground truth as the wire burn and the nuisance ground truth as the eight candles that were burned. The results from the fixed and adaptive sensitivity data sets were then analyzed to decide if the output of the detector was a true positive or a false alarm.

The ROC analysis is displayed in the figure below. In the fixed sensitivity operation, the detectors are able to identify smoke quickly leading to a higher true detection rate (Fixed threshold at 0.3 %Obs/m), but at the cost of an increase in false alarms. At the least sensitive setting, obscuration at 2.3 %Obs/m, the detector did not false alarm but the sensitivity was reduced by 50 %. This observation from the modeling results matched with the DUT 2 (blue diamonds). In fixed sensitivity operation, equivalent performance was observed for both detectors.

The adaptive algorithm performance (Red Squares) plotted in the figure below demonstrates how decision making improves performance. The improvement in performance predicted was then validated with DUT 1, which showed a reduced FAR at a TPR of 0.833. Note that the simulated results under predicted performance due to the conservative assumptions of the model. In the present case monitoring variance of background particulate levels provides the additional information necessary to improve the overall detector performance. The shift can be attributed to the detector monitoring the variance in the background particulate levels that occur over 24+ hours.

A key requirement for a system level analysis is the availability of high quality, independent ground truth data. In the present case, the fire ground truth is defined as from the start of the wire burn test until 60 minutes afterwards. This means that a true positive detection occurs when the detector alarms for part or all of the 60 minutes. An increase in interdependence between ground truth data and the DUTs will generate spuriously high performance of all detectors. Given that high quality ground truth data is often lacking, comparisons of relative performance along a ROC may be more informative and avoid inherent test bias that may result from selection of ground truth data. As an example, fixed sensitivity detectors operating at different thresholds reflects positions on the ROC curve (in this case a straight line) enabling selection of a true detection rate (at the expense of the false positive rate), but has no impact on the overall shape of the curve. This is the case for comparing fixed threshold operation and adaptive sensing. However, improvements in performance are shown as movement of data points and curves closer to the goal of a 100 % true detection rate and 0 % FAR. In the present case we see adaptive sensitivity enables settings that improve the detector performance by changing the shape of the ROC curve.

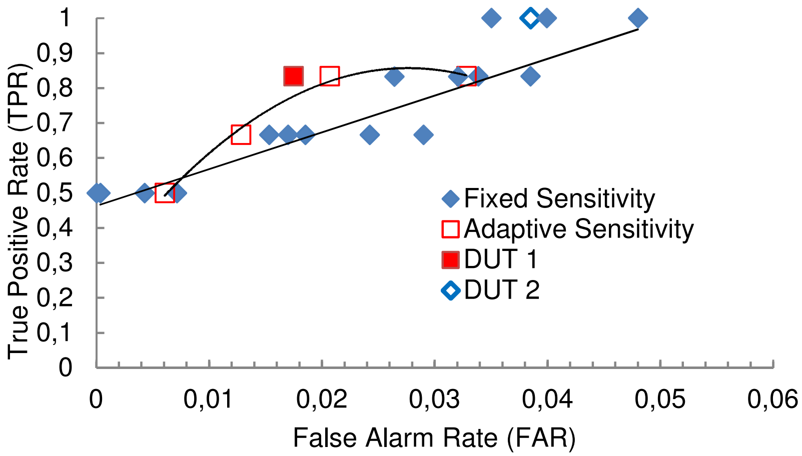

Figure 4: Results from the ROC analysis

The model based approach combined with an ROC analysis demonstrates the ability to compare the overall performance of two fundamentally different ASD constructions. The results also show the improvement enabled by using adaptive algorithms. This finding is similar to previous work by Rose-Pehrsson on early warning fire systems for a specific naval application. In that case, early warning fire detection systems were experimentally evaluated with an ROC analysis to support detector down selection [6]. However, building applications can have a large number of operating conditions. This requires a model based approach to analyze larger data sets required for building applications.

Discussion (extensions to other data sets)

The model approach under development and presented in this paper can be applied to any building context and better illuminate the tradeoffs between early detection and false alarm risk. The benefit from visualizing (via ROC analysis) performance and drawbacks for various use cases for different ASD settings will provide more informed and consistent design decisions. Fixed threshold systems offer a rather predictable linear relationship between loss of sensitivity and false alarm probability. However, adaptive systems show a ROC performance that is generally closer to optimal but depends on the temporal profile of air pollutants and the dynamics of the adaptive algorithms. This makes ROC analysis further desirable to plan the configuration of ASD systems with adaptive sensitivity.

Any number of scenarios can be envisioned during ASD operation since the environment is dynamic. As a starting point, we confine the study to normal operating conditions. A system level study of performance is very dependent on the environmental data sets chosen for analysis. Achieving a balanced view of the detector requires evaluation over long operational periods in real environments substituted with a balance of simulated environments that span a diverse set of backgrounds.

The use cases in the present study will include situations that provide a balanced view of the scenarios. These scenarios are based on historical data of normal building operations with ASD systems installed for three scenarios:

1. Daily fluctuations – operations in buildings that contain situations with frequent exposure to large fluctuations in background particulate levels.
2. Seasonal fluctuations – operation over the course of a year that exposes ASD to fluctuations in background particulate levels.
3. Infrequent background fluctuations – clean room/telecom/data center operations that have been built with an ASD and are under normal operation.

These scenarios are generated by hybrid datasets including synthetic data and/or data from real environments. Response time, sensitivity and FAR will be assessed in this context. An ROC analysis for fixed threshold and adaptive sensitivity will be analyzed for a given parameter. The overall detector performance will then extracted by evaluation of the ROC curve to distinguish between nuisance and fire cases.

Summary

The goal of this work was to extend the current capabilities of predictive tools for ASD smoke detectors. The methodology for predicting the system level performance of ASD in deployed environments was developed. The integrated computational and experimental methodology for predicting ASD performance in normal environments is key to understanding the balance between detection and false alarms. Looking forward, the validation of this methodology will help the community to understand ASD performance in normal environments and may help shed light on contentious issues like fixed threshold and adaptive sensitivity.

References

[1] "*2012 CBECS Survey Data: Table B3. Census region, number of buildings and floorspace*," U.S. Energy Information Administration, 2015.

[2] http://www.nfpa.org/news-and-research/fire-statistics-and-reports/research-reports/detection-and-signaling/smoke-detection/smoke-detection-performance-prediction-methodology

[3] Dinaburg, Joshua and Gottuk, Daniel T., 2012, "*Xtralis Aspirated Smoke Detector Exposure Testing: Full Report of Tests*," Hughes Associates, Baltimore, MD.

[4] http://www.nfpa.org/~/media/files/news-and-research/resources/research-foundation/symposia/2016-supdet/2016-papers/supdet2016milke.pdf?la=en

[5] Green, David M.; Swets, John A. (1966). *Signal detection theory and psychophysics*. New York, NY: John Wiley and Sons Inc. ISBN 0-471-32420-5

[6] Rose-Pehrsson, S.L., Hart, S.J., Street, T.T. et al. Fire Technology (2003) 39: 147. doi:10.1023/A:1024260130050