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TOPICAL REVIEW

Review Study on Recent Developments in Fire Sensing Methods

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ABSTRACT Scientific society has envisioned a considerable advancement in various fire detection methods due to the development in the field of machine learning, information technology, sensors, and signal processing technology. These intelligent processing technologies help in reducing the detection time and false alerts from the sensors. Over the past few decades, there is substantial improvement in the computing power of computers and a decrease in the cost of image sensors, enabling video-based fire detection technology for real-time applications. The ability to differentiate between fire and non-fire threats is improved with the development of the Internet of Things (IoT) or Wireless Sensor Networks (WSN). Unmanned Aerial Vehicles (UAVs) are becoming a more realistic solution for monitoring and detecting fire due to their remote sensing capabilities. This paper summarizes various fire detection methods and the technologies behind them. The issues related to the present fire detection methods and future research initiatives are discussed. The primary aspects of the fire signatures like flame, smoke, ambient temperature, and surrounding gaseous levels concerning different sensors are analyzed with their benefits and drawbacks based on evaluating a range of parameters.

INDEX TERMS Fire sensors, smoke detectors, flame detectors, heat detectors, gas detector.

I. INTRODUCTION

Despite the extensive use of fire-detecting methods in both residential and industrial areas, fires continue to cause numerous fatalities and accidents as well as significant financial damage. According to the international association of Fire and rescue services (CTIF), the death due to fire accidents and fire hazards in India is approximately 16714 on average per year from 2014 – 2018 [1]. Fig. 1 shows the trend of fire death in India in that period. The recent advancements in the technologies like sensing methods, information, and telecommunication, fire sensing methods have made considerable progress in recent years. Identification of an emerging fire incident and prompt warning of the building's residents and fire emergency organizations are essential facets of fire safety. This has resulted in the emergence of modern fire sensing and detection technologies, which paves the way for the development of smart buildings [2]. Cooking, smoking and electrical damage are the most frequent sources of fires in residential environments [3]. Electrical fire hazards demand specific consideration since they account for a significant percentage of fire fatalities worldwide. The common causes of electrical fires in residential areas may be due to faulty sockets and appliances, extension leads, portable heaters, outdated wiring systems, overload, loose contacts, short circuits, etc. [4], [5], [6].

A fire can be identified by several occurrences whose corresponding physical or chemical manifestations can be

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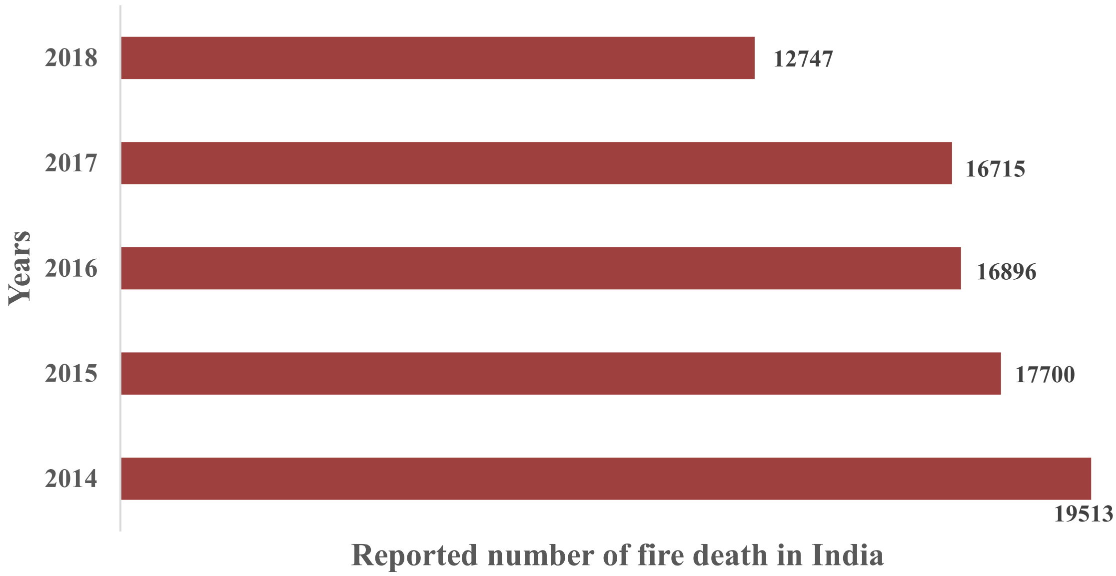

FIGURE 1. The trend of fire death in India.

measured and utilized to trigger an alert. Although all these phenomena are used in fire detection systems, none of them can consistently offer accurate detection.

The characteristic scent of smoke is normally the first sign that a fire is on its way. Early warning (either human or automatic) accompanied by a prompt response by trained fire emergency personnel can control the fire until it causes serious damage. When a fire approaches the end of its incipient phase, it normally generates enough heat to allow the emergence of open visible flames. The ability of fire detection is very much essential for the safety of people and their belongings. The important alarming signs of fire are heat surrounding the environment, flames, smoke, and the quality of the surrounding air. The sensing technique is very important for the real-time measurement of any physical quantity. Fire sensing methods are still facing challenges related to minimizing false alerts, and improving sensitivity and dynamic response. This paper concentrates on reviewing different fire-sensing methods from the literature for the detection of fire in a confined environment.

The organization of the paper is as follows: Section II discusses the various fire detection techniques. The research involved in multi-sensor data processing and monitoring is explained in Section III and conclusions are drawn in Section IV.

