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INTERNATIONAL DEVELOPMENTS IN FIRE SENSOR TECHNOLOGY

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SUMMARY

There have been a number of developments in fire sensor technology over the past ten years. Some, such as incipient smoke detection systems, have become readily available, while others remain in the research, pre-production, or newly released stage. This second group of sensors utilizes technologies ranging from optical fibers and wax, to integrated video and infrared sensors controlled by artificial intelligence algorithms. This paper presents an overview of several less known, yet promising, fire sensor technologies. Although it does not address specific applications, it illustrates the wide range solutions available for addressing a variety of fire detection needs.

HEAT SENSOR DEVELOPMENTS

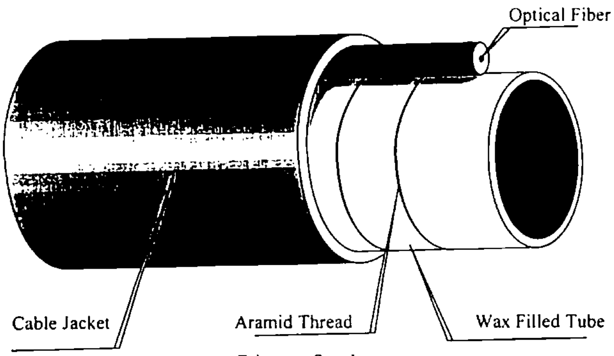
There have been several developments in heat sensor technology in recent years. Two promising approaches are in the use of fiber optic cables as line-type heat detectors, and the detection of thermal fluctuations instead of temperature increase.

Ericsson, a Swedish company, has developed a very sensitive line type heat detection system using laser and optical fiber technology.[1] The sensor cable can be up to 2 km long, and when the length of heated cable is at least 200 mm, the fire location can be pinpointed with an accuracy of about +/- 1 m. Up to 100 of these fire or overheat locations can be detected with the +/- 1 m accuracy as long as the separation between hot points is at least 3.5 m. The activation temperature (alarm temperature) of the sensor is between 40°C and 90°C with a +/- 1°C resolution. Although a specific activation temperature within this range can be selected, it is a function of the sensor materials, and is not currently field adjustable.

The sensor cable itself is composed of three primary components: an optical fiber, a wax-filled tube, and a protective covering material (jacket). The optical fiber is in parallel with the wax filled tube, connected to it by an aramid thread (Figure 1). Utilizing an optical reflectometry technique, a short laser pulse is transmitted into the optical fiber 40,000 times per second. As the light pulse travels at a

Figure 1: Optical Fiber Line Type Heat Detector Assembly[1]

Fiber Optic Heat Detection System, Sweden



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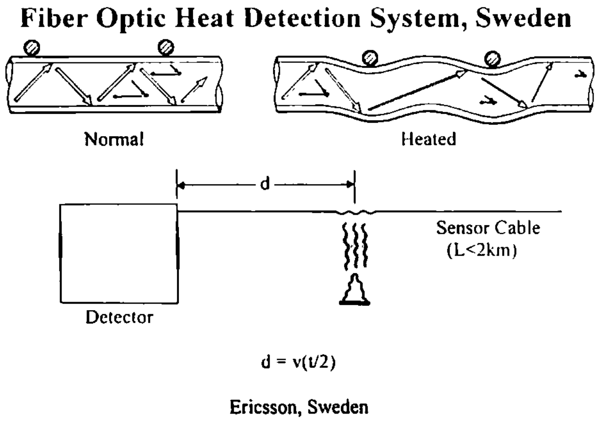
near constant velocity along the length of the fiber, small irregularities within the fiber material cause some of the light to be scattered according to Rayleigh scattering theory.

In the quiescent state, the sensing unit detects the loss of signal due to scatter along the fiber. This defines the "normal" signal. When part of the cable assembly (200 mm nominal) becomes heated, the wax in the tube begins to melt and expand. As it does so, microbending of the optical fiber occurs causing a change in the amount of reflected light (Figure 2). The sensor detects this change in light signal, and the distance to the heated part is calculated from the relationship d = (v)(t/2), where t is the time difference from when the light pulse is transmitted until the reflected light is received, and v is the velocity of the light pulse. This signal evaluation method provides the location resolution of about +/- 1 m. Should a break occur in the fiber, a separate and unique signal will be received and processed as a trouble condition.

