Fire Safety Journal 53 (2012) 13–18

Contents lists available at SciVerse ScienceDirect

Fire Safety Journal

journal homepage: www.elsevier.com/locate/firesaf

Wavelet based flickering flame detector using differential PIR sensors ☆

Fatih Erden [a,*], B. Ugur Toreyin [b], E. Birey Soyer [c], Ihsan Inac [d], Osman Gunay [c], Kivanc Kose [d], A. Enis Cetin [d]

[a] *Department of Electrical and Electronics Engineering, Hacettepe University, Ankara, Turkey*
[b] *Department of Electronic and Communication Engineering, Cankaya University, Ankara, Turkey*
[c] *ASELSAN Inc., Ankara, Turkey*
[d] *Department of Electrical and Electronics Engineering, Bilkent University, Ankara, Turkey*

ARTICLE INFO

Article history:
Received 7 July 2011
Received in revised form
9 April 2012
Accepted 5 June 2012
Available online 6 July 2012

Keywords:
Flame detection
Pyro-electric Infrared (PIR) sensor
Wavelet transform
Markov models

ABSTRACT

A Pyro-electric Infrared (PIR) sensor based flame detection system is proposed using a Markovian decision algorithm. A differential PIR sensor is only sensitive to sudden temperature variations within its viewing range and it produces a time-varying signal. The wavelet transform of the PIR sensor signal is used for feature extraction from sensor signal and wavelet parameters are fed to a set of Markov models corresponding to the flame flicker process of an uncontrolled fire, ordinary activity of human beings and other objects. The final decision is reached based on the model yielding the highest probability among others. Comparative results show that the system can be used for fire detection in large rooms.

1. Introduction

Conventional point smoke and fire detectors typically detect the presence of certain particles generated by smoke and fire by ionization or photometry. An important weakness of point detectors is that the smoke has to reach the sensor. This may take significant amount of time to issue an alarm and therefore it is not possible to use them in open spaces or large rooms. The main advantage of differential Pyro-electric Infrared (PIR) based sensor system for fire detection over the conventional smoke detectors is the ability to monitor large rooms and spaces because they analyze the infrared light reflected from hot objects or fire flames to reach a decision.

An uncontrolled fire in its early stage exhibits a transition to chaos due to the fact that combustion process consists of nonlinear instabilities which result in transition to chaotic behavior via intermittency [2–5]. Consequently, turbulent flames can be characterized as a chaotic wide band frequency activity. Therefore, it is not possible to observe a single flickering frequency in the light spectrum due to an uncontrolled fire. In fact, we obtained a time series from the sampled read-out signal strength values of a PIR sensor with flickering flames in its viewing range (cf. Fig. 3). It is clear from Fig. 3 that there is no single flickering frequency and that flame flicker behavior is a wide-band activity covering 1–13 Hz. It is also reported in the literature that turbulent flames of an uncontrolled fire flicker with a frequency of around 10 Hz [6,7]. Actually, instantaneous flame flicker frequency is not constant, rather it varies in time. Recently developed video based fire detection schemes also take advantage of this fact by detecting random high-frequency behavior in flame colored moving pixels [8–10]. Therefore, a Markov model based modeling of flame flicker process produces more robust performance compared to frequency domain based methods. Markov models are extensively used in speech recognition systems and in computer vision applications [11–14].

In [15,16], several experiments on the relationship between burner size and flame flicker frequency are presented. Recent research on pyro-IR based combustion monitoring includes [17] in which monitoring system using an array of PIR detectors is realized.

A regular camera or typical IR flame sensors have a fire detection range of 30 m. The detection range of an ordinary low-cost PIR sensor based system is 10 m but this is enough to cover most rooms with high ceilings. Therefore, PIR based systems provide a cost-effective solution to the fire detection problem in relatively large rooms as the unit cost of a camera based system or a regular IR sensor based system is in the order of one thousand dollars.

In the proposed approach, wavelet domain signal processing methods are used for feature extraction from sensor signals.

☆ An earlier version of this study was presented in Turkish in part at the IEEE 16th Signal Processing, Communication and Applications Conference, SIU-2008 [1].

* Corresponding author. Tel.: +90 312 290 1525; fax: +90 312 266 4126.
E-mail addresses: erdenfatih@gmail.com (F. Erden), toreyin@cankaya.edu.tr (B.U. Toreyin), bireysoyer@gmail.com (E.B. Soyer), ihsaninac@gmail.com (I. Inac), gunayosman@gmail.com (O. Gunay), kkoseug@gmail.com (K. Kose), enis4cetin@gmail.com (A.E. Cetin).

0379-7112/$ - see front matter © 2012 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.firesaf.2012.06.006

This provides robustness against sensor signal drift due to temperature variations in the observed area. Notice that, differential PIR sensors are sensitive only to the changes in the intensity of the IR radiation within the viewing range rather than the absolute infrared radiation. In a very hot room the differential PIR sensor does not measure the temperature of the room, it only produces a constant output value which is not related with the temperature value. Regular temperature changes in a room are slow variations compared to the moving objects and flames. Since wavelet signals are high-pass and band-pass they do not get affected by slow variations in sensor signal.

There are two different classes of events defined in this approach. The first class represents fire events whereas the second class represents non-fire events. Each class of events is modeled by a different Markov model. The main application of PIR sensors is hot body motion detection. Therefore, we include regular human motion events like walking or running in the non-fire event class.

