AUTOMATIC FIRE DETECTION: A SURVEY FROM WIRELESS SENSOR NETWORK PERSPECTIVE

Majid Bahrepour, Nirvana Meratnia, Paul Havinga

Pervasive Systems Group, University of Twente
{m.bahrepour, n.meratnia, p.j.m.havinga}@utwente.nl

Abstract. Automatic fire detection is important for early detection and promptly extinguishing fire. There are ample studies investigating the best sensor combinations and appropriate techniques for early fire detection. In the previous studies fire detection has either been considered as an application of a certain field (e.g., event detection for wireless sensor networks) or the main concern for which techniques have been specifically designed (e.g., fire detection using remote sensing techniques). These different approaches stem from different backgrounds of researchers dealing with fire, such as computer science, geography and earth observation, and fire safety. In this report we survey previous studies from three perspectives: (1) fire detection techniques for residential areas, (2) fire detection techniques for forests, and (3) contributions of sensor networks to early fire detection.

1 Introduction

There are many concerns in automatic fire detection, of which the most important ones are about different sensor combinations and appropriate techniques for quick and noise-tolerant fire detection. Researchers have been studying fires taking place in various places such as residential area (Milke and McAvoy 1995), forest (Yu, Wang et al. 2005; Bagheri 2007) and mines (Tan, Wang et al. 2007) to find some solutions for fire monitoring.

An important issue in automatic fire detection is separation of fire sources from noise sources. For the residential fires, being flaming or non-flaming (smouldering smoke fires), the general trend is to focus either on the sensor and sensor combinations or detection techniques. In another word, researchers have focused either on identifying the best set of sensors which collaboratively can detect fire using simple techniques (Milke and McAvoy 1995; Milke 1999; Cestari, Worrell et al. 2005) or on designing complex detection techniques that use single or at best very small set of simple sensors (Okayama 1991; Thuillard 2000).

Several decades of forestry research have resulted in many advances in field of forest fire monitoring. The Fire Weather Index (FWI) system being developed by the Canadian Forest Service (CFS; Bagheri 2007) and the National Fire Danger Rating System (NFDRS) introduced by the National Oceanic and Atmospheric Administration (NOAA; Yu, Wang et al. 2005) are two examples of such advances.

Studying the state-of-the-art techniques reveals two main trends in fire detection, i.e., existing techniques have either considered fire detection as an application of a certain field (e.g., event detection for wireless sensor networks) or the main concern for which techniques have been specifically designed (e.g., fire detection using remote sensing techniques).

The rest of this paper is organised as follows. Section 2 presents related work on residential fire detection. Section 3 introduces some indices for forest monitoring. Section 4 reviews contribution of wireless sensor networks (WSN) for fire detection that may occur in any places. In Section 5 some conclusions are drawn.

2 Automatic Residential Fire Detection

Human nose is a terrific fire detector. It can smell odours by using millions of neurons (sensors) and then process the signals in the brain, where patterns are classified, decisions are taken, and the best reaction is generated. Human nose is sensitive enough to smell even light concentrated gases. Then, brain seeks its database to find out what is the source of such a smell. If the odour is not familiar and does not match with the previous experiences, it is labelled as 'strange odour' that should be learnt as a new pattern signature (Bryan 1988; Shurmer and Gardner 1992).

Many commercial products can only detect airborne smoke by using either ionization sensors or photoelectric sensors (Brain 2000). An alarm is generated upon increase of the airborne smoke. The problem with such detection is nuisance sources such as a cigarette or a toasting bread (Milke 1999; Gottuk, Peatross et al. 2002). Therefore, many researchers agree on the fact reducing false alarm rates in fire detection necessitates using more than one sensor along with an appropriate detecting algorithm (Milke and McAvoy 1995; Milke 1999; Gottuk, Peatross et al. 2002).

