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Review of Recent Development in Fire Detection Technologies

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Abstract

The progress on fire detection technologies has been substantial over the last decade due to advance in sensor, microelectronics and information technologies, as well as a greater understanding of fire physics. This paper provides a review of progress in fire detection technologies over the last decade, including various emerging sensor technologies (e.g., computer vision system, distributed fiber optic temperature sensor, and intelligent multiple sensor), signal processing and monitoring technology (e.g., real-time control via Internet) and integrated fire detection systems. Some problems and future research efforts related to current fire detection technologies are discussed.

1.0 Introduction

With advances in sensor, microelectronics and information technologies, as well as greater understanding of fire physics, many new fire detection technologies and concepts have been developed over the last decade. For example, techniques are available now for measuring almost any stable gaseous species produced prior to or during combustion [1]. The distributed fiber optical temperature sensors have been introduced to provide fire protection for those applications with difficult ambient conditions such as tunnels, underground railways and stations [2]. More than one fire signature detected by a multiple sensor, such as smoke, heat and CO signatures, can be processed at the same time through an intelligent algorithm to intelligently discriminate between fire and non-threatening or deceptive conditions [3]. In addition, fire detection systems are integrated with other building service systems to reduce false alarms, speed building evacuation and assist in fire fighting [4]. Advances in fire detection technology has effectively reduced the loss of property and life by fire. The National Fire Protection Association (NFPA) data showed that in the USA, a decline in the number of significant "home" fires – from 723,500 in 1977 to 395,500 in 1997, representing a decline of 45.3 percent over 21 years, in part because low-cost fire detectors have been introduced in residential houses [5].

Over the last decade, however, insulation and building materials, furnishings and furniture have undergone a major transformation from natural materials, such as wood and cotton, to synthetic materials. Consequently, the risk to life and property has changed radically since burning synthetic materials release not only highly dangerous smoke and toxic fumes, but also carbon monoxide at rates far in excess of natural materials [6], resulting in dramatic reduction in the available time for escape. Many of the locations in most need of protection, such as telecommunication facilities, are unattended and/or remote [7], and interruptions to the service caused by fires are becoming more costly. For example, electrical fires occurring at a Bell Canada switching station in Toronto, 1999 and at the CDNX's operation center in Vancouver, 2000, disrupted nationwide communications, knocked out stock trading operations, shut down police service, merchants, businesses and federal agencies in various degrees, and caused loss of many millions of dollars. In addition, false fire alarms in aircraft cargo have significantly increased over the last few years. It caused around $12 million of direct loss for US-registered aircraft in 1998 [8], and indirect loss includes increasing danger by landing in an unfamiliar or less adequate airport, increasing risk to passengers or crew members in evacuation, and loss of confidence in fire detection systems. For many cases, fires can only be detected once they are fully developed, resulting in severe damage to properties or loss of lives. One such disaster, the 1998 Swissair crash near Peggy's Cove in Nova Scotia, killed all 229 people on board, because the fire, caused by faulty electrical wiring, occurred in an inaccessible space and was not properly detected and located.

Fire detection technology still faces challenges related to reducing false alarms, increasing sensitivity and dynamic response, as well as providing protections for highly expensive and complex installations to better safeguard the public and meet evolving regulations. This paper aims to review recent research and development in fire detection technology, including emerging sensor technology, fire signal processing and monitoring technology and integrated fire detection system. Some problems and future activities related to the fire detection technology are discussed.

2.0 Emerging Sensor Technology

2.1 Heat Detectors

The distributed fiber optic temperature sensor is considered as one of the new and promising heat detection technologies for fire protection applications [2, 9]. Optic fiber has been widely used for the transmission of information, and it can also be used for sensing changes in temperature, strain and tensile force subjected to the fiber optic cable, as the variation of these physical parameters alters the refractive indices and geometric properties of the optical fiber and then perturbs the intensity, phase, or polarization of the light wave propagating within the optical fiber. Unlike the conventional thermal detectors, the distributed optical fiber sensor uses the entire optical fiber as the sensing medium. Temperature measurement can be made at any and every point along the fiber cable. The measured temperature is in the range of -160 to 800^{o}C, which is limited only by the durability of the fiber, or more specifically, its primary coating. In comparison to conventional thermal detectors, the optical fiber sensor cable responds much more quickly to temperature fluctuations due to its low mass. The fiber cable itself is strong, resilient, flexible for different geometry and can be directly placed near or into protected facilities. It is also immune to all kinds of interference emissions. Conceivably, the location, size, and development of a fire can be determined with higher spatial and temperature resolutions and unmatched flexibility in measurement locations. The distributed fiber optic temperature sensors based on Rayleigh and Raman scattering were introduced for fire detection in the late 1980's [2, 9]. They have been used to provide fire protection for those applications with difficult ambient conditions such as tunnels, underground railways and stations, conveyor lines, steelworks and petrochemical plants [10 - 12].