Once the fire is extinguished, the wax cools and the cable returns to its ambient state. If there is no damage to the optical fiber, the system re-establishes a base reference signal, and the system returns to normal. Should the fire damage the fiber, the damaged section can simply be removed and a new section spliced in. Through the use of an optical fiber and protective jacket, the sensor cable has proven to be extremely resistant to EMI, RFI, corrosive vapors and severe environmental conditions encountered in several road tunnel tests performed throughout Europe. The sensor cable is currently available for operation in ambient temperatures between -20°C and 120°C, with a version capable of operating at up to 300°C anticipated.

The use of optical fibers for heat detection was also studied at the Center Suisse d' Electronique et de Microtechnique S.A. in Neuchatel, Switzerland.[2] In this work, the researchers also looked into fire detection based on the optical power loss of the light

Figure 2: Optical Fiber Line Type Heat Detector Operation[1]



beam through microbending of the fiber, however, the microbending was induced by a bimetallic effect rather than through deformation of a wax filled tube.

Similar to the Ericsson system, this system utilizes an optical reflectometry technique in which a short light pulse is transmitted through the fiber, and the scattered light intensity is measured at the receiver. In this case, instead of utilizing a wax-filled tube to cause microbending of the optical fiber, the fiber is coated with a periodically interrupted metallic coating. As the temperature around the cable increases, the metallic coating expands and causes the fiber to deform in a specific manner (Figure 3). Because the radiated power in the fiber is proportional to the square of the modulation amplitude, the resulting amplitude modulation can be translated to a temperature. This results in a system that can identify both fire location and temperature.

Although this approach provides both location and temperature information, there is some question as to the manufacturability of the cable assembly with the bimetallic coating. In addition, compromises were made with respect to location sensitivity and signal resolution. As a result, the sensitivity is somewhat less than the Ericsson system, with a spatial resolution of about

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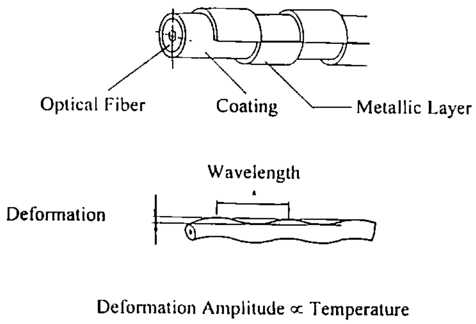
Figure 3: Metal Cladded Optical Fiber Line Type Heat Detector[2]

Fiber Optic Heat Detection System, Switzerland



Center Suisse d' Electronique et de Microtechnique S.A. - Switzerland

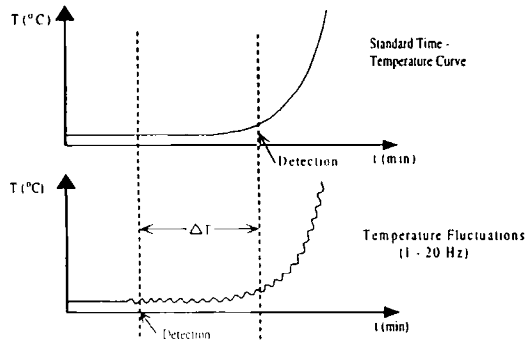
10 m over the length of cable. Should these items be resolved, the ability to detect the location and temperature of an overheat condition over a several kilometer length of cable could find several applications.

A U.S. company took a slightly different approach in the development of their fiber optic-based fire detection system[3]. This system, as with the previous two, uses a computer-based controller to transmit light signals along the length of the fiber. However, instead of using microbending of the fiber to detect the fire location, heat from the fire melts the cladding around the fiber allowing light to escape. This in turn causes a decrease in the signal received at the controller. As this signal continues to decrease, the system transitions from trouble (35% reduction) to alarm (50% reduction). A complete and immediate loss of signal, indicative of a break in the fiber, also results in a trouble signal. This concept is very similar to the more traditional, bimetallic line-type heat detector, but offers greater installation flexibility due to the non-conductive nature of the optical fiber.