Some standards such as the European EN 54 standard and the Dutch NEN 2575 standard have been compiled for fire detection. EN 54 is a suit of many standards for fire detection and alarm systems. Each part relates to a different part of an equipment, e.g., part 3 relates to alarm devices, part 11 to call points and part 4 to power supplies (EU; Wikipedia; Cooper 2008). NEN 2575, on the other hand, is a Dutch national standard for all evacuation alarm systems that are meant for emergency situations such as fire. It does not only specify requirements and standards that products used in case of emergency situation (e.g. smoke detector and fire alarms) should conform to but also the guidelines covering installation and cabling process (Ooperon).

Okayama presented a residential fire detection technique by incorporating neural networks (Okayama 1991). Milke et al (Milke and McAvoy 1995) extended Okayama's work in two facets: (1) introducing more sensors for reducing false alarms by using the same feed-forward neural network as used in (Okayama 1991), and (2) presenting an expert system working with three sensors, i.e., CO, CO_2 and Taguchi sensor.

To obtain the necessary data, an apparatus was made to collect sensory data such as CO, CO_2, photocell, Taguchi, and temperature. The apparatus and principle of data collection are shown in Figure 1. The key conclusion of this study is to prove the merit of multi-sensory classification, instead of uni-sensory classification, to reduce false alarm rates. In addition, it was demonstrated that the neural network with multi-sensory inputs results in more accurate classification compared to the proposed expert system in (Milke and McAvoy 1995).

In (Muller and Fischer 1995), the authors employed an optical smoke detector along with a temperature sensor to monitor and record environmental information. Fires are distinguished from noises by using a fuzzy expert system. They proposed optical smoke detectors due to the fact that they are more robust compared to ionization smoke detectors.

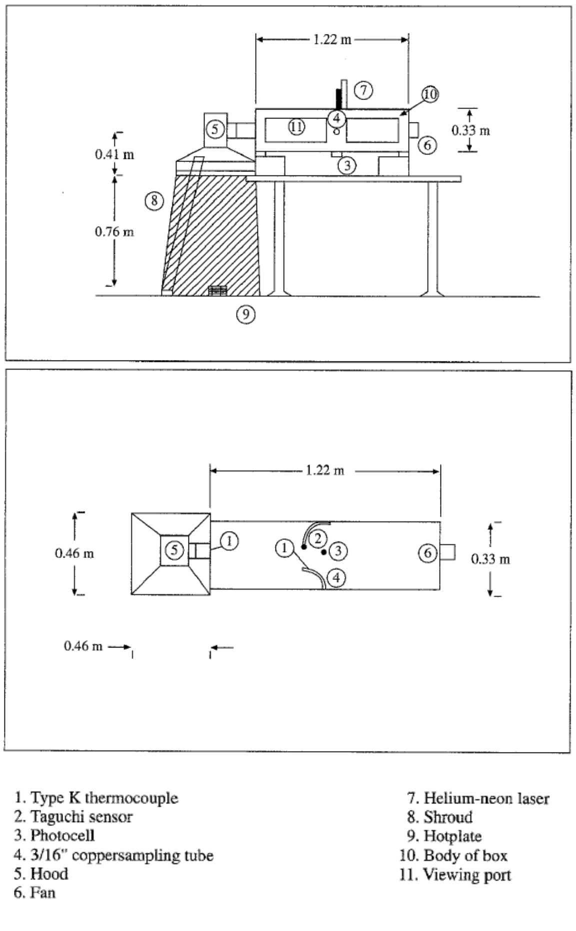

Figure 1: The Experimental Apparatus for Collecting Data (Milke and McAvoy 1995)

Milke investigated use of different gas sensors on fire dataset of the National Institute of Standards and Technology (NIST) to find-out the best sensor combinations to distinguish fire from nuisance sources (Milke 1999). He concluded that, rising rate of CO concentration can appropriately indicate non-flaming fires and rising rate of CO_2 concentration can properly indicate flaming fires. The rising rate can be computed by a simple algebraic equation given in (Milke 1999).

