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Heterogeneous sensor arrays: Merging cameras and gas sensors into innovative fire detection systems

Angelika Hackner[a,*], Helmut Oberpriller[a], Alexander Ohnesorge[a], Volker Hechtenberg[b], Gerhard Müller[a,c]

[a] Airbus Group Innovations, D-81663 Munich, Germany
[b] Innovation Team Bremen, D-17111 Meesiger, Germany
[c] Munich University of Applied Sciences, Fachbereich 06, Lothstraße 34, D-80335 Munich, Germany

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ABSTRACT

An innovative way of multi-criteria fire detection is introduced. In this concept image information about the monitored area is combined with knowledge about the reactive gas concentrations inside this same area to produce a fire alarm and to enable alarm verification. Key component in this new mode of fire detection is a low-cost CCD camera which is operated in a difference image (DI) mode. In the unsupervised DI mode, the average grey scale values in consecutive difference images are evaluated and compared with the outputs of a metal oxide gas sensor array which measures the reactive gas concentrations in this same area. Fire alarms are generated upon observing concurrent changes in all sensor outputs. Once obtained, the camera can be switched to the supervised imaging mode and the validity of an alarm can be assessed by normal and/or difference imaging of the monitored area. In this paper the concept of DI-based fire detection is explained, demonstrated and possible enhancements and ramifications of this new technique are discussed.

1. Introduction

Fires represent severe danger to human lives, property and environment. In order to cope with such dangers, efficient methods of fire detection and firefighting are required. As far as fire detection is concerned, this field can be broadly subdivided into two sub-fields: (i) wide-area surveillance for the detection of fires in unconfined spaces, such as in forests, road tunnels or underground stations, and (ii) point-detection where fire hazards occur in closely confined spaces such as in office and in residential buildings or in factory plants. Whereas camera surveillance is the method of choice in the first class of environments, point detectors such as smoke, ionization, heat and gas detectors are being used in confined spaces. State of the art reviews of these existing fire detection technologies can be found in references [1–8]. As revealed there, video image processing focuses on the detection of spatial-temporal features such as color probability, contour irregularity in individual frames, and on temporal changes in between consecutive frames, i.e., on all pieces of information that can be conveyed over large distances via electromagnetic radiation. Point detectors, in contrast, concentrate on those fire indicators which derive from localized chemical reactions that occur in open and smouldering fires and that are transported much more slowly over smaller distances via convection and diffusion processes. As both kinds of detectors are only sensitive to a limited sub-set of all possible fire features, sensor- and application-specific false-alarm issues arise.

A fire detection application with a very high damage potential, which is plagued by false alarm issues, is aeronautic fire detection [9–11]. Active fire protection inside commercial airplanes comprises fire detection by photo-electric automatic fire detectors as well as firefighting with extinguishing equipment [12,13]. Such equipment is installed in all those areas that are inaccessible during flight. These include electronic compartments such as avionics and in-flight entertainment equipment and, last not least cargo compartments and cargo containers. Among those the cargo compartments bear a particularly high danger potential because very few requirements actually restrict the flammability of any potential cargo. In the current state of the art, fire detection in such critical areas is performed with the help of smoke detectors [5–8], similar to those that are routinely used in office and in residential buildings. Such sensors detect open fires by scattering light on airborne particles. As smoke particles are only one sort of airborne particulate matter that might turn up, false alarms will almost certainly occur [9–11]. Well known causes of false alarms are dust particles and/or

* Corresponding author. Fax: +49 89 60724001.
E-mail address: angelika.hackner@airbus.com (A. Hackner).

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condensing humidity. These latter forms of false alarms can easily occur in aircraft operation when an airplane is loaded on ground in a hot and humid environment and as the air inside the cargo compartment cools down as the airplane climbs to its cruising altitude. Statistics issued by the Federal Aviation Agency (FAA) [9], show that the probability of such false alarms is indeed very high. Investigations over a five year period showed that in hindsight only 1 out of 200 reported alarms could be unambiguously traced to a true smoke event. While false alarms of this type may be acceptable on ground, these cause severe problems when they occur in flight. As a fire, that may be harmless on ground, might become catastrophic in flight and as false alarms cannot be verified as such during flight, tight authority requirements exist on how to deal with such alarms [14]. These require that any fire alarm—whether true or not—needs to be answered by fire-fighting measures and by emergency landings. Statistics show that such events occur with a rate of about 200–300 per year with most of them ending in unscheduled flight interruptions [9–11]. The associated cost of such flight interruptions is estimated to range in between 30–50 thousand €/per event, depending on the size and occupancy of the airplanes [11]. Trying to decrease false alarm rates from the current rate of about 1 in 10^5 flight hours to the newly requested standard of 1 in 10^7 flight hours [12], several attempts have been made to develop multi-criteria fire detectors which measure several fire criteria at the same time, thereby enabling lower false alarm rates [15–17]. All these existing multi-sensor approaches employ heterogeneous arrays of sensors with scalar output signals, chiefly smoke, heat, and CO.