II. FIRE DETECTION TECHNIQUES

The existing detection methods rely on a variety of sensors [7], [8], [9], [10] like smoke sensors, heat sensors, gas sensors, and flames sensors. The existing fire sensing system consists of a sensor array for converting the physical parameter to be measured into a suitable electronic signal, a signal conditioning circuit to make the signal suitable for processing, a processing unit that processes the signal based on some algorithms and alarm for an indication as shown in Fig. 2.

Over time, several fire detection methods have progressed. Few of these approaches are in use currently, whereas, many of them have become outdated. The smoke detectors are designed to detect fire when it is still smoldering or in the early stages of flame. They function on either ionization or photoelectric principle with both having advantages in certain applications. Thermal detectors are the earliest types of automated detecting devices available in a variety of designs. The most popular are fixed heat detectors, which turn ON after the chamber attains a prearranged temperature value.

The most prevalent form of the temperature sensor is a rate-of-rise sensor, which recognizes abnormal rises in temperature over a rapid duration of time. Both the above-mentioned detectors are spot-type detectors. Another form of thermal sensor is a line-type detector which is made of two cables and an insulating wrapping that breaks down when exposed to heat. The maintenance of thermal sensors is very easy and inexpensive. But the disadvantage here is it does not function until it reaches some preset temperature value.

Flame detectors are the third important detecting device that works when they are in a line of sight. The important benefit of a flame detector is that it is consistent but very expensive. A flame detector is mostly utilized in energy and carriage applications, where further detectors could be prone to false instigation. The importance of the different gases produced by flames has been thoroughly investigated with the result that carbon monoxide is the sole accurate gaseous indication of fire. Due to their sensitivity, reduced cost, and low footprint, semiconductor metal-oxide gas sensors have attracted many gaseous detection methods. However, they

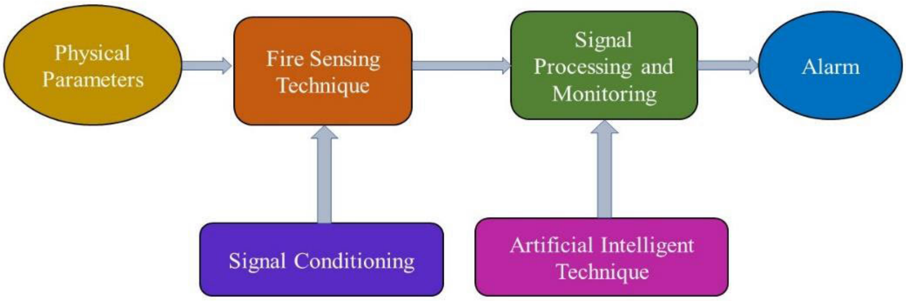

FIGURE 2. Fire sensing method.

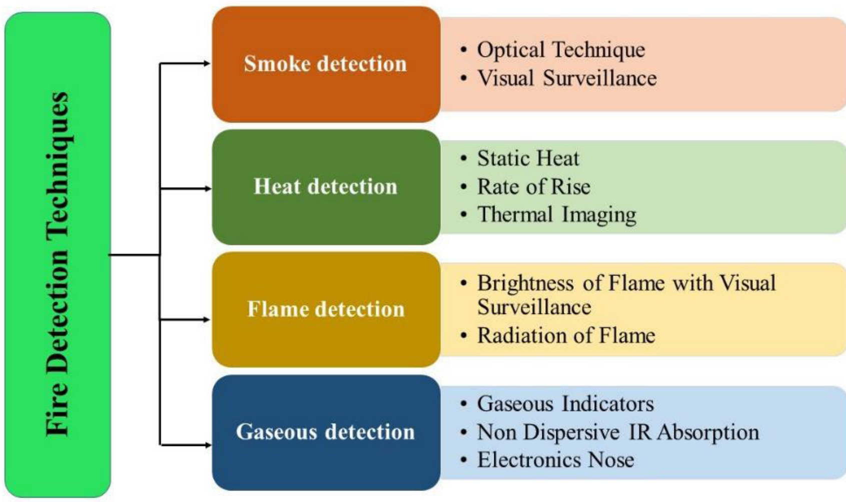

FIGURE 3. Fire detection techniques.

have a stability issue that needs to be addressed. The various sensing techniques involved in different types of sensors are shown in Fig. 3.

A. SMOKE DETECTORS

Smoke is generated significantly sooner as compared to further fire indicators. The ability to detect smoke at an early stage can increase the chances of successful fire control and survival. Smoke is produced because of the combustion of things and it affects the quality of the air in the surroundings [11]. There are two broad techniques available for smoke detection: optical technique and visual surveillance.

In optical technique, the communication of elements with a ray of light or electromagnetic fallout can be utilized to sense the smoke as displayed in Fig. 4. Optical smoke sensors are more delicate to ablaze flames and display a wider operating temperature range. The sensitivity of the detectors is not largely affected by the atmospheric temperature. It can detect smoke particles whose length varies from 1.0 to 10 μm and shows difficulty in detecting smoke particles less than the given range. Apart from that, the particles which are generated from dust and aerosols can cause the optical smoke detectors to give false alerts.