Thuillard introduced a flame detector sensor along with a fuzzy-wavelet or multi resolution fuzzy system technique to distinguish between fires and possible interferences (Thuillard 2000). He demonstrated that a fuzzy-wavelet technique can appropriately separate the two.

The authors of (Gottuk, Peatross et al. 2002) investigated a number of sensor combinations for different fire and noise scenarios. As the result of many investigations, they finally demonstrated that ION and CO sensors are the best sensor combination and a threshold approach based on (ION $\times$CO) $\geq$10 condition is an optimal algorithm to separate fire sources from nuisance sources. In their study, combination of smoke and CO rates indicate a fire event. They proposed a two-pass filtering technique to remove data spikes. Their conclusions can be summarized as:

- ION detectors are advantageous for flaming fire detection,
- Photo detectors are beneficial for non-flaming fire detection,
- Combining CO and ION can more accurately detect fire.

Chen et al. used combination of three sensors i.e., smoke, temperature and CO, and a fuzzy system technique to fuse the sensory data. They, then, made an electronic nose to distinguish fire from nuisance sources (Chen, Bao et al. 2003).

Cestari et al. investigated different sensor combinations with some multi-criterion functions (Cestari, Worrell et al. 2005). They combined some nuisance data with flaming and non-flaming fire data and conducted several tests. A two pass filtering technique was also proposed to remove data spikes. Conclusion of their study was:

- Ionization detector is more beneficial for detecting flaming fires,
- Photoelectric detector is more beneficial for detecting non-flaming fires,
- Ionization and photoelectric sensors are noise sensitive,
- Rising rates are more helpful for flaming fires,
- CO and temperature’s rising-rate improve noise immunity,
- Combination of temperature’s rising-rate together with CO and ionization can lead to an accurate, yet noisy immune, classification.

One can notise that the first two conclusions are also in line with what reported in (Gottuk, Peatross et al. 2002).

Although temperature sensors are probably the simplest and the most obvious sensors for fire detection, studying various sources in this field reveals that all researchers agree on the fact that it alone is not a suitable indicator for fires and gas concentration sensors result in a better fire detection and discriminating fire and noise sources.

3 Automatic Forest Fire Detection

There are many ways to monitor forest fires. Traditionally, some personnel in a lookout tower located in a high point performed the monitoring tasks (Fleming and Robertson 2003). This method of monitoring is still used in some countries such as US, Canada, and Australia (Towers).

Due to difficult life condition at lookout towers and unreliability of human observations, some vision techniques such as Automatic Video Surveillance Systems (AVSS) were proposed to monitor small forests (Breejen, Breuers et al. 1998; Baumann, Boltz et al. 2008).

More recent advances regarding forest fire detection is based on satellite imagery. Advanced Very High Resolution Radiometer (AVHRR) and Moderate Resolution Imaging Spectroradiometer (MRIS) are examples of such monitoring systems (NASA; National Environment Satellite; Cracknell 1997).

Low spatial and temporal resolution of satellite imageries cause late fire detection and by the time fire is detected it may have grown large (Yu, Wang et al. 2005; Bagheri 2007).

Sensory information can provide a more comprehensive forest fire monitoring (Nasipuri and Li 2002; Bagheri 2007) and with a finer grained spatial and temporal resolution. Moreover, sensor nodes can be deployed in the regions where satellite signals may not be available (Nasipuri and Li 2002). Fire Weather Index (FWI), illustrated in Figure 2, achieved based on several decades of forestry, is one of the recent advances in forest monitoring (CFS; Bagheri 2007). Multi-sensory nature of the technique increases the possibility of detecting fire with higher accuracy and lower false alarm.