Distributed optic fiber sensors based on Rayleigh scattering measure the temperature by detecting changes in the amount of reflected light, when the fiber is micro-bent due to heating. Ericsson in Sweden has developed a special sensor cable based on Rayleigh scattering [9]. It is composed of three primary components: an optical fiber, a wax-filled tube, and a protective covering jacket. The optical fiber is in parallel with the wax filled tube and connected together by the thread. When part of the cable assembly is heated, the wax in the tube begins to melt and expand, causing a change in the amount of reflected light. The maximum sensing range of the system is up to 2 km. It can identify a fire location with an accuracy of about 1 m when the length of heated cable is at least 0.2 m. The sensor cable is available for operation in ambient temperatures between −20°C and 120°C. The main drawback of the system is that it does not provide any temperature increase information with time and has a single alarm actuation temperature between 40°C and 90°C, which leads to low sensitivity of such a system to a fire. In addition, the sensor cable itself cannot be bent due to its inflexible wax-filled tube. The fiber optic sensors based on Rayleigh scattering are mainly used in applications such as road tunnels and underground installations.

The distributed fiber optic sensor system based on Raman scattering detects the temperature by measuring the ratio of the Stokes to anti-Stokes back scattered intensity signal as a function of temperature. The system uses a bare multi-mode fiber or the fiber encapsulated within a suitable cable sheath. The level of the Raman-scattering signal is weak, that restricts the sensing range and spatial resolution of the Raman scattering system. A long integration time is needed. The maximum sensing range of the current Raman system is up to 4 km and its spatial resolution varies from 8 m to 1 m, depending on the requirement for response time and temperature resolution [13, 14]. For example, if the required temperature resolution is ± 2°C for distance resolution of 1 m, the response time is 60 s for a detected distance of 1 km and it increases to 4 min and 48 min for detected distances of 2 km and 4 km, respectively [13]. As a result, to protect an application with a long sensing range requirement, a few of the distributed Raman scattering detective systems must be used together.

One potential replacement for the Rayleigh and Raman scattering systems for temperature measurement is the Brillouin scattering-based fiber optical system [15 - 20]. The current Brillouin scattering technology detects temperature changes by measuring the Brillouin back scattered intensity and its frequency shift as a function of temperature. Although Brillouin scattering yields signals that are approximately 10^5 to 10^6 times weaker than the incident light, they may be enhanced through a process known as *Stimulated Brillouin Scattering* (SBS) by sending light from two lasers into opposite ends of the sensing fiber. Through modulation, the pulsed laser's light intensity is amplified at the expense of the second continuous wave (CW) laser. This amplification process allows the sensing range of the fiber to be significantly increased to approximately 100 km due to improved signal-to-noise ratios resulting from nonlinear amplification in the fiber. Also, the distributed optical fiber sensor based on Brillouin scattering has higher spatial and thermal resolutions, compared to Rayleigh and Raman scattering systems. An overheated location can be detected within a distance resolution of ± 0.15 m by the Brillouin scattering system [20]. Temperature resolution of ± 0.1°C can be achieved. However, the data acquisition time of the Brillouin scattering system for temperature measurement is directly proportional to the number of frequency steps within the scanning range. Therefore, measurement of a high range of the temperature and the temperature with large variations requires lengthy acquisition times. With increasing fiber lengths and shorter spatial resolutions, this processing time is further increased. Clearly, this scanning technique would be inappropriate for fire detection where prompt response times are required.

Recent research has showed that there is a clear relationship between the Brillouin power gain and the fiber temperature [21]. The Brillouin power gain increases with fiber temperature and is maximized when the Brillioiun frequency is equal to the frequency difference between the two lasers for the fiber temperature at a specified fiber location(s). As a result, by directly measuring the intensity of the Brillouin gain/loss signal versus time, rather than sweeping through a range of frequencies, the Brillouin system can achieve a real-time fire detection, while maintaining good spatial and temperature resolutions and high signal-to-noise ratios (SNR >20 dB). This can be achieved by turning the frequency difference between the pump and pulsed lasers to match the Brillouin frequency of the fiber at a known threshold temperature, T_{th}, based on specified fire detection conditions. Once the Brillouin power gain becomes a maximum due to the occurrence of a fire, an alarm signal would immediately be triggered indicating that the threshold temperature has been reached.

Initial research has demonstrated the competence of the distributed Brillouin system for fire detection applications. More research will be needed to focus on improving spatial resolutions of the distributed Brillouin system, providing information not only on real-time fire alarm, but also on fire size and development, and establishing operating system conditions corresponding to the optimum signal-to-noise ratios (SNR) for different fiber lengths. The performance of the distributed Brillouin system in real fire conditions, such as fires involving telecommunication facilities and tunnel applications, will also need to be evaluated and studied.

2.2 Smoke Detectors

Smoke is produced much earlier than other fire signatures during the stages of fire growth and development. The rapid detection of smoke at very low levels can maximize the probability for successful fire suppression, escape and survivability. Smoke can be sensed from the interaction of the particles with a beam of light or electromagnetic radiation. The mass concentration, volume fraction and size distribution of the smoke are identified as key parameters for smoke detection [22]. A smoke detector must be capable of responding to smoke from both smoldering and flaming combustion, because the smokes from these fires are significantly different in structure and composition [23]. Smoke from a smoldering fire tends to have bigger particles of combustion products than those generated from flaming combustion. The detector may be located at the sensing location (spot detector) or at a remote location with the smoke pumped to the detector.