According to the literature, the degree of incident light dispersed by an element is primarily affected by the particle's magnitude, profile, wavelength of incident light, angle of scattering, and refractive index [12]. In [13], the authors described the feasibility of reducing false alerts and increasing the sensitivity of the smoke detectors by employing the multi-sensing approach. The investigational results display that the capability of the smoke detector

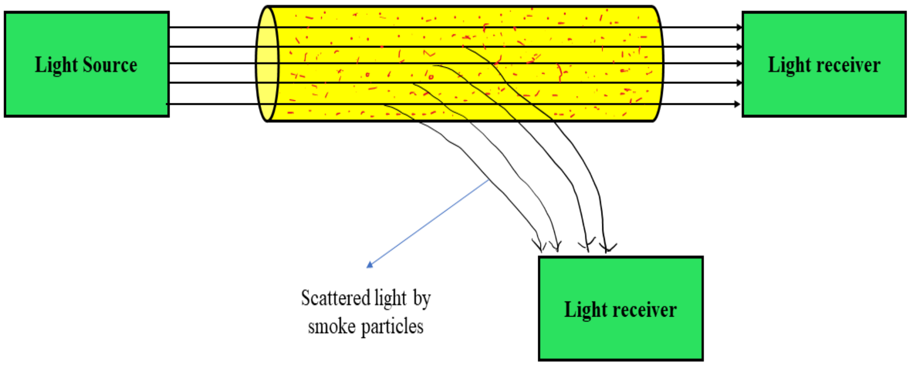

FIGURE 4. Interface of smoke particle with ray of light.

is improved with a simple approach to alarm algorithm development. The fire detection technology with the help of spectral analysis of the smoke particle is reported in [14]. This process is carried out in two stages. The first stage is to acquire the spectral data based on the optical reaction of the smoke elements by the sensor and the next stage is to determine the presence of fire by intellectual investigation of the spectral data. In [15], a smoke detection method is proposed which incorporates dual-polarized channels to adjust the sensitivity of both white and black smoke. The sum is differentiated by the polarization degree of the channel and sensitivity is adjusted by a correction factor. To lessen the false alerts by the smoke detectors, a methodology was adopted [16] where many trials were done to gather the data of signals generated by the detectors. The signal pattern produced by the smoke detectors was carefully analyzed and it is concluded that the pattern generated by the flaming fire, smoldering fire and non-fire sources were different. This result is used to enhance the effectiveness of the alarm system. Similarly, the authors in [17] presented an approach for smoke detectors to reduce false alerts by analyzing the particle size dispersal of smoke. In [18], the authors devised a system that detects aerosol/smoke and delivers data about the burning substance. For that optical arrangement is used which contains a white polychromatic LED, optical fiber, and photodiodes.

In most of the optical techniques used for smoke detection, the concept of scattering of light by smoke particles is used. Usually, a single light source and off-axis photodetectors are used in typical residential smoke sensors. It is constructed in such a way that the alarm turns on when scattered optical intensity reaches the threshold value. The threshold level depends on the concentration of smoke particles inside the chamber where the smoke detector is placed. This type of arrangement is insensitive to the size of the particles and refractive index which results in false alerts. So, many studies have demonstrated the feasibility of estimating these parameters using multi-angle scattering data and multi-wavelength illumination.

Smoke can also be detected by the visual surveillance system, provided the area should have enough ambient light. The basic visual smoke detection system comprises many CCTV cameras that are connected to a processing system. This system makes use of a specialized algorithm for detecting smoke. This technique is used in a variety of applications like paper mills, cement plants, historical sites, power generating plants, etc. The main limitation of this type of detection technique is its incapability to function in low-light conditions [19]. Smoke travels faster and is more prevalent through the primary phases of a fire. Nevertheless, detecting it is more difficult than detecting flames. Smoke detection by visual surveillance is based on the extraction of image features like color, texture, energy analysis, and movement analysis. The extracted features are processed with appropriate image processing techniques to detect the presence of smoke. In [20], the authors presented an approach based on the statistical analysis of color models for both smoke and flames.

To distinguish between flames and fire-like resembling entities, fuzzy logic is used. The dynamic texture analysis is employed in [21] for smoke discovery in the audiovisual. In [22], the authors used Adaboost with staircase discovery method for smoke recognition and utilized active investigation for smoke rationality. If the proficient dataset is large sufficient and the procedures are light enough, this technique for fire detection yields good results without compromising the accuracy. In [23], the authors created a color and motion-based flame and smoke-finding arrangement. They improved the system's performance by doing morphological procedures. The fire detection technique was developed in [24] by utilizing the You Only Look Once (YOLOv2) algorithm for identifying and locating smoking objects using a video camera.

B. HEAT DETECTORS

Many fire detectors are constructed with sensors that react to the change in heat or temperature. Heat is a form of thermal energy that travels from the hotter environment to the cooler

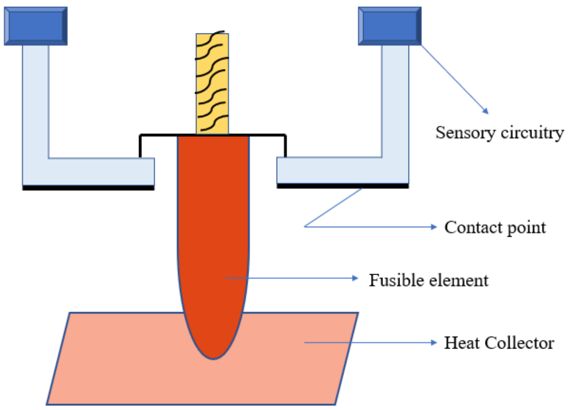

FIGURE 5. Fusible element based static heat detector.

environment. Through thermal imaging or heating element, the amount of heat transferred can be detected. The heating element along with the signal conditioning circuit constitute heat detectors. The heat detectors are utilized to quantify the ambient heat in any environment which results due to fire. Heat detectors can be categorized as static heat detectors and rate of rise detectors based on their functionality. With the help of thermal imaging techniques, the invisible pattern of radiation is converted into visible images, which are then used for feature extraction and analysis.