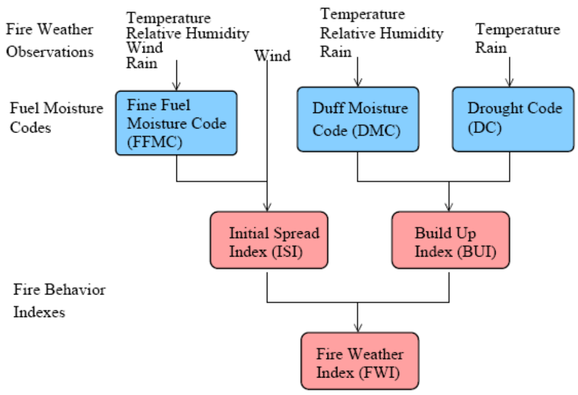

Figure 2: Structure of FWI System (Bagheri 2007)

Another system for forest monitoring is the National Fire Danger Rating System (NFDRS), which was introduced by the National Oceanic and Atmospheric Administration (NOAA; Yu, Wang et al. 2005). Figure 3 shows this system. Due to importance of these two indices, in what follows they will be explained in more details.

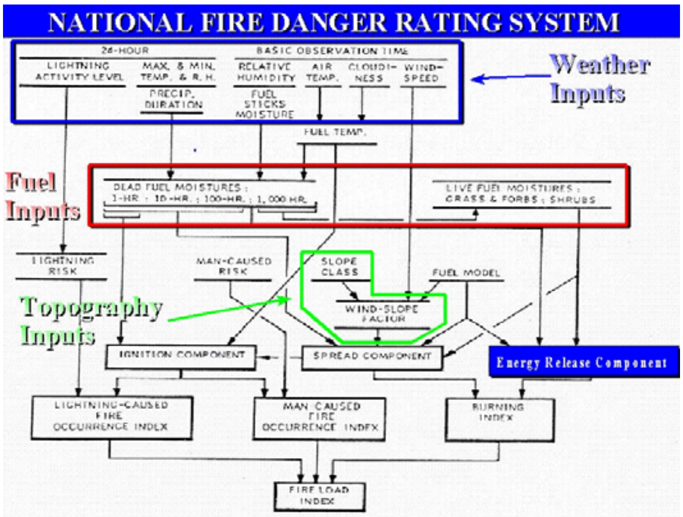

Figure 3: The National Fire Danger Rating System (NOAA)

3.1 Fire Weather Index (FWI)

FWI indices are as follows:

- FFMC: accepts four sensory information, i.e., temperature, relative humidity, wind, and rain, and generates ignition potential of fire. Table 1 shows the Ignition potential per FFMC value range.
- DMC: accepts three sensory information, that are, temperature, relative humidity and rain, and indicates the fuel consumption in average duff layers, the first layer of forest soil, and medium-size woody materials
- DC: accepts two sensory information, i.e., temperature and rain and indicates average humidity content of deep, compact, organic layers. This code is a practical sign of seasonal drought effects on forest fuels and amount of smouldering in deep duff layers, the first layer of forest soil, and large logs.
- ISI: receives FFMC index and wind sensory information to produce expected rate of fire spread.
- BUI: receives DMC and DC indices to produce the total amount of fuel available for combustion.

- FWI: receives BUI and ISI indices to create potential fire danger. Table 2 demonstrates different possible values for FWI index and corresponding potential fire danger.

Table 1: Ignition Potential Based upon the FFMC Code (Bagheri 2007)

Ignition Potential	FFMC Value Range
Low	0-63
Moderate	63-84
High	84-88
Very High	88-91
Extreme	91+

Table 2: Potential Fire Danger Based on the FWI index (Bagheri 2007)

FWI Class	**Range**	**Type of Fire**	**Potential Danger**
Low	0-5	Creeping surface fire	Fire will be self extinguishing
Moderate	5-10	Low vigor surface fire	Easily suppressed with hand tools
High	10-20	Moderately vigorous surface fire	Power pumps and hoses are needed
Very High	20-30	Very intense surface fire	Difficult to control
Extreme	30+	Developing active fire	Immediate and strong action is critical

3.2 National Fire Danger Rating System (NFDRS) Index

NFDRS indices are as follows (NOAA; NWCG 2005):

- Occurrence Index: indicates the potential of fire incidence.
- Burning Index: specifies the possible amount of effort required to control a single fire in a particular fuel type within a rating area.
- Fire Load Index: shows the total amount of efforts needed to surround all probable fires within the rating area during a particular period of time.