Ionization Chamber Smoke Detector (ICSD) detects a fire when the smoke particles enter into the ionization chamber and change the current by interfering with ion flow. The ion flow is sensitive to ambient temperature, ambient pressure, gas composition and humidity. To achieve sensitivity of detection, one type of ICSD with separated ionization chambers has been developed, in which one chamber is sealed and unaffected by the environmental conditions, while the other is open to sample ambient air [24, 25]. ICSD has been widely used in domestic dwellings because it can provide good protection with low cost. However, dust particles, water droplets, or other materials can deposit on the radioactive source, absorb some of the ions being emitted and reduce the electric current. This would lead to false alarms for ICSD. In addition, ICSD is very sensitive to false alarm due to making toast, bacon and general cooking, because it detects smoke particles ranging from 0.01 to 1.0 micron. Some frustrated households have removed the battery from detectors to prevent spurious operation [25]. Another concern for use of ICSD is that ICSD contains radioactive material [25]. It may cause environmental problems during disposal.

Efforts are being made to find replacements for the ionization chamber smoke detector. One of such efforts is focused on investigating the feasibility of a smoke detector that operates on the ionization principle without the use of a radioactive source. University of Duisburg in Germany has developed an electrostatic smoke detector based on the principle that some percentages of smoke particles formed during combustion carry an electric charge [26]. Charged smoke particles can be detected once they enter into the electrostatic detector that consists of a sensing electrode sandwiched between two parallel reference grids. Test results showed that the detector was able to detect open flaming fires, but was insensitive to smoldering combustion, because the charged smoke particles from smoldering fires were substantially reduced as the smoke produced from the smoldering combustion quickly cooled.

An optical smoke detector has been considered as a replacement for the ionization chamber smoke detector [27]. It detects a fire when smoke particles interact with a beam of light passing through it. Two physical phenomena are important: obscuration and scattering. Obscuration systems are sensitive to the attenuation of a beam of light shining across a space, caused by the scattering and absorption of the light by smoke particles, while scattering systems depend on the detection of scattered light from suspended smoke particles. Compared to ionization chamber smoke detectors, the optical smoke detectors are very sensitive to smoldering fires and have more tolerance to ambient conditions. Their sensitivity is largely unaffected by ambient temperature and they are better at resisting general cooking smoke. However, optical smoke detectors detect smoke particles in the range of 1.0 to 10.0 micron and they have difficulties in detecting a flaming fire with small smoke particles. In addition, non fire-generated particles, such as dust and other nuisance aerosols, may cause false alarms in optical smoke detectors.

Studies have shown that the amount of incident light scattered by a particle is mainly determined by the size, shape and refractive index of the particle, wavelength and intensity of incident light and the angle of scatter [28]. Therefore, by employing one or more of the following methods: such as increasing the number of angles at which scattered light is received; decreasing the solid angle in field of view; measuring the polarization ratio; increasing the spectral selectivity of the light source and the quantity of incident light wave-lengths transmitted, the optical scattering detectors are able to detect a broader range of particle sizes at various refractive indices and their capabilities to discriminate smoke particles from nuisance aerosols can be enhanced [9, 22]. Based on these concepts, Notifier in the UK [29] recently developed an optical smoke detector in which an extremely bright laser diode and integral lens are designed to focus the light beam to a very small point near the receiving photo sensor. When smoke enters into the chamber, a specially-designed mirror reflects and concentrates most of the scattered light into the photo sensor. It was claimed that such an optical smoke detector combined with advanced software algorithms has sensitivity up to 50 times higher than present photoelectric detectors. It also reduced false signals caused by larger airborne particles such as dust, lint and small insects.

The multi-criteria sensing detectors that combine smoke sensing with other types of sensing have been considered as an effective method that is able to provide a wide range of detection capability and at the same time, reduce nuisance alarms without sacrificing smoke detector sensitivity [30]. For example, Thorn Security Ltd. [31] developed a multi-sensing detector that combined optical smoke sensing with thermal sensing to detect both flaming and smoldering fires. The optic scattering smoke detector was used to detect smoldering combustion at the stable sensitivity and the heat detector was used to detect the rapid increase in temperature associated with a fast growing and flaming fire. The combination of optical and heat sensors with intelligent algorithms offers an alternative to the use of ionization detectors. Other recent studies on multi-criteria sensing include detectors that combine photoelectric with gas sensing [32], ion with gas sensing [33], and photoelectric with ion and heat sensing [34].

2.3 Flame Detectors

The fire, itself, is a source of radiation, and it can be detected by the recognition of radiation produced in the burning zone [23]. Currently there are two types of flame detectors based on the measurement of the range of flame radiation: infra-red detector and ultra-violet detector. Infra-red detectors (IR) detect fires when a characteristic flame flicker produced by fire is received, while ultra-violet detectors (UV) detect fires when any ultra-violet radiation produced by flaming combustion is detected. Flame detectors can be used to protect large areas and they have rapid response because they do not have to rely on smoke or heat from the fire. They can also be used in the open air, unlike the smoke detectors that need a ceiling to function effectively. However, false alarms may be generated by radiation from other sources such as welding, sunlight, and tungsten lamps.