In other heat sensor research, recent studies have shown a temperature fluctuation in the range of 1 to 20 Hz to be present in many fire situations.[4] Up to now, the maximum detectable thermal fluctuation frequency has been about 1 Hz. This is due to the thermal mass and associated heat transfer parameters of the sensing elements most often used. However, by using a fast responding pyroelectric sensor that can detect the higher frequency fluctuations,[5] much earlier thermal detection can result (Figure 4). In fact, laboratory tests have shown such a sensor to respond to open flaming fires in the same time frame as ionization type smoke detectors.[4]

Figure 4: Thermal Fluctuation Sensor Operating Theory[4]

Thermal Fluctuation Sensor



Cerberus AG, Switzerland

Gas Sensors

Gas detection devices have been another source of sensor development in recent years.[6] Because gases are produced in all stages of combustion, it would seem that a specific gas signature could be used for reliable fire detection. However, many of the gases produced during the combustion process also occur naturally, or are generated by non-threatening combustion processes such as automobile engines. In addition, the sensor technology utilized often requires a significant power source, thus restricting its application as a cost effective fire sensor. By focusing on these two concerns, research has produced gas sensing technology that will become more widely applicable in coming years.

One promising gas sensing device is the HCl detector developed by researchers at Bell Labs.[7] In this case, a sensor was developed specifically to detect HCl given off by the pyrolysis or combustion of PVC cable insulation. Such a sensor provides two basic data points: an early indication of HCl production, which can be damaging to electronic components, and a true indication of a PVC cable fire. Because it only senses HCl, it does not respond to common nuisance signals such as cigarette smoke, steam or dust, yet provides very reliable detection of HCl-producing fires such as burning PVC cable insulation. However, this also means that a different type of fire detection device is required for detection of non-HCl-producing fires. Although it may be more costly in the beginning, such a two-fire signature detection system could be more reliable than a single sensor system, thus becoming more cost effective operationally over time.

Another major development comes in the area of increasing the widespread applicability of sensors of more common gases like CO. It has been shown that semiconductor gas sensors can detect CO at concentrations in air in the range of a few parts per million, considerably lower than concentrations that might be expected in a fire of organic material. The problem, however, has been that some of these detectors may also respond to other gases, and have required a significant power source (operating temperatures of 300°C or higher) for operation.

In research performed at Harwell Laboratory in the UK, a hybrid CO detector was developed which could operate at room temperature from a low power source like a battery.[8] The obvious benefit is that a battery operated spot-type CO detector, similar to a battery powered spot type smoke detector could be feasible. Tests were performed using British Standard test fires, as well as common nuisance alarm signatures such as high humidity, high velocity and toasting (charring) of bread. Results were good in all cases.

Similar research was also performed in Japan, where researchers developed a CO sensor that could be powered by a standard fire detection system.[9] The CO sensor is made of a solid-state macromolecular membrane, and is fabricated using integrated circuit and large scale integrated circuit technology. This results in a low power consumption requirement, allowing the CO sensor to be combined with smoke and heat sensors in a common housing and powered from a fire detection system control panel. Together, the three sensor signals provide information that is used to differentiate between deceptive phenomena and actual fire conditions.

Fire Sensor Development

Much of the research in the area of "fire" detection has focused on reducing nuisance alarm problems with ultraviolet (UV) and infrared (IR) radiation sensors. These devices, which are used to detect electromagnetic radiation produced during the combustion process, are primarily used to detect radiation from flames. However, they can also detect radiation from overheated materials which can result from numerous deceptive phenomena, including sunlight, arc welding sparks, tungsten lamps and other hot bodies. Middleton[10] provides a good discussion on various approaches that have been used to address this problem, including detection of the frequency of flame flicker, single channel detection with narrow band filtering, dual channel IR detection, and a combination of UV and IR detection.