4 Fire Detection Using Wireless Senor Networks

Yu et al. incorporated the National Fire Danger Rating System (NFDRS) into their work. NFDRS accepts four sensory information being humidity, temperature, smoke and windy speed; and generates a fire-likelihood index. The contribution of this study is the application of a feed-forward neural network for data aggregation and reducing communication overhead (Yu, Wang et al. 2005).

Lu Zhiping et al. (Zhiping, Huibin et al. 2006) proposed a forest fire detection solution using wireless sensor networks. Their system is made of sensor nodes, gateway(s), and task manager(s). Each sensor node is equipped with temperature and humidity sensors. After obtaining sensory information at sensor nodes, data are fused at gateways and data-analysis and decision making are done by task manager nodes.

A wireless sensor network for early fire detection of mines was proposed in (Tan, Wang et al. 2007). Authors introduced a system composed of data-collecting, data-processing and monitoring subsystems. Their study focused on appropriate network topology, scheduling mechanism and communication protocol.

Lim et al. proposed an innovative framework for residential fire detection (Lim, Lim et al. 2007). They introduced metric of interval-message-ration (IMR) and evaluated their framework using the IMR metric. They concluded that the framework is not only applicable for fire-detection but can also be applied for other disaster recoveries.

To help with fire fighting operations, an alarm application based on Telos B motes (Polastre, Szewczyk et al. 2005) was proposed in (Bernardo, Oliveira et al. 2007). The authors used a combination of temperature, light and humidity sensors in difficult access environments. They considered a scattered WSN consisting of several isolated WSNs. The situation, in which sensor nodes are destroyed by fire, was also taken into account. They concluded that mote longevity (avoiding synchronisation costs during idle period) can be applied in the fire situations where a timely response to destructive events is needed.

In (Bagheri 2007), the author utilised FWI index and his novel k-coverage algorithm to detect forest fires. K-coverage algorithm monitors each point by using *k* or more sensor nodes to increase fault tolerance. Therefore, some sensors can be put in standby mode to extend network lifetime. Although there are many algorithms to find the minimum number of sensors to be used, they are usually NP complete problems (Yang, Dai et al. 2006). The proposed k-coverage solution proved to prolong the network life time. Forest fire detection was not the focus of this work and was considered as an application for the novel k-coverage problem.

A sensor network was used for real-life forest fire detection in (Vescoukis, Olma et al. 2007). The authors equipped each sensor node with a GPS and a thermometer. They proposed that each sensor node should be mounted on a tree with a height of at least 3.5m. To keep sensor nodes protected against direct sunshine, sensor nodes should be covered. Since the sensor nodes might be destroyed by fire, a dynamic routing protocol was proposed. They concluded that a sensor node with the structure of Figure 4 can sense and transmit data more accurately. In addition, they deduced that if three nodes monitor the same location, fire can more accurately be detected.

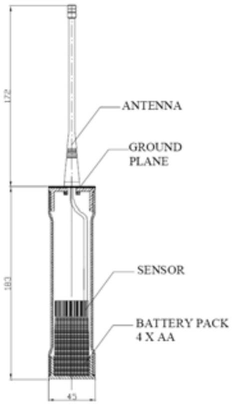

Figure 4: Sensor Node Type Proposed in (Vescoukis, Olma et al. 2007)

Zervas et al. proposed a sensor network approach for early fire detection of open spaces such as jungles and urban areas (Zervas, Sekkas et al. 2007). They incorporated a temperature sensor and maximum likelihood algorithm to fuse sensory information. Their proposed system architecture, which is illustrated in Figure 5, is composed of (1) sensing subsystem, (2) computing subsystem, and (3) localized alerting subsystem. The author concluded the applicability of their approach for early fire detection.