Efforts have been made to minimize nuisance alarms by IR and UV detectors, by combining multi-wavelength radiation sensing with algorithms that determine object temperature, flame temperature, surface area and presence of a flame. The combination ultraviolet/infrared (UV/IR) flame detector significantly reduces the spurious alarm problems associated with the old UV detectors. Because the UV/IR flame detector detects both UV and IR radiation emitted from the flames, it prevents false alarm from other common sources of ultraviolet radiation other than a flame that do not emit infrared radiation at 4.3 μm [35]. The UV/IR detector, however, still depends on the vacuum photodiode tube to detect ultraviolet radiation. It has failure-to-alarm problems associated with the absorption of ultraviolet radiation by aerosols such as smoke or vapors in the air, or liquid and solid contaminants on the detector window.

The dual-wave-length infrared (IR/IR) flame detector abandons the ultraviolet portion of the spectrum entirely and operates in the infrared portion of the spectrum. It detects the flaming combustion of hydrocarbons by comparing the radiant intensity typically at 4.2 - 4.7 μm (emitted by CO_2) with the radiant intensity at the reference wavelength of 3.8 - 4.1 μm (near the CO_2 peak) that serves as background energy monitoring [36]. The IR/IR flame detector eliminates the interference of smoke as well as the liquid and solid contaminants on the detector window. However, there are two factors that limit the detection range of the dual IR detector. The first one is that the fire radiation intensity around 4.3 μm significantly decreases as the distance increases. The second one is that the ratio between the 4.3 μm spectral band released from the fire and the 4.0 μm spectral band used as the reference background approaches equality, which could give no fire signal when the algorithm processes the fire signals.

To overcome the drawbacks of dual IR detectors, a triple IR flame detector has recently been developed [36]. The triple IR detector utilizes a combination of three IR sensors of extremely narrow band response: one covering the typical CO_2 flame emission spectral band, and the two others covering different adjacent specially-selected spectral bands. The high sensitivity of the triple IR detector is achieved by extracting extremely low signals deeply buried in noise by adopting digital correlation techniques. The triple IR detector does not produce any false alarm to any continuous, modulated or pulsating radiation sources other than fires. It offers an extended detection range up to 60 m, compared to 15-20 m for the standard optical flame detector [36]. The triple IR flame detector has been used in rough working conditions where all types of flames need to be detected during day or night, under hot or cold, dry or wet weather conditions.

CCTV (Closed Circuit Television) technology has great advantage for use on sensing and monitoring a fire. Compared with other types of fire detectors, the video cameras cannot be fooled by visible, or emissions from common background sources, eliminating false alarm problems. It processes multiple spectral images in real time to reliably detect a small fire or smoke at greater distances in very short times, and at the same time, it can identify the location of a fire, track its growth and monitor fire suppression. It can be trained for very rapid response, making it suitable for explosion suppression systems. The application areas for video fire detection systems are developing fast. Detecting smoke plumes in forests and fires in aircraft hangars have been the first applications. Video surveillance in various manufacturing plants, power generating stations, and tunnels are additional areas [37].

The original CCTV technology was intended to transfer or record a video signal and then present it to the human eye. Attempts have been made to develop an automatic detection system for the specific application of flame detection. One such technique is the combination of CCTV technology with radiation sensors (UV and IR) to detect a fire, and a CCD camera automatically evaluates the scene, identifies bright regions associated with the radiation and determines if there is a fire [7, 39]. Tests conducted in an aircraft hangar environment showed that the system that combines machine vision technology with radiation sensors successfully detected fires in the range of 0.1 to 0.2 m^2 at a distance of 30 m within about 0.5 seconds after reaching the threshold size.

Another automatic CCTV detection technique is the machine vision fire detection system (MVFDS) that is a combination of video cameras, computers, and artificial intelligence techniques [36, 37, 39]. The video charged-couple device (CCD) camera in the MVFDS is used to monitor the environment. The spectral output of the camera is stored in computer memory as a function of time and space. Pattern recognition and image processing logic are used to analyze the images on the fly. As summarized by Wieser and Brupbacher [38], there are three major image processing techniques for fire detection: histogram, temporal and rule based techniques. Histogram based technique includes approaches in which the histogram of an acquired image is calculated and then the information in the histogram is used to detect the presence of the fire; or the computed histogram is compared with pre-computed histograms of typical smoke/fire scenes; or statistical measures such as the mean and standard deviation is used to determine the likelihood of the presence of a fire. The temporal based technique mainly uses the difference between frames to generate growth patterns and determine if fire/smoke is present. For the rule based technique, domain specific information is coded and used as rules to infer the presence of a fire from a sequence of images. With the progress in artificial intelligent techniques, digital imaging is able to detect not only a flame but also smoke. The video smoke detection system developed by Siemens, for example, employed a contrast-analyzing video smoke detection algorithm to overcome difficulties generated by moving vehicles and their lights in the tunnel [38]. Experiments showed that the system was quick to detect smoke in video sequences and at the same time to be immune to false alarms. The system will be installed in several road tunnels to further test its capability.