In a somewhat new approach to minimizing nuisance alarms, researchers in Japan have recently combined multi-wavelength radiation sensing with algorithms that determine object temperature, flame temperature, surface area, and presence of a flame.[11] The object temperature algorithm is derived from Plank's law, which states that the intensity of radiation emitted in hemispherical space is proportional to temperature and wavelength. Given four discreet wavelengths and measured intensities, the temperature of the object is determined by the relationship:

$$T = (C_2)\bullet[(\lambda_1-\lambda_2)]\bullet 1/\ln[(P_2/P_1)(\lambda_2/\lambda_1)^5]\ K \quad (1)$$

where λ_1 and λ_2 are two of the wavelengths, P_1 and P_2 are the measured intensities at wavelengths λ_1 and λ_2, and $C_2 = hc/k$. Temperatures below 350°C are calculated using wavelength bands 3(4.6 to 5.4 microns) and 4(8.0 to 9.0), and temperatures over 350°C are calculated using bands 1(2.8 to 3.2 microns) and 3. The flame temperature and combustion surface area are calculated in similar fashion. A comparison of the temperature and surface area with the resonance radiation of the CO_2 band then determines whether the body is in flames. The system also determines the "degree of danger" by evaluating the increase in radiation energy and CO_2 ratio.

Tests were performed using a variety of fuels, including methanol, heptane, and beech wood cribs. The system was able to detect a 10 cm square pan of burning methanol from a height of 10 m, and was able to continuously detect changes during the transition from smoldering to flaming of the beech crib.

This approach is similar in concept to machine vision fire detection, an area that has recently been studied in some detail.[12,13] In short, machine vision technology is a combination of video cameras, computers, and artificial intelligence techniques. Cameras are used to image information such as brightness, color and shape. Pattern recognition and image processing techniques process the cameras' input, and specific algorithms or other artificial intelligence techniques are used to determine certain information required for a specific decision.

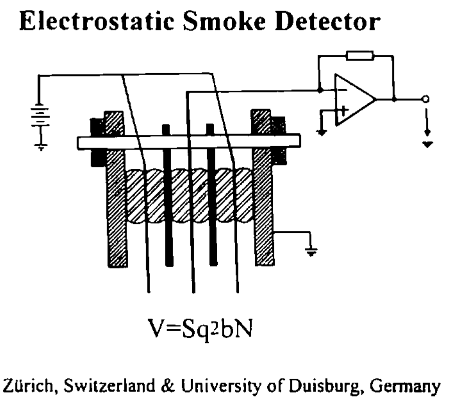
The machine vision system developed by Goedeke *et. al.*[12] for fire detection uses radiation sensors (UV and IR) to detect a fire, a CCD camera for imaging, and artificial intelligence techniques to automatically evaluate the scene, identify bright regions associated with the radiation and determine if there is a fire. It does this by capturing a scene from the camera, digitizing the image and storing the frame in memory. In normal mode, a new scene is captured every few seconds and the previous reference frame is replaced. When UV or IR radiation is detected, the frame capture rate increases and the system computes size, growth rate, stationarity, mean spectral content, spatial variation, and temporal variation for each new frame. The system then decides if the radiation is produced by a fire, and can discontinue tracking, issue an alarm or activate suppression systems as required. Tested in an aircraft hangar environment, the system has 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.

This is similar to a combination IR sensor and video camera system developed in Europe that can detect a relatively small fire (3 m^2) from a significant distance away (2 km.)[14] The optical system is based on a passive infrared sensor array with appropriate filtering and amplification circuits. A video camera is integrated with the sensor array to remotely image, locate and estimate the distance to the event detected by the sensor. Unlike the machine vision system, however, the image is displayed to an operator who manually controls the scanning of the sensor to gain additional information and make decisions. Although an operator is required, the sensors' field of vision is a full 360° for a distance spanning 2 km.

At the other end of the spectrum, research at the Santa Barbara Research Center resulted in the development of an IR sensor using optical fibers that allows remote fire sensing in enclosed or environmentally harsh areas.[15] The system is composed of optical fibers, IR detection devices, and an embedded microcontroller for signal processing. The optical fibers act as the sensors, allowing them to be located remotely from the signal processing equipment. At the end of the fiber, a lens is added to increase the nominal 20° field of view to 60 or 90°. Radiant energy is viewed at the sensing end of the fiber and transmitted to the microcontroller where the signals are amplified, digitized and processed. The signals, which include flicker frequency, modulation randomness and spectral power ratios, are then analyzed to make a fire/no-fire decision. Originally designed for use in aircraft engine nacelles, tests have also shown the sensor to be useful in open area fire detection applications such as storage areas, cargo holds, and aircraft hangars.