Static heat detectors usually operate when the sensor exceeds its predefined temperature [25]. There are many categories of static heat detectors. In a fusible element-based static heat detector, there will be a fusible element that melts and creates a short on the sensing circuit to operate as shown in Fig. 5. They are non-restoring type detectors since once the detector is operated, this fusible element must be replaced. When the static heat sensor is turned on, the surrounding temperature will always be greater than the device's operating temperature. The difference between these two temperatures is called thermal lag which will be proportional to the temperature rise.

Distributed optical fiber static heat sensing is an emerging and effective heat sensing technology for fire prevention scenarios [26], [27]. Here, the heat distribution over the length of the optical fiber cable is measured, which uses the fiber itself as a sensor module. In distributed heat sensing method, the Raman effect is used to measure the amount of heat. As shown in Fig. 6 When an optical pulse is transferred via the fiber, some of the pulses get scattered and return to the transferring end, where the data is processed. The intensity of the Raman scattering is the measure of temperature along the cable. The distributed heat sensing method also uses Brillouin back scatters for temperature detection which is considered an effective replacement for the Raman scattering sensing method [28], [29], [30]. In [31], the authors investigated the groundwater flow and heat transport in the fractured medium by using the optical fiber distributed heat sensing method. Using recordings of distributed heat sensing from 0.5 m above to 1.5 m below the surface, [32] offers a new approach for verifying surface flux and heat balance measurement at the lake surface.

Bimetallic sensing is another type of static heat detecting method, where it contains two different metals with different expansion rates fused to form a single metal strip. A low-voltage current is used to activate the strip electrically. When the strip gets heated due to fire in the surroundings, the metal with a high expansion rate will bend towards the electrical contact to trigger the alarm. The temperature that will set off the alarm is determined by the gap between the contacts [33].

The rate-of-rise detector, which detects an excessively fast temperature rise over a short period is the second most prevalent form of thermal sensor. Rate of rise detectors also features a set temperature backstop, which ensures that even extremely modest temperature increases will ultimately trigger an alert if they persist for long enough. Because they detect a temperature rise of 12 to 15 degrees Fahrenheit each minute, the rate of rise detector is rarely utilized in suppression systems. As a result, they are too sensitive to abrupt environmental changes, resulting in false alarms and unanticipated discharges.

Thermal imaging is also used to detect smoldering fires in some specialized situations. An infrared thermal imaging camera with a pan and tilt mechanism may be used to scan huge regions of combustible materials, and this method is used to monitor stock heaps in the coal business. When coal absorbs oxygen from the air, hotspots occur, and the heat produced can ignite a smolder that, in the case of a stockpile, can burn under the surface and be unnoticed by the naked sight. This method is also used to keep track of coal on conveyors and during rail car unloading. The performance of the heat detectors is strongly influenced by the thermal parameters particularly, its trend toward increased spatial resolution. So, assessing them is crucial for the performance improvement of the detectors. In [34], a self-test approach for evaluating the thermal characteristics of uncooled IR focal plane arrays is developed. This method was inspired by the conventional optical frequency domain concept and Joule's heating effect of the pixels. The results show that this method significantly improves the measurement efficiency.

In [35], the authors designed a system that would measure the temperature variance among the two barrier shells. The system is verified in both inner and outer wall surfaces from which the stage of fire can be determined by evaluating the temperature difference. The concept of near-field and far-field grounded fire estimation is developed in [36] which utilizes a heat sensor collection for evaluating various stages of fire. This prototype is appropriate for determining the optimal location for the fire sensor. Experimental and simulation studies have been done in coaxial cables with three different lengths for detecting fire and localization [37]. The results conclude that the characteristics of coaxial cable

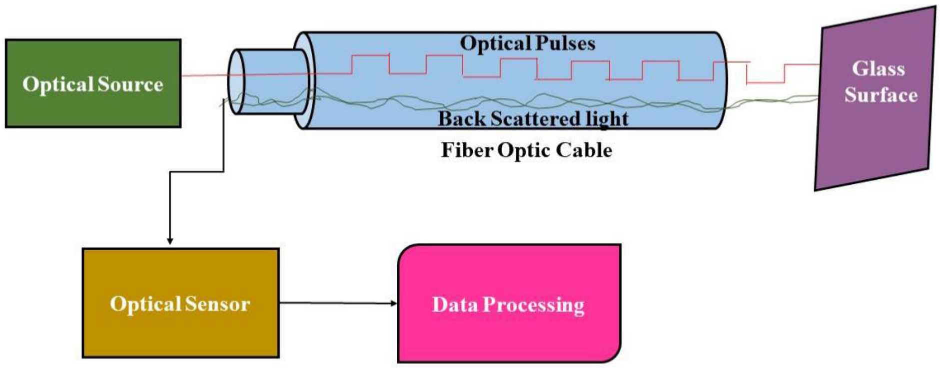

FIGURE 6. Distributed optical fiber static heat sensing.

like resistance, capacitance, and impedance vary with the temperature change.

C. FLAME DETECTORS

Flame detectors are designed to sense the presence of flame and play a crucial role in a variety of industries such as chemical plants, hydrogen stations, drilling and constructions, industrial gas turbines, industrial heating and drying systems, printing and paper manufacturing industries, etc. Flames are the visible and gaseous portion of the fire that results from the reaction between oxygen and fuel. So, this type of fire detector is otherwise called a light detector [38]. Based on the chemical composition of the burning material, the frequency spectrum of a flame will be in the visible, Ultra Violet (UV), or Infrared (IR) region. Due to the technique utilized to detect the flame, a flame detector may typically respond faster and more precisely than a smoke or heat detector.