Another benefit of the video sensor system is that it can be used as a multi-function sensor in the building service system. Video sensor systems have been used not only for fire detection [40] but also for building security, improving response rate and energy saving for HVAC systems by identifying occupant numbers and their locations [41], monitoring electrical power switchboards and control panels [42] and lighting level sensing and control [43]. Cameras and corresponding facilities required in the video sensor system are already standard features of many buildings. Additional sensibility can therefore be added with minimal cost through changes in software and correlating results between the video system and other sensors.

One drawback of the video fire detection system is that its visibility decreases rapidly with the increase in smoke concentration. Thermal cameras that image the infrared radiation emitted from hot surfaces are capable of overcoming the drawback of the video sensing system in smoke filled environment. They can locate the fire origin, burning wall or people in danger through the smoke. Thermal cameras have been used for fire fighting for many years. Recently, Kozeki [44] studied the use of the thermal video camera system for detecting and monitoring smoldering fires by employing a suitable image processing algorithm. The discrimination between the real smoldering fire and the non-fire was based on the time-dependent variation of the centroid and size of the high temperature cluster. Experimental verification showed that the image processing software worked correctly for the smoldering stage of a silk cotton cushion and for identifying non-fire threats, such as an electric radiant heater.

The microwave (MW) radiation emitted from the hot spot has also been considered for use on fire detection [45]. In comparison to other radiation methods for fire detection, such as infrared methods, MW-radiation is able to penetrate all materials (including optically thick smoke and vapor) except metals and it is insensitive to environmental conditions, such as water, dust and high temperature. Experimental results showed that with an MW radiometer, all fires containing some glowing materials, such as wood, can be easily detected. However, fires without glowing materials, such as liquid fuel fires, cannot be detected. The achievable spatial resolution of the MW radiometer is also limited.

2.4 Gas Sensors

Since gases are produced in all stages of combustion, a specific gas signature could be used for reliable fire detection. Jackson and Robins [46] measured CO, CO_2, H_2, O_2, and smoke density generated by open cellulose fires (wood), smoldering pyrolysis (cellulosic) and cotton fires, open plastic fire (polyurethane), and liquid n-heptane and methylated spirit fires. Their research showed that there were large differences in the chemical composition of the smoke involving different types of fires. Of the four warning gases, the best was carbon monoxide that presented in all six types of fires. Its concentration was high in relatively slow burning fires and low in faster burning fires. There were also large differences in the oxygen concentrations involving six types of fires in which the oxygen concentrations changed significantly when involving faster burning fires, such as liquid fuel fires, while the change in the oxygen concentration was hardly detected when involving smoldering fires. Based on test results, they believed that gas sensors can be used not only for fire detection but they can also be used to provide information on whether the fire is flaming, smoldering, or intermediate.

Techniques are available now for measuring almost any stable gaseous species produced prior to or during combustion [1]. Chemical species can be sensed through a multitude of interactions, including catalytic, electrochemical, mechanic-chemical, and optical processes. However, many of the gases generated during combustion process also occur naturally, or are generated in non-threatening combustion processes. In addition, to detect specific gas signatures, the sensor needs a significant power source, which restricts it as a cost-effective fire detector.

With research efforts, carbon monoxide fire detectors that operate at room temperature from a low power source have been developed and are now available in the market. Compared to the conventional fire detectors, the carbon monoxide sensor is able to provide protection against smoldering fires involving combustion of organic materials in which significant quantities of carbon monoxide are produced at an early stage of the combustion [46 - 50]. CO sensors would also prevent false alarms from dust, steam, fog and other optical disturbance variables, and at the same time, provide protection against carbon monoxide poisoning, for example, generated from faulty flue extraction. However, CO sensors would not be suited to the detection of open flaming fires and overheating but not combusting materials such as the pyrolisis of electric cables in which the amount of CO generated is very low. In addition, other sources of CO, such as exhaust gases released from fire places and vehicles may cause false alarms with CO sensors [51].

The combined CO and smoke sensor is capable of overcoming the drawbacks of either CO or smoke sensors in fire detection and can provide better fire detection by discriminating many nuisance sources and by increasing sensitivity [32, 52]. Gottuk, etc. [32] have carried out extensive testing and analysis to compare capabilities of smoke detectors (both ionization and photoelectric), CO sensors and combined CO/smoke sensors in detecting real fire alarms involving both flaming and smoldering fires and nuisance alarms (12 types of nuisance alarms, such as toast, cigarettes and steam). They developed alarm algorithms consisting of the product of smoke obscuration and the change in CO concentration. The combined CO/smoke detector with the alarm algorithm responded to real fire sources faster than conventional smoke detectors, affording the occupants several extra minutes of time to escape. Also, it provided better nuisance alarm immunity, especially in two of the most common residential nuisance sources: cooking and steam. The smoke sensors combined with CO detection have already been used for professional applications and they will be also used for residential applications in the near future.

Since electronic equipment and components emit a complex range of chemical vapours when heated, these emitted chemical vapours can be used for the early fire detection in electronic equipment. Bell Labs developed an HCl detector to detect HCl generated by the pyrolysis or combustion of PVC cable insulation [53]. It does not respond to common nuisance signals, such as cigarette smoke, steam or dust. However, in order to detect non-HCl-producing fires occurring in electronic facilities, other types of fire detection devices are required.