In a completely different and unique area of fire sensor research, the detection of acoustical emissions (ultrasonic events) associated with the combustion of building materials has recently been studied. Grosshandler and Jackson[16] discuss a variety of ways in which acoustical radiation has been used for fire detection, and suggest that detection of acoustical emissions could prove beneficial in detecting hidden structural fires. By applying a small flame to various structural materials on which piezoelectric transducers had been mounted, they were able to detect distinct differences in the number of acoustical signals emitted per unit time for the different materials being tested. This would suggest that such a method could be used to detect a fire that could not be seen or otherwise sensed in a confined space.

Figure 5: Electrostatic Smoke Detector Block Diagram[17]



Smoke Sensor Development

There has also been considerable research in the area of smoke sensor technology. Although much of the focus has been on incipient smoke detection systems, there have also been developments in the more traditional spot-type devices. One such area of focus has been to investigate the feasibility of a smoke detector that operates on the ionization principal without the use of a radioactive source.

An interesting approach to this situation has been proposed by researchers at the ETH Zürich, Switzerland and the University of Duisburg, Germany that involved development of an electrostatic smoke detector.[17] The detector is based on the principle that some percentage of smoke particles formed during combustion carry an electric charge that can be detected. The detector consists basically of a sensing electrode sandwiched between two parallel reference grids (Figure 5).

Charged particles that enter the space between the electrodes are deflected by the electrostatic potential, with some of the particles precipitating on the sensing electrode. A current is then established which is proportional to the amount of precipitated charge per unit time. Tests have shown this detector to be sensitive to open flaming fires, but insensitive to smoldering combustion. This is due in large part to the fact that particles of combustion are initially highly charged, yet as the smoke cools, it coagulates and reduces the net charge as particles of opposite charge combine. The researchers indicate a possible application of such a sensor in specific applications, such as alcohol fire detection, or in combination with a light scattering type smoke detector to provide a wide range of detection capability.

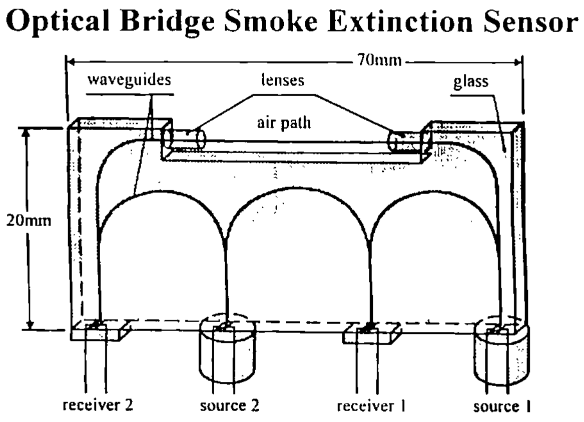
A somewhat different approach to smoke detection using electrostatic charge was taken by French researchers.[18] Instead of using parallel plate electrodes, they used single point type electrodes, one of which carried a 6kV–12kV potential used to ionize the surrounding air, and the other which measured the conductivity of gases passing through the volume. This arrangement showed similar response characteristics: good for flaming fires, not good for smoldering combustion. Other potential drawbacks of this technique include high current requirements to maintain the high voltage charge on the source electrode and sensitivity to leakage currents along the critical insulation path. With a trend to reduce the use of radioactive materials, however, continued research in this area may prove beneficial.