There are three basic classifications of flame detectors depending on the frequency spectrum of radiation of the flame. They are IR flame sensor, UV flame sensor, and visible light or multi-wavelength flame sensor that senses light in both regions. There are two methods of flame detection. One is by measuring the brightness of the flame and the other is by measuring the radiation of the flame. In comparison to visible and IR sensors, the UV sensor is employed to detect brightness, since the influence of IR emissions on the UV sensor is relatively minimal. The radiation of the flame is measured using IR and visible sensors which are appropriately compared to UV sensors.

The IR region contains most of a flame's radiant energy and the burning of hydrocarbons causes the CO_2 peak at 4.3μm wavelength. By integrating a multi-wavelength radiation sensing algorithm, which calculates the material temperature, flame radiation level, surface area, and the existence of a flame, efforts have been made to reduce false alerts from UV and IR detectors. The combination of these two detectors greatly eliminates the issues associated with traditional flame detectors. Since the multi-wavelength detector monitors both UV and IR radiations generated by flames, it avoids false alerts by UV radiation from sources other than fires and also the alerts from fires which do not emit IR radiation at 4.3 μm. However, the multi-wavelength detector still uses a vacuum photodiode to detect UV light [39].

In [40], the authors developed and commercialized solid-state flame sensors for turbine control applications by utilizing the electrical and optical properties of silicon carbide. The integrated high-temperature companionable optical flame detectors are designed in [41], which can able to differentiate flame regions and can show steady functionality at 340 °C. In this sensor, dual gallium phosphide photodiodes and a silicon on insulator are placed on top of aluminum nitride with spotted Titanium/Platinum/Gold (Ti/Pt/Au) metallization for withholding high temperature. For the detection of the flame, the authors in [42] developed a low-cost IR photodetector that is manufactured with Lead Sulphide (PbS) utilizing the colloidal quantum dot method. Using a UV flame detector, a model was presented in [43] to eliminate the influence of spark.

Most of the conventional types of flame detectors require proximity to the flame. They have a high possibility of giving false alerts because apart from detecting combustion, it also detects the byproducts of combustion. And also, conventional flame detectors do not provide more information about the location of the flame, its size, its burning degree, etc. Many research works have been proposed in literature based on the visual surveillance of the flame because the images can convey reliable information. In [44], the radiation emitted by the flame is calculated based on the flame spectral combustion diagnostics. A flame detector is proposed and developed using three photovoltaic cells in [45], where the frequency spectrum of visible, IR, and UV regions are monitored by them individually. The frequency of oscillation of the flame and the intensity of the flame are used to monitor the stability of the flame. Flame detection using a deep learning algorithm is implemented in [46], which uses a training set of digital images to identify the fire flames which in turn improves the efficiency of the fire detection process. In [47], a database of different fire colors was created by collecting thousands of images of fire pixels from various scenarios. These fire pixels were remapped in 2D color space which leads to a result that fire pixels have some mathematical correlation with RGB data. This correlation is measured in the color space model to provide the standard for extracting and segmenting fire flames from the images. Similarly, image-based flame detection is proposed in [48] and [49] to estimate the burning degree of the flame.

Visual surveillance provides a lot of advantages in addition to sensing and identifying a fire. These are not affected by the emissions from the typical background sources resulting in reducing false alert problems. It can consistently sense a tiny burn for wider regions in rapid duration by processing numerous spectral images in real-scenario. The range of applications for video fire sensing systems is rapidly growing which includes power generation plants, manufacturing plants, tunnels etc. Utilizing the color, boundary, zone, and shape of the flame, the authors in [50], presented a technique utilizing flame variations and motionless indoor sensing. A tiny fire, such as a candle, is used as a minor element of their approach. This approach may have a noteworthy struggle in primary fire warning since it eliminates and then smears flame expansion topographies to evaluate. Spatial and temporal variation by wavelet method is used in [51] for monitoring the brightness and mobility information of the flame. However, some significant constraints and criteria make it unsuitable for practical fire sensing.

A probabilistic strategy based on color and motion characteristics was proposed in [52]. An effective method for sensing the flame from the video is proposed in [53], which not only employs the data about the color and temporal variation, but it also uses the temporal wavelet transform to detect the flicker and spatial wavelet transform to evaluate the color variation in the moving region. In [54], a method is proposed to detect the flame in the video by processing the information collected. This method not only gives the intensity ad movement information but also senses the flickering using a hidden Markov model. In [55], the authors proposed a method for sensing flames from video sequences using multistage pattern recognition techniques. Initially, it uses the Gaussian model for detecting the movement. Then based on the color of the fire, the region is identified using a fuzzy algorithm. Then the parameters are extracted from the spatial and temporal variation of the fire region. Finally, the support vector machine is used to identify the flames of the fire. A method of flame detection which employs intensity and movement detection along with the flickering analysis in a single approach is proposed in [56]. Here, the Gaussian model is used for extracting moving objects and then they are categorized into candidate and non-candidate flame regions by the color filtering techniques. Finally, the flicker identification algorithm is used to distinguish the flames of fire.

D. GAS DETECTORS

The major causes of fire are due to the combustion of organic components. In that, some gaseous components like Carbon Monoxide (CO), and Carbon-dioxide (CO_2) may be anticipated with reasonable accuracy. Even if a fire was initiated with the combustion of non-organic components, it is capable of spreading promptly to nearby organic components. The importance of different gases produced by the flames has been widely researched and the conclusion was made that CO is present in all types of flames produced and can be treated as a reliable gaseous indicator. It is also analyzed that the concentration of CO is large in slow-burning and small in fast-burning fires. So, it is believed that, apart from fire detection, gas sensors can also be used to determine if the fire is blazing, fuming, or intermediate [57]. Two forms of CO sensors are available for fire detection: non-dispersive IR and electrochemical. Non-dispersive IR sensors are based on the optical method of fire detection, while electrochemical gas sensors are based on the electrochemical reaction of the sensing material. In [58], the authors did a comprehensive survey on different gas sensing technology by considering sensitivity and selectivity as the main performance indicators. According to their survey, the other performance indicators are the response time (the time taken by the sensor to give an alert if it detects the gas), energy consumption, reversibility (whether the sensing material reverts to its original state after detection), fabrication cost, lifetime, etc.