Riches, etc. [54] evaluated sensitivity of surface acoustic wave (SAW) sensors and metal oxide semiconductor (MOS) sensors in detecting electronic fires. The SAW sensor detected a fire by measuring the change in frequency of a piezoelectric crystal due to the absorption of gas or vapour on its surface. The MOS sensor detected a fire by measuring the change in the conductivity of metal oxide films in the presence of organic vapours. Test results showed that SAW sensors had good sensitivity and ability to be used for special fire detection applications by the careful selection of chemical coatings. The MOS sensors showed reasonable stability and long-term repeatability for fire detection but lacked selectivity for the different character of the vapours.

Since each polluting substance has a unique absorption line in the infrared (IR), visible or the ultraviolet (UV) spectral range, selective absorption in the infrared by fuel molecules or combustion products can be used to measure gas concentrations for fire and explosion detection [1]. The US Army [55] has been involved in the development of a gas sensor to measure binary mixtures of oxygen and the fuel vapor from a series of volatile organic compounds, with a time resolution of 10 ms. The gas sensor detects absorption of radiation near a wavelength of 760 nm by oxygen, and absorption of radiation near a wavelength of 1700 nm by hydrocarbon based fuels. Based on the same concept of the optical absorption in hazardous gases, Dankner, etc., [56] constructed an electronic-optical gas detector. It was able to monitor and transmit an alarm signal prior to the occurrence of fire or explosion by detecting low concentration of flammable paraffins, aromatics and toxic hydrogen-sulfide. In addition, the constructed gas detector could also operate through significant interference such as rain, fog, aqueous vapours and nebulized salt water.

The use of Fourier Transform Infrared (FTIR) spectrometers for fire detection has been studied for many years [1, 57, 58]. FTIR can examine the entire spectrum from about 2.5 μm to 25 μm, and quantify the presence of multiple species of interest to provide early fire warning with low false alarms. FTIR measurement also provided significant amounts of additional data prior to ignition and during early stage of combustion, including monomeric species, unburned fuel, oxygenates, olefins, and pyrolysis products [57, 58]. Commercial FTIR instruments are now available, and have the potential to sense CO, HCN, HCl, CO_2, H_2O, and miscellaneous hydrocarbons. Their measurements for CO, CO_2 and total hydrocarbons were found to follow similar trends as the measurements of single parameter instruments. However, advanced data analysis scheme for the FTIR-based fire detection system must be developed to quantify the gas and smoke concentrations and to determine if a fire condition is present. In addition, a wide range of applications of FTIR-based fire detection systems is limited by high initial costs and maintenance requirement.

3.0 Signal Processing and Monitoring Technology

With the introduction of artificial intelligence techniques, the effectiveness of fire detection technology is significantly enhanced. Fire signal received by the sensor is processed by the microcomputer-based technology (software algorithms) and compared with known information and data base of generic fire signatures, and then an output response based on the total quantity of available information is generated. More than one fire signature detected by multiple sensors, such as smoke, heat and CO signatures, can be processed at the same time through an intelligent algorithm [3, 59]. Meacham [60] has summarized the intelligent algorithms used for fire detection, including cross-correlation, algorithmic comparison, neural networks and fuzzy reasoning. Some new fire detection algorithms, such as the Hidden Markov Model based on a signal classification principle [61], are also being developed. Advance in artificial intelligent techniques and semiconductor technology allows the fire detection system to accurately and intelligently discriminate between fire and non-threatening or deceptive conditions; to be sensitive to a variety of fires; to be used in monitoring the fire development; and to provide possible “environmental compensation” and continually adjust for temperature changes, dust and dirt accumulation, humidity, voltage fluctuations and component aging

– all factors having a negative effect on the detector's sensitivity and contributing to false alarms. Intelligent fire detection systems now represent approximately 50% by value of all new systems installed world-wide [62].

Currently there are two types of intelligent fire detection systems: one is where the fire signal processing and decision making are carried out in the detector and the other is where the fire identification and decision making are carried out in the panel. For medium to large fire detection systems, intelligence in the panel is a cost-effective selection. Detectors that do not contain a microprocessor and associated support circuitry are less complex and more reliable. The powerful central processing unit (CPU) can be fitted into the control panel to allow the system to use complex algorithms and advanced signal processing for fire signature identification. Many addressable multiple sensors at different locations will be able to connect together and transmit separate sensitivity information to the panel for processing and decision making. This may enhance fire detection capability while at the same time lowering total system costs, because the sensor primarily used for another purpose may provide useful information related to early fire detection. Higher than expected levels of CO_2, for example, may be a sign of poor air circulation within a room, but may also be the signs of a fire. Similarly, parameters such as temperature and air movement can be used for the maintenance of the indoor working environment but also for fire detection purposes. Various inputs, such as thermal, smoke, CO and CO_2, provided by the distributed sensors to the control panel would be expected to reduce the rate of false alarms and increase the speed of detection of real problems. The study carried out by Cleary and Notarianni [63] has demonstrated that such distributed sensing may improve time to alarm over single-station detectors.