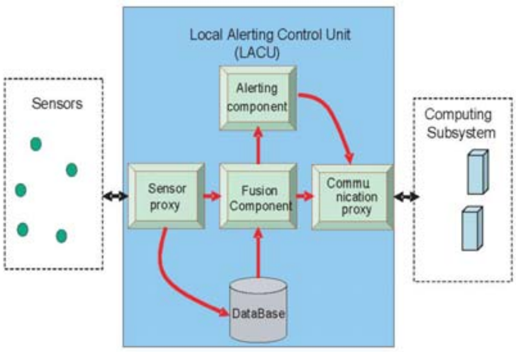

Figure 5: System Architecture Proposed in (Zervas, Sekkas et al. 2007)

A skyline approach for early forest fire detection is proposed in (Pripužic, Belani et al. 2008). Skyline is built using greater values, i.e., those sensor readings with large temperature and high wind speed. Figure 6 shows the proposed skyline. Only data on skyline are sent to a sink to be used for fire detection. Sink processes the data according to the suggested algorithm and results in a fast and energy efficient forest fire detection.

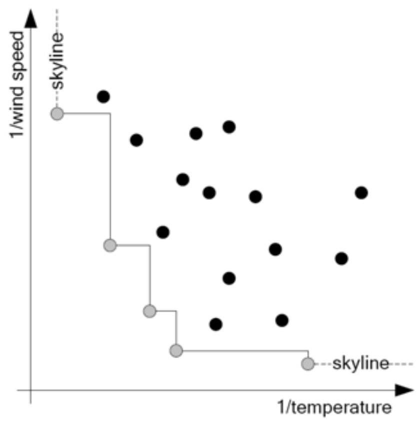

Figure 6: Skyline of Sensor Readings (Pripužic, Belani et al. 2008)

Marin-Perianu and Havinga proposed a distributed fuzzy inference engine in wireless sensor networks, so called D-FLER, for event detection (Marin-Perianu and Havinga 2008). They studied fire detection as an event in their work utilising smoke and temperature sensors for residential fire detection. D-FLER combines individual sensor inputs with neighbourhood observation using a distributed fuzzy logic engine. The prototype of their work was implemented in practise using Ambient µNode 2.0 platform (Hofmeijer, Dulman et al. 2004). Figure 7 shows D-FLER structure.

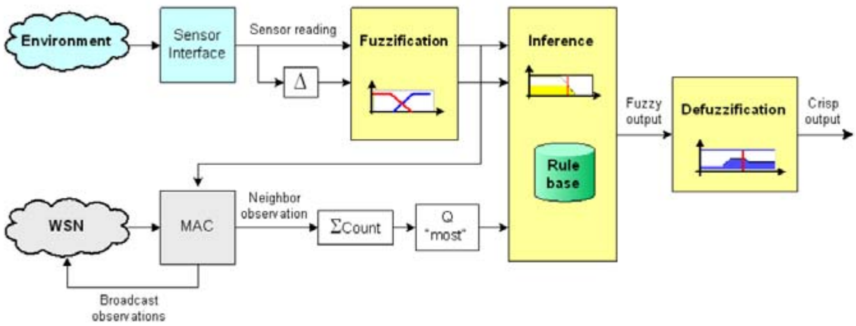

Figure 7: D-FLER Structure (Marin-Perianu and Havinga 2008)

5 Conclusion

In this paper previous work in fire detection domain were surveyed from different perspectives. Our interest for this literature survey is to identify which sensor combinations and algorithms can detect fires accurately and quickly. The general conclusions that can be drawn are as follows:

- In residential areas ION detectors are advantageous for flaming fire detection, while photo detectors are beneficial for non-flaming fire detection. However, to achieve more reliable and fault-tolerant results and higher detection rates more than one sensor should be used. This assures that flaming and non-flaming fires can be discriminated.
- Although temperature sensors are probably the simplest and the most obvious sensors for fire detection, studying various sources in this field reveals that all researchers agree on the fact that it alone cannot accurately indicate fire and gas (e.g., CO, CO_2) concentrations are main features for fire detection.
- Fire Weather Index (FWI) and other indices resulted from several decades of forestry research can be used as strong indications for forest fire detection.
- The WSN community needs to use the general knowledge about fire patterns, best combination of sensors and appropriate detection techniques from the fire-related disciplines. It is apparent that selection of sensors was often carried out randomly or assumption-basely.

6 Acknowledgement

The authors would like to thank Prof. James A. Milke at Department of Fire Protection Engineering of the University of Maryland for his valuable directions for progress of this study. The work described in is paper is in the context of the SENSEI project, supported by the European 7th Framework Programme, contract number: 215923.

References

Bagheri, M. (2007). Efficient K-Coverage Algorithms for Wireless Sensor Networks and Their Applications to Early Detection of Forest Fires. Computing Science, SIMON FRASER UNIVERSITY. MSc**:** 75.

Baumann, A., M. Boltz, et al. (2008). "A Review and Comparison of Measures for Automatic Video Surveillance Systems." EURASIP Journal on Image and Video Processing

Bernardo, L., R. Oliveira, et al. (2007). A Fire Monitoring Application for Scattered Wireless Sensor Networks: A peer-to-peer cross-layering approach International Conference on Wireless Information Networks and Systems (WINSYS'07), Barcelona, Spain.

Brain, M. (2000). "How Smoke Detectors Work ", from http://home.howstuffworks.com/smoke1.htm.
Breejen, E., M. Breuers, et al. (1998). Autonomous forest fire detection. Third International Conference on Forest Fire Research and Fourteenth Conference on Fire and Forest Meteorology, Luso, Portugal.
Bryan, J. L. (1988). 'Behavioral Response to Fire and Smoke,' SFPE Handbook of Fire Protection Engineering,, National Fite Protection Association, Quincy.
Cestari, L. A., C. Worrell, et al. (2005). "Advanced Fire Detection Algorithms Using Data from the Home Smoke Detector Project." Fire Safety Journal **40**: 1-28.
CFS. "Canadian Forest Service." from www.nrcan.gc.ca/cfs.
Chen, S., H. Bao, et al. (2003). A fire detecting method based on multi-sensor data fusion. Systems, Man and Cybernetics, 2003. IEEE International Conference on
Cooper (2008). Fire Detection System Design. http://www.cooper-ls.com/dg_firesystem.html, Cooper Lighting and Safety CO.
Cracknell, A. P. (1997). The Advanced Very High Resolution Radiometer (AVHRR), CRC Press.
EU European Union Website, http://ec.europa.eu/enterprise/newapproach/standardization/harmstds/reflist/construc.html.
Fleming, J. and R. G. Robertson (2003). Fire Management Tech Tips: The Osborne Fire Finder. T. R. 1311-SDTDC, USDA Forest Service.
Gottuk, D. T., M. J. Peatross, et al. (2002). "Advanced fire detection using multi-signature alarm algorithms." Fire Safety Journal **37**(4): 381-394
Hofmeijer, T., S. Dulman, et al. (2004). "AmbientRT - Real Time System Software Support for Data Centric Sensor Networks." Intelligent Sensors, Sensor Networks and Information Processing (ISSNIP): 61-66.
Lim, Y.-s., S. Lim, et al. (2007). A Fire Detection and Rescue Support Framework with Wireless Sensor Networks. Convergence Information Technology.
Marin-Perianu, M. and P. Havinga (2008). D-FLER – A Distributed Fuzzy Logic Engine for Rule-Based Wireless Sensor Networks Heidelberg, Springer Berlin.
Milke, J. A. (1999). Using Multiple Sensors for Discriminating Fire Detection. Fire Suppression and Detection Research Application Symposium, National Fire Protection Research Foundation
Milke, J. A. and T. J. McAvoy (1995). "Analysis of signature patterns for discriminating fire detection with multiple sensors." Fire Technology **31**(2): 120-136.
Muller, H. C. and A. Fischer (1995). A robust fire detection algorithm for temperature and optical smoke density using fuzzy logic. Security Technology, Sanderstead, Institute of Electrical and Electronics
NASA. "National Eronautics and Space Administration." from http://modis.gsfc.nasa.gov/.
Nasipuri, A. and K. Li (2002). A Directionality Based Location Discovery Scheme for Wireless Sensor Networks. Proceedings of the 1st ACM international workshop on Wireless sensor networks and applications Atlanta, Georgia, USA ACM New York, NY, USA
National Environment Satellite, D., and Information Service (NESDIS). "Advanced Very High Resolution Radiometer - AVHRR." from http://noaasis.noaa.gov/NOAASIS/ml/avhrr.html.
NOAA, N. O. a. A. A. "National Fire Danger Rating System ", from http://www.wrh.noaa.gov/sew/fire/olm/nfdrs.htm.