In Section 2, we present the operating principles of PIR sensors and how we modified the PIR circuit for flame detection. In Section 3, the wavelet domain signal processing and the Markov based modeling of the flames and human motion are described. In Section 4, comparative experimental results with other sensing modalities are presented.

2. Operating principles of a PIR sensor system and data acquisition

The main motivation of using a PIR sensor is that it can reliably detect the presence of moving bodies from other objects. Basically, it detects the difference in infrared radiation between the two 'segments' in its viewing range. Sensing normal variations in temperature and also disturbances in airflow are avoided by the elements connected in pairs. When these elements are subject to the same infrared radiation level, they generate a zero-output signal by canceling each other out [18]. Therefore, a PIR sensor can reject false detections accurately. The block diagram of a typical differential PIR sensor is shown in Fig. 1. A single sensor system requires additional expensive IR filters to distinguish ordinary hot bodies from CO and CO_2 emissions. In this article, we show that it is possible to distinguish the flames from other hot bodies by analyzing the motion information captured by the differential system.

Commercially available PIR motion-detector read-out circuits produce binary outputs. However, it is possible to capture a continuous time analog signal indicating the strength of the received signal in time. The circuit diagram of a typical PIR motion-detector is shown in Fig. 2. It is possible to capture an analog signal from this circuit.

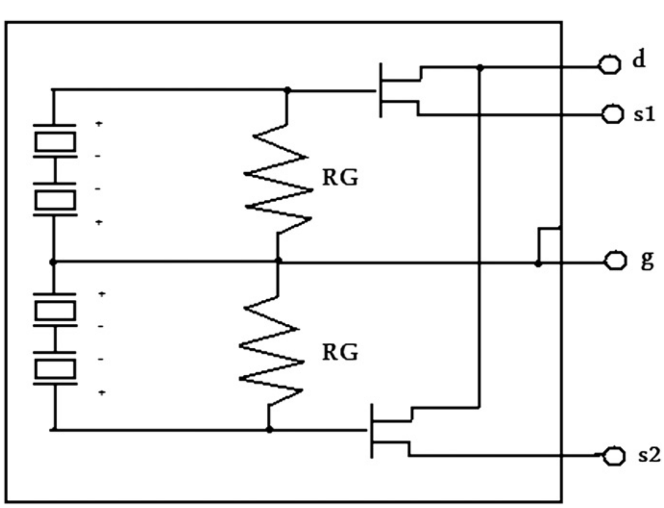

Fig. 1. The model of the internal structure of a PIR sensor.

The circuit consists of four operational amplifiers (op. amps.), IC1A, IC1B, IC1C and IC1D. IC1A and B constitutes a two stage amplifier circuit whereas IC1C and D couple behaves as a comparator. The very-low amplitude raw output at the 2nd pin of the PIR sensor is amplified through the two stage amplifier circuit. The amplified signal at the output of IC1B is fed into the comparator structure which outputs a binary signal, either 0 V or 5 V. Instead of using binary output in the original version of the PIR sensor read-out circuit, we directly capture the analog output signal at the output of the 2nd op. amp. IC1B and transfer it to a computer or a digital signal processor for further processing. The goal is to distinguish the flame signal from other signals due to ordinary moving bodies.

In uncontrolled fires, flames flicker. Following the discussion in Section 1 regarding the turbulent wide band activity of the flame flicker process, the analog signal is sampled with a sampling frequency of $f_s = 50$ Hz because the highest flame flicker frequency is 13 Hz and $f_s = 50$ Hz is well above the Nyquist rate, 2×13 Hz [7]. In Fig. 3, a frequency distribution plot corresponding to a flickering flame of an uncontrolled fire is shown. It is clear that the sampling frequency of 50 Hz is sufficient. Typical sampled signal for no activity case using 8 bit quantization is shown in Fig. 4. Other typical received signals from a moving person and flickering fire are presented in Figs. 5 and 6, respectively.

The strength of the received signal from a differential PIR sensor increases when there is motion due to a hot body within its viewing range. In fact, this is due to the fact that pyro-electric sensors give an electric response to a rate of change of temperature rather than temperature itself. On the other hand, the motion may be due to human motion taking place in front of the sensors or flickering flame. In this paper the differential PIR sensor data is used to distinguish the flame flicker from the motion of a human being like running or walking. Typically the PIR signal frequency of oscillation for a flickering flame is higher than that of PIR signals caused by a moving hot body. In order to keep the computational cost of the detection mechanism low, we decided to use Lagrange filters for obtaining the wavelet transform coefficients as features instead of using a direct frequency approach, such as the FFT based methods.

3. Sensor data processing and Markov models

Two different Markov models corresponding to flames and other motion are trained using the wavelet transforms of PIR recordings. Training of Markov models are carried out using various fire and motion recordings. During testing, the sensor signal is fed to both Markov models and the model producing the highest probability determines the class of the signal.

There is a bias in the PIR sensor output signal which changes according to the room temperature. Wavelet transform of the PIR signal removes this bias. Let $x[n]$ be a sampled version of the signal coming out of a PIR sensor. Wavelet coefficients obtained after a single stage subband decomposition, $w[k]$, corresponding to [12.5 Hz and 25 Hz] frequency band information of the original sensor output signal $x[n]$ are evaluated with an integer arithmetic high-pass filter corresponding to Lagrange wavelets [19] followed by decimation. The filter bank of a biorthogonal wavelet transform is used in the analysis. The low-pass filter has the transfer function:

$$H_l(z) = \frac{1}{2} + \frac{1}{4}(z^{-1} + z^1) \quad (1)$$