The control panel is also able to provide information on the exact location of a fire or its development in a building based on the spatial relationship and status of adjacent detectors through the integrated fire detection system. The Building and Fire Research Laboratory at NIST [64 – 66] has carried out a project to develop advanced fire detection alarm panels in which a sensor-driven fire model and associated algorithms will be used to discriminate between fire and non-fire threats, and provide continuous estimates on the short and long term behavior of fire growth and smoke spread in the building, based on building plans, the contents of the buildings, and the sensor data. The sensor-driven fire model in the panel uses ceiling jet algorithms for temperature and smoke concentration to convert the analog or digital data from heat and smoke detectors to a heat release rate. The information on layer temperatures and depths for the room of fire origin as well as surrounding rooms is then obtained from the calculation of a two-zone model. Studies show that fire status information provided by such a sensor-driven fire model, including the upper layer temperature, flashover temperature, visibility and the concentration of toxic gas, were in reasonable agreement with experimental measurements [66]. Such fire information will be provided to the control panel. It will allow building operators and fire fighters to make a more accurate and responsive evaluation of any fire-related incident in the building.

Detailed sensor information can also be accessed remotely now. It is estimated that 67 percent of all fires occur outside of office hours [67]. With remote monitoring of fire detection and alarm systems, it will reduce response time and increase response effectiveness by providing adequate fire information to the building supervisor and the appropriate fire brigade. Intelligent remote monitoring can significantly increase efficiency and reduce costs for building management operations. They may be especially important for small facilities where skilled technical supervision would otherwise be too expensive to consider. These systems could allow a single person to supervise a number of buildings.

Most commercial monitoring systems use a modem and remote dial-up to access the building's operating system. Studies have been carried out to do real-time control of a building automation system via the Internet [68, 69]. Compared to "voice/touch-tone" interface, the Internet is able to provide more information (text, images and sound clips). The City University of Hong Kong has carried out an initial research project to use the Internet for real-time control of building automation systems [68]. One air-handing unit (AHU) simulator was used in the test. A camera was used to monitor AHU so that the operation of AHU can be monitored through the Internet. Every User around the world can retrieve the updated status from 23 analog and digital points, such as temperature and humidity. The user, through the Internet, is also able to send commands to the simulator to operate any one actuator by simply clicking the scroll bar. Their study has shown that the Internet has the potential to extend the monitoring and control of a typical building automation system so that users can gain access to it at anytime and from anywhere. Their work also showed that one central 24-hour management office is able to manage a real estate portfolio with hundreds of buildings.

More recently, Setrix [70] developed a wireless video monitoring system in which a video camera, CPU, local storage and wireless GSM module are integrated in a small embedded device. The video information is continuously analyzed or recorded. Once an unusual event, such as a fire, is detected, an alarm message is sent to the selected recipients via a GSM network. The recipient can then access the past event log of the server device or watch the live remote video using a PC with Internet connection, or a PDA with a GSM network connection, or a GSM cellular phone, at anytime and from anywhere.

With the development of real-time control/monitor via the Internet or wireless network, prompt human intervention at the first sign of a warning permits very efficient discrimination between fire and non-fire threats [69]. When a fire is detected and confirmed, the fire suppression system is activated immediately, and detailed and adequate local fire information can be sent directly to the appropriate fire department. Firefighters can access information from the mobile Internet terminal or a GSM cellular phone in a fire truck, before they arrive there. This will help firefighters identify the locations of potentially hazardous materials or occupants who will need special assistance to leave the fire location. Fully integrated remote access systems will allow planning for fighting fires to take place enroute to the fire, rather than at the building's fire panel. Remote monitor systems should therefore provide valuable additional time for property and life protection.

However, real-time control via the Internet, is still in its infancy [68]. Some significant issues, such as real-time control of security and safety, still need to be considered. Internet access to fire safety systems also creates its own unique safety issues concerning computer and network security. The full implementation of Internet-based monitoring systems will require strong assurances of data integrity and resistance to computer hacking. Without these protections, firefighters may receive false information about the existence, location or size of fires.

4.0 Integrated Fire Detection System

The integration of a fire detection system with other building systems on a common backbone will allow the building systems to communicate with each other. The fire messages will be released not only from fire detection systems but also from other building systems. They will have priority at all times in the network. The decision-making components of the integrated system will assess the conditions and then determine what actions are required based on the sensor data. The appropriate commands will be sent to the system's transducers and control devices. Once a fire occurs in a building, fire detection and alarm systems in buildings will be able to activate various fire safety systems, such as smoke control, and various pressurization and smoke exhaust systems. They will also activate elevator recall, the door release systems, flashing exit signs and fire suppression systems. The integrated systems have the potential for reducing false alarms, speeding building evacuation and assisting in fire fighting. These changes will increase the level of protection to life and property and create new markets for fire detection, alarm and fighting systems [71]. As these technologies mature, changes to building practices may also result.