The Metal Oxide Semiconductor (MOS) gas sensor works on the principle of electrochemical reaction between the gaseous component and the oxygen ion in the air. The material used in this type of sensor is nickel oxide, tin oxide, iron oxide, zinc oxide, etc. [59], [60], [61], [62]. These materials are utilized in the fabrication of gas detectors, particularly for detecting oxygen comprising gases. The large temperature of the detecting mechanism that induces temperature shift is the most significant challenge in the MOS sensors. To overcome this issue, nanotechnology is employed to vary the shape and construction of the metal oxide [63]. These sensors have the advantages like improved sensitivity and reduced cost with reliability issues. In [64], the authors developed a setup that supplies regulated current by using feedback control for temperature compensation. By overlaying appropriate materials on metal oxides, such as zeolites, the selectivity of these sensors may be enhanced [65]. The utilization of polymers in gas-detecting materials is described in works that function efficiently in both room and low-temperature environments [66]. Carbon nanomaterials (graphene and carbon nanotubes) based gas sensors are highly sensitive with good detection capability when compared with MOS sensors. Particularly, with the advancement of graphene as graphene oxide and reduced graphene oxide, this sensor gains considerable interest because of its good sensitivity to various gases [67], [68], [69], [70].

The early detection of gas type and concentration is important for avoiding fire explosions in residential areas.

Normally, multi-component gas cannot be detected by a single semiconductor sensor. So in [71], a multi-component gas detection technique based on the sensor's temperature response was developed. To reflect the greatest variation in the temperature response relationship, the parameters were first tuned based on the cosine distance. By using coordinate system transformation, the difference between gases is enhanced. Then, the rational Taylor function fitting was used to identify the multi-component gas.

Another cost-effective way of fire sensing is by the optical method in which the sensing material tends to change its color when it is exposed to gas. This method can achieve high selectivity, sensitivity, and stability when compared to non-optical-based fire detection. Optical detectors are extremely complex and larger, so it is used only in specialized applications. And also, unlike electrochemical counterparts, optical sensors need not be replaced at regular intervals. In [72], the authors presented the characterization, and methodology of fabrication of nanostructures-based optical sensors for detecting CO. In this work, different substrates with different thicknesses, and diverse sputtering times of nanostructures were investigated, and concluded that the hetero-nano structure performed better when compared with the single component-based structure, thereby increasing the gas sensing properties. In [73], the authors proposed a methodology to fabricate miniature optical sensors suitable to sense CO, CO2, and some toxic gases based on the microfluidic penetration technique.

The calorimeter gas sensors are fabricated using micro-machining technology which can be able to sense the heat radiation emitted by the burning flames. The sensing elements have small shell-based structures whose resistance changes according to the type and amount of gas exposed. This method of sensing is stable at room temperature and is of low cost. It provides adequate sensitivity for industrial applications but has the problem of intrinsic deficiency in selectivity. A miniaturized calorimeter gas sensor was fabricated and analyzed in [74] by integrating different catalysts on the surface of the device. This device can be able to detect hydrocarbon-based gases with lower response time.

In some literature, the acoustic signal parameters like the speed of the sound, its attenuation, and its acoustic impedance get altered with the change in parameters of sensing material like concentration of the target gas, gas density, etc. [75], [76], [77], [78], [79], [80], [81]. Many fire detection technology based on the electronic nose concepts has been reported in the literature. It incorporates sensor arrays that sense different gases in diverse ways. The output of the sensor array will be connected to the signal conditioning circuitry and pattern recognition algorithms for further processing [82].

E. DISCUSSION ON VARIOUS FIRE DETECTION METHODS

Numerous fire sensing techniques have been developed in past years to minimize false alarms and enhance sensitivity and rapid reaction to fire, which ensures fire protection. The comparison of various sensors employed for fire detection techniques is given in Table 1.

Heat sensors are consistent and provide fewer erroneous signals, but have a slower response rate. Providing mobility to these detectors can increase their reaction time. In most cases, heat detectors are placed on top ceilings, and fire blowouts typically over the carpeting. Optical heat sensors based on a variation in refractive index caused by a little change in ambient temperature are exceedingly sensitive. It is necessary to research their usage in fire-sensing applications. Video-based fire-sensing methods are very useful in detecting and monitoring fires. Many buildings already have cameras and related equipment that are necessary for a video sensory system. Video data may be transmitted out or viewed through the Internet or a wireless network as the field of microelectronics and information technologies progress. The video sensor system is projected to play a bigger part in delivering low-cost fire prevention and additional construction supervision and amenities in the future.

Smoke sensors have a high rate of false positives; however, a grouping of optical detection systems may help them to progress. The prime responsibility of gas detectors is irreversibility, instability, and poor discrimination. MOS gas detectors provide high selectivity at a low cost. Nevertheless, their incapability to preserve stability need temperature regulation. And when temperature changes widely through a fire threat, this element is critical, as it might impair the functioning of gas detectors. Intelligent regulator boards with cutting-edge signal processing and a detector-driven fire system will significantly minimize false alerts and offer additional accurate data on fire and smoke spread. Involving robots in fire detection offers a new area of research to explore. Though robots are involved in fire detection processes, they can only supplement the work of human firefighters as the human intellect is currently superior to that of robots. With the development of artificial intelligence and intelligent automation, the application of robots in fire detection without human intervention can be explored.