In the area of optical type smoke detectors, researchers at Cerberus AG in Switzerland have developed an optical sensor for measurement of light extinction that requires an optical path length of only 25 mm [19,20] (Figure 6). Smoke detection by the extinction method is based on Bouguer's law, which relates the intensity of the incident monochromatic light (I_λ^O) of wavelength λ, and the intensity of the light (I_λ) transmitted through a path length L of smoke with an extinction coefficient K[21]:

$$I_\lambda / I_\lambda^O = e^{-KL} \qquad (2)$$

Currently available light extinction sensors that operate on this principle require separate transmitter and receiver units spaced at least 10 m apart. This new sensor, however, utilizes an integrated optical wave guide system containing multi-mode channel waveguides that allows the air path to be reduced to millimeters.

Figure 6: Optical Bridge Smoke Extinction Sensor Block Diagram[20]



Referring to Figure 6, the signals from Source 1 (S1) and Source 2 (S2) are split by means of a Y-junction waveguide at given ratios K1 and K2, and are detected at two receiver locations (R1 and R2). Individual signals are identified by driving the sources at different modulation frequencies, and the transmission (T) across the air path is given by:

$$T=(K_1/1-K_1)\bullet(1-K_2/K_2)\bullet[A_1(f_1)\bullet A_2(f_2)/A_1(f_2)\bullet A_2(f_1)] \qquad \textbf{(3)}$$

where $A_1(f_1)=K_1TS_1R_1$, $A_2(f_1)=(1-K_1)S_1R_2$, $A_1(f_2)=(1-K_2)S_2R_1$, and $A_2(f_2)=K_2S_2R_2$. The signal through the wave guide and across the air path under normal conditions provides the reference value. When smoke particles enter the path, the signal decreases until an alarm is given when a predetermined threshold is reached. Because light extinction is used in most smoke density measuring devices and smoke detector test equipment, and considerable data on the extinction characteristics of smoke from various materials is known, further developments in this area may prove to be useful in evaluation of detector response and perhaps even computer modeling of detector response.

Additional research in optical smoke sensing technology at Cerberus AG includes the use of two light sources of different wavelengths, the use of two detection angles (forward and backward scatter) and the measurement of the polarization of the scattered light[22]. Whereas the operation of the previously described optical bridge sensor is based on light extinction principles, all three of these parameters relate to the application of light scattering theory. In particular, they relate specifically to broadening the size distribution of particles that can be detected.

The scattering of incident light by smoke particles is often described using Mie theory, which states that the amount of incident light scattered by a particle is dependent on the size, shape and refractive index of the particle, wavelength and intensity of incident light and the angle of scatter.[23] It has been shown that this relationship can be described for a smoke detector in the following manner:[24]

$$I_s = I_0(\lambda^2 N_0 V_s / 8\pi^2 l^2)(i_1+i_2) \quad (4)$$

where:

I_s = Intensity of scattered light, (W/m^2)

I_0 = Intensity of the incident light, (W/m^2)

λ = Wavelength of the incident light, (m)

N_0 = Particle concentration in the detection chamber, (particle/m^3)

V_s = Volume of the detection chamber, (m^3)

l = Distance from the scattering volume to the scattered light receiver (m), and

i_1+i_2 = Mie scattering coefficients (functions of the scatter angle θ, particle diameter d, and refractive index, m)

This relationship indicates that for a fixed scatter angle and wavelength of incident light, the intensity of scattered light received will be maximized for a specific particle size and refractive index. As a result, by increasing either the number of angles at which scattered light is received, or the quantity of incident light wavelengths transmitted, a broader range of particle sizes at various refractive indices can be detected. It has been suggested that such information could be used not only to detect smoke across broader particle size and color ranges, but also to identify different smoke characteristics of burning materials.[24,25] By using two incident light sources that are polarized, even more information concerning the smoke particles can be determined.

CONCLUSION

World wide research efforts have resulted in the development of a number of new fire sensor technologies, many of which have been described here. Although fire sensor research continues, it is clear that the means to detect fire at any stage of development, under most environmental conditions, currently exists. As a result, one might expect that future research may focus more on the integration of existing sensor technology with signal processing techniques intended to verify fire conditions and reduce nuisance alarms. In fact, some of the developments described in this paper have done just that. However, because the goal of a fire detection system is to reliably detect fire at that stage necessary to meet specific fire safety objectives, continued advancements in both sensor technology and signal processing techniques are both needed and welcomed.

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