Another push to integrate the fire detection system with other building systems is that the new generation of the building is expected to add the capability to learn about the building's circumstances and its occupants' needs and change the behaviour of its control systems accordingly [72]. For example, the building will use sensors to identify how a particular person tends to react to particular circumstances and to learn different behaviours from different people. To do this, a large number of sensors within the building will be required to operate the building in a responsive manner, rather than using pre-programmed control models. This will increase the cost of buildings and make it difficult to manage the resulting large amount of data. However, when various types of sensors are integrated to be used as multi-function sensor, the number of sensors required for monitoring building environment will be reduced and the amount of data that need to be processed will also be reduced.

Studies on integration of fire detection systems with other building systems have been carried out for many years. However, only limited integration of fire detection systems with other building service systems has been achieved by using the same cabling backbone provided by the same manufacturer [73, 74]. Various building service systems involving HVAC, lighting, fire safety and security monitoring in the building are not integrated together on the basis of a common communication protocol. There is a limited level of information-sharing among the systems. The slow progress for the integration is mainly due to fragmentation of the building and communication industries, a reluctance to change established practices as well as the lack of standardized, broadly-based communication protocols that allow different types of building service systems to communicate with each other [73]. Many tenants and developers also prefer to have a lesser degree of system integration due to fears of excessive complexity, potential total system failure and possible slowdown of the central control [75, 76].

Various methods and concepts have been developed to enhance integration of building systems and to increase reliability of the integrated systems [4, 73, 74]. Efforts are also being made to develop communication protocols that enable different manufacturers to "interoperate" together and allow the building systems to communicate with each other over a network. These proposed protocols include BACnet, LonWorks, CAN, NEST, EHSA and CAB. They prescribe a detailed set of rules and procedures that govern all aspects of communicating information from one cooperating machine to another. BACnet prefers a hierarchical model in which the whole system is divided into a number of subsystems, each with a separate central processing unit [77]. The coordination of the subsystems is achieved by hardwired interconnection or software interconnection. This method simplifies installation and maintenance. The damage caused by the failure of the central processing unit to the building service systems and the fire safety system is only limited to the local level, instead of to the whole integrated system. BACnet is most suitable to the traditional processing and communications models used by current HVAC hardware. However, BACnet does not support dynamically-structured networks, nor does it emphasize distributed processing. Efforts are being made to expand BACnet beyond the HVAC realm. The first commercial BACnet fire system products will be introduced in the near future, and new features are also being added to the protocol that will enhance the use of BACnet in life-safety systems [64].

5.0 Discussion and Conclusion

Many new fire detection technologies developed over the last decade have strong potential to reduce false alarms, increase sensitivity and dynamic response to a fire and improve fire safety. The Brillouin scattering-based distributed fiber optic sensors has a long sensing range, responds quickly to temperature fluctuation and is immune to all kinds of interference emission. It has the potential to provide fire detection in applications where small fires might be encountered (e.g., telecommunication facilities), and areas with restricted access or with difficult ambient conditions (e.g., tunnels, underground railways and stations, nuclear and petrochemical plants). However, further research efforts are needed to improve its spatial resolution, and establish a cost-effective and reliable distributed fiber optic system for fire detection.

Video fire detection systems have also demonstrated great advantages for use in sensing and monitoring a fire as well as on multi-function applications. Cameras and corresponding facilities required in the video sensor system are already standard features of many buildings. With further development in microelectronics and information technologies, video information can be sent out or accessed via Internet or a wireless network. It is expected that the video sensor system will play a more important role in providing cost-effective fire safety and other building management and services.

In recent years, fire detectors tend to be more intelligent in discriminating between fire and non-threatening or deceptive conditions due to the introduction of artificial intelligent techniques as well as the development of microelectronics technology. Multiple sensors that combine smoke and thermal sensors or CO sensor are capable of overcoming the drawbacks of single sensor in fire detection, and provide better fire detection by discriminating many nuisance sources and extend detection capability for many fire sources.

The use of advanced control panels with advanced fire signal processing and sensor-driven fire model would substantially reduce false alarms and provide more accuracy information on fire and smoke spread in the building. This will allow building operators and firefighters to make a more accurate and responsive evaluation of any fire-related incident in the building and to control fires and supervise the evacuation from the building more efficiently.

The use of real-time control via the Internet or wireless network will extend the monitoring and control of fire safety systems outside of the building. The status of the fire safety system and other building systems can be monitored at anytime and from anywhere via the Internet or wireless network. The fire safety systems located in many buildings will be controlled from one central facility office. This will increase the efficiency and reduce costs for building management operations, more efficiently discriminate between fire and non-fire threats, and increase the time available for property and life protection. However, Internet-based monitoring and control of building service systems will need security protection to prevent false fire information being provided to building owners and fire brigades.

The integration of fire detection and alarm systems with other building systems should increase fire safety in the building. The fire detection system will be able to communicate with other building systems, correctly discriminate between fire and non-fire threats, identify the exact location of a fire in the building and provide continuous estimates on smoke and fire spread in the building. However, the integration technology may also create new risks. Sensor technologies, for example, will need to be robust enough to prevent false alarms, and ensure that vital information such as the location of occupants is not lost due to data overload during a fire. Integrated building systems will need to be designed not only to give fire safety priority over other building activities but also that fire emergencies do not crash the building service system.

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