The majority of fire detection research emphasis on rapid detection of fire. However, just limited research has focused on initial warning signs of fire. Electrical arrangements are a foremost source of fire dangers across the world. As a result, more research into improved sensing systems is needed. For detecting early fires, precise cable selection and real-time cable temperature measurement are required. A high cable load current might potentially signal anomalous activity that could result in a fire.

Because of the limitations that occur in traditional fire detection methods, there has been a lot of interest in wireless sensor networks for use in rural environments. Even though it would be impossible to put fire detectors in every part of the natural world, wireless sensor networks can be utilized to monitor vulnerable regions and they will provide all the required information accurately related to fire in real-time at any instant of time. For this technology to be useful for detecting fire in rural environments, a lot of randomly placed

TABLE 1. Comparison of various methods and sensors for fire detection.

Detection Techniques	Related Works	Type of Sensor	Working Principle	Detection Characteristics	False Alarm	Advantages	Limitations
Smoke Detection	[15]	Optical Sensor	Scattering light intensity	Differentiation of black and white smoke from polarization degree	Yes	Enhanced Response Sensitivity Discriminate white and black smoke	Increase in Relative measurement error
	[16]	Optical Sensor / Ionization	Euclidean distance	Classifies flaming fire, smoldering fire, and non-fire sources	Yes	Deploy multi-sensor fusion technique	Accuracy is limited to 80%
	[26]	Grating / Interferometer Sensors	Point sensors based on Bragg grating or interface	The sensor withstands an upper temperature of 1200^0C for a length of 5 mm	No	The sensor displays high accuracy for monitoring structural engineering applications	The fabrication effort is high and technology is emerging
	[14]	Photoelectric detector	Analyzing the Smoke Spectrum	Multi-wavelength light source	No	Characterization of type of particles and cause of the smoke	Training of neural network with suitable variables
Heat Detection	[35]	Temperature Difference Sensor	Conversion of analog to digital pulses	Based on CMOS technology	No	Reduction of non-linear error	Maximum linear error of 1.35%
	[36]	Temperature Sensor Array	Estimate of signal time delay and replicas	Based on Planar or circular wavefronts	Yes	The fire detection is carried out for a dimension of 10.5 m x 9 m	Error due to geometrical relationships
	[37]	Linear Detectors	Using coaxial cable	Analysis of resistance, impedance, and attenuation factors	Yes	Usage of existing infrastructure to detect the fire	Relative error and response time are very large
Flame Detection	[50]	Vision-based Detector	Color Segmentation	Make use of static and dynamic features to detect the fire with a suitable denoising technique	No	Detection accuracy is close to 99.1%	Need high-resolution cameras for detection
	[44]	Radiation Sensor	Combustion diagnostics of the radiation	Flame spectra analysis	Yes	Use to classify and detect the pollutant emissions	The presence of strong radicals results in weakening the other radicals to be sensed
	[45]	Photovoltaic Sensor	Cross-correlation of signals from various cells in UV, IR, and Visible regions	Monitor the flame presence, blockage, and flame stability	No	Reliability is improved with a multi-cell flame monitor	Precise hardware is required for monitoring the oscillation frequencies
	[46]	Optical Sensor	YOLO Model	Deployment of deep learning methods	Yes	Usage of 24 convolution layers with 2 fully connected layers	Reduction in the accuracy of flame detection
	[49]	Optical Sensor	NLPLS-based Preprocessing of Raceway Image	Monte-Carlo method for	Yes	The flame temperature and flicker frequency	Variation in absolute error and relative

TABLE 1. *(Continued.)* **Comparison of various methods and sensors for fire detection.**

				reconstruction of images		measurements are carried out	error based on the calibration temperature
	`[59]	NiO Sensor	Detection of Xylene using hydro-thermal method	Exploring the intrinsic hole carrier concentration	No	The response time is very high	Working temperature is restricted to 180^0 C
Gaseous Detection	[60]	SnO_2Gas Sensor	Detection of ethanol by doping SnO_2 with palladium and graphene	Palladium and graphene improve the sensing properties by reducing the humidity and working temperature	Yes	The response time varies as a function of ethanol concentration	The rGO affects the sensing functionality
	[62]	NO_2 gas sensor	Detection of NO_2 gas using ZnO/ZnS nanostructure	Detection of NO_2 at room temperature	Yes	Sensor response is very high for varying concertation of NO_2	Precise fabrication is required as the ZnS shell over ZnO rods may be altered
	[63]	Photonic Crystal Gas Sensor	Refractive index-based sensors	Based on the periodicity of the photonic crystals	No	Display high sensitivity in the detection of nano-sized chemical components	Fabrication of sensors is not widely available

nodes are needed to provide a reliable network. For fire detection, each node was provided with a lot of sensors for measuring physical parameters like temperature, humidity, wind speed, and flickering of fire to define fire incidents.

The choice of a particular type of fire detection system depends on the residential environment, the number of occupants, and desired level of protection. To be effective, fire detection must be adapted to the structure and potential fire types. Many fire detection system incorporates a combination of smoke detectors, heat detectors, and manual pull boxes to achieve the appropriate level of protection. The type of detector to be utilized in a given environment relies on the expected nature of fire, desired response time, and the operating condition of the detector.