NWCG (2005). National Fire Danger Rating System Weather Station Standards, http://www.nwcg.gov/pms/pubs/PMS426-3.pdf.

Okayama, Y. (1991). Approach to Detection of Fires in Their Very Early Stage by Odor Sensors and Neural Net. Proceedings of the Third International Symposium of Fire Safety Science.

Ooperon Norm NEN 2575, Ooperon praktisch met systemen. **In Dutch:** http://www.ooperon.nl/producten.asp?content_id=11&menu=producten.

Polastre, J., R. Szewczyk, et al. (2005). Telos: enabling ultra-low power wireless research. Information Processing in Sensor Networks.

Pripužic, K., H. Belani, et al. (2008). Early Forest Fire Detection with Sensor Networks: Sliding Window Skylines Approach. University of Zagreb, Faculty of Electrical Engineering and Computing, Department of Telecommunications, White Paper.

Shurmer, H. V. and J. W. Gardner (1992). "Odour Discrimination with an Electronic Nose." Sensors andActuators B: 1-11.

Tan, W., Q. Wang, et al. (2007). Mine Fire Detection System Based on Wireless Sensor Network. Information Acquisition, 2007. ICIA '07. International Conference on.

Thuillard, M. (2000). Application of Fuzzy Wavelets and Wavelets in Soft Computing Illustrated with the Example of Fire Detectors. Wavelet Applications VII.

Towers, B. C. F. L. http://www.firelookout.com/bc.html.

Vescoukis, V., T. Olma, et al. (2007). Experience from a Pilot Implementation of an "In-Situ" Forest Temperature Measurement Network. Personal, Indoor and Mobile Radio Communications (PIMRC2007).

Wikipedia EN 54, http://en.wikipedia.org/wiki/EN_54.

Yang, S., F. Dai, et al. (2006). "On Connected Multiple Point Coverage in Wireless Sensor Networks " International Journal of Wireless Information Networks **13**(4): 289-301.

Yu, L., N. Wang, et al. (2005). Real-time forest fire detection with wireless sensor networks. Wireless Communications, Networking and Mobile Computing.

Zervas, E., O. Sekkas, et al. (2007). Fire Detection in the Urban Rural Interface through Fusion Techniques. Mobile Adhoc and Sensor Systems (MASS 2007).

Zhiping, L., Q. Huibin, et al. (2006). The Design of Wireless Sensor Networks for Forest Fire Monitoring System. School of Electronics and Information, Hangzhou Dianzi University, White Paper.