III. MULTISENSOR DATA PROCESSING AND MONITORING

The majority of the fire alarm system which is in use today have relatively limited capabilities. They are designed in such a way that when a certain threshold is reached, they trigger the alert. There is no precise information on the circumstances and conditions of the fire. However, to assist the fire crew in making decisions, it is necessary to understand the progression of the smoke and flames of the fire. As a result, in addition to fast and effective detection, processing and prediction are also very essential. The video processing methods, unlike traditional fire detection, may not only increase and hasten fire detection but also enable fire analysis and forecasting. Valuable fire features like the size of the flame, the height of the smoke layer, and the location of the fire can be identified at the initial stages of the fire by applying intelligent analysis and techniques on the video camera images.

There may be two kinds of smart fire sensing systems. The first one is the smart sensor which contains processing and decision-making in a single sensor and the other is a smart integrated device where the identification of the fire and the decision-making occurs in the control panel. The smart integrated circuit is the cost-effective solution for the large fire detection system since it does not contain complex circuitry in the sensor. The processor with the complex algorithm can be incorporated into the control panel for fire identification. This smart integrated circuit can gather fire-related information from multiple sensors which are in different locations and can be smartly processed, which in turns lowers the processing time and system cost.

There is a limited number of methodologies have been put forth in the literature that gives additional details on the processing of fire features. In [83], the authors propose an approach that examines contour pixels from the digitized images of the video. Based on the adopted dynamic programming, a displacement vector is created for each of the contour pixels. These vectors are then subjected to histogram analysis to determine their orientation. In [84], the authors developed a fire monitoring framework to enhance the existing fire sensing based on a support vector machine with a dynamic time-warping kernel function. This kernel function calculates the temporal dynamics present in the sensory data of fire.

The advancement in the field of the Internet of Things (IoT) or Wireless Sensor Networks (WSN) had enhanced the ability to differentiate fire and non-fire threats. Furthermore, the machine learning and deep learning approaches pose a potential framework for analyzing data from IoT sensors [85], [86]. In [87], the authors developed a new algorithm based on a convolution neural network to increase the performance of fire detection methods that uses video images. Similarly, in [88], a new method to detect fire using an improved YOLO4 network is presented. The improved YOLO4 network is obtained by increasing the size of training data sets for the techniques that use strategy for enhancing data in real-time monitoring of fire. Using two or more sensors for fire detection can improve accuracy when compared to using a single sensor. Multi-sensor fusion approach for fire detection can be based on either the probability theory and statistics approach or the artificial intelligence approach.

Some literature discusses the work carried out in fire detection using the probability approach and some discusses the artificial intelligence approach. To analyze the fire alarm system, a multi-sensor Bayesian network model is proposed in [89]. This work elaborates on the relation between the fire alarm system and the physical-chemical attributes developed throughout the burning process by examining the fire mechanism. The elements causing the forest fire are unpredictable and nonlinear where the effectiveness of the fire detection with only one sensor is very low. In [90], the authors presented the forest fire detection system based on a fuzzy Kalman filter. In this work, many sensors are integrated along with high-level processors to form a fire alert device. The data obtained from different sensors are preprocessed and then they are given to the Fuzzy Kalman filter for filtering and deciding the occurrence of fire. Similarly, a fire sensing system is developed in [91] by using wireless multi-sensors that operate on fuzzy logic rules for the indoor environment. In [92], a predictive neural network model is developed that processes data from a multi-sensor fire detector. To achieve early detection and alerting, a multi-sensor data fusion method based on neural networks is used [93]. In this work, the neural network-based fire detection approach is created utilizing the temperature, density of smoke, etc. to predict the likelihood of a fire situation.

Fixed sensors-based fire detection systems have their limitations. The mobility given to fire detectors allows them to be comparatively harmless in adverse situations. The limitations of the fixed fire sensing systems can be solved by robotic manipulators equipped with fire detectors and sprinklers. In this context, the weight of the robot is reduced for them to fly more effortlessly. In [94], The authors examined current research in this field and outlined several elements of present firefighting cobots and detectors that are used in them. In [95], the authors devised a hose-type robot for fire extinguishing purposes. This robot is lightweight and is propelled by a water jet. It features a nozzle module on top, as well as motors that regulate the direction of emission. In [96], the authors built a firefighting snake robot out of hydraulics and examined its uses and design issues. The primary goal of these firefighting robots is to put out fires.

Unmanned Aerial Vehicles (UAVs) with computer vision-based remote sensing systems are becoming a more realistic option. They can be used to monitor and detect fires because they are fast, mobile, and inexpensive. There has been much theoretical investigation into UAVs' capability for monitoring and detecting fires. A dynamic, six-degrees-of-freedom UAV model was used to verify a numerical propagation model for fire monitoring and detection [97]. While the aforementioned studies show that UAVs could be used to detect fires, very little progress has been made in developing such systems, which include hardware, software, and application techniques. Further research is needed on all facets of UAV utilization, such as optimal system platforms, remote sensing payloads and sensors, and algorithms for autonomous guidance, navigation, and control as well as the use of UAVs in tandem with other remote sensing methods [98].

IV. CONCLUSION

In this paper, an overview of the research conducted on different fire-sensing technologies was carried out. There is a high risk of fire in rural areas because of the distance between communities and the people in those communities. This makes it hard for the fire departments to get these fires in rural areas promptly. So early fire detection and fire safety are very important in these areas. The key characteristics of fire signatures, such as flame, smoke, ambient temperature, and surrounding gaseous levels, are evaluated in connection to various sensors. The advantages and disadvantages of these characteristics are also discussed based on the evaluation of a variety of criteria. The detection and treatment of fires is a challenging task. These intricacies stem from the many distinct phases, changing outward appearance, colors, emission spectra, combustion fuels, and locations. The current fire detection system can benefit from the application of fuzzy logic and deep learning-based algorithm in these circumstances. So, it is important to refine optimization methods to reduce the number of false positives.

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