Our current work contributes to this effort of attaining lower false-alarm rates by employing heterogeneous sensor arrays. In our approach conventional gas sensor arrays are combined with low-cost CCD cameras to detect fire gases and concurrent optical changes in the confined spaces of aircraft compartments. To the best of our knowledge, this is the first attempt to include cameras into heterogeneous sensor arrays to attain higher levels of false alarm rejection and unpresented possibilities of alarm verification. The fire detection system discussed below can be operated in an unsupervised monitoring mode in which the CCD camera is operated in a difference image (DI) mode in which grey scale changes in between consecutive images are monitored alongside with the potential appearance of fire gases which might correlate with the observed visual changes. In case concurrent changes in the gas evolution and consecutive image frames are detected, an alarm is issued and the system is switched into its verification mode. In this latter mode the CCD camera provides a straight-forward picture of the monitored scene which allows the pilot to take an informed decision as to the actual necessity of emergency measures. In the following, this innovative sensor concept is introduced (§2) and the processes underlying DI signal generation and DI monitoring (DIM) are explained (§3). §4 presents the results of feasibility tests in which two realistic fire detection scenarios are monitored using a heterogeneous array of sensors consisting of a DI camera and a metal oxide gas sensor array. In the concluding §5 possible enhancements and ramifications of the DIM approach are discussed.

2. Sensor concept

The sensor concept evaluated in this paper is presented in Fig. 1. The monitored area in the center is assumed to be one of the aircraft's critical compartments (avionic, in-flight entertainment, cargo containers and cargo compartments). As explained above, these areas need to be monitored in an unsupervised manner for the presence of certain fire indicators. While in the current state of the art this task is performed by smoke detectors, we chose in our case a metal oxide (MOX) gas sensor array which presents an interesting enhancement and/or an alternative to the currently employed smoke detectors [5,6,8]. As illustrated in the left-hand part of Fig. 1, reactive gas monitoring is performed with the help of a gas sensor array consisting of three MOX gas sensors [18]. These sensors contain different sensitive materials and/or are operated at different temperatures to exhibit cross sensitivity profiles oriented toward different components in the fire gas mix. Such an array produces six analog output signals, which form a signal vector. These signals consist of the sensitive layer resistances of the three MOX gas sensors (resistive/RES response) and of the electrical heater powers that need to be supplied to the substrate heater meanders to maintain constant sensor operation temperatures (catalytic/CAT response). Whereas the first three signals contain information concerning the oxidizing or reducing properties of the adsorbed fire gases, the latter three carry information with regard to the catalytic combustion powers generated by the adsorbed gases [18].

Low false alarm rate requires additional and independent fire indicators to be assessed inside the controlled area. In our approach we chose to monitor optical changes which coincide with open and smouldering fires. These are chiefly flames, smoke or aerosols of combustible liquids. As indicated on the right-hand side of Fig. 1, such visual changes are observed with the help of a low-cost CCD camera [19]. For our purpose a commercial CCD camera, which simply produces straight-forward images of the monitored scene, was modified to produce difference images (DI), which highlight visible changes in between two successive normal images (NI). As a second feature our camera allows to be operated in an unsupervised monitoring and in a supervised verification mode. In the unsupervised mode the DI data are compressed into a sequence of average grey scale values in each difference image. In this way, an additional analogue output signal is generated which can be combined with the six output signals of the gas sensor array to form an output signal vector. This vectorial output can be processed using standard pattern recognition techniques to form a multi-criteria fire detector with a sharply decreased false alarm probability. In the supervised verification mode, the full two-dimensional (2d) image information contained in the NI and/or DI images is used to enable alarm verification by a human observer. This observer (pilot) can then take informed decisions as to the necessity and extent of possible emergency measures.

3. Difference-image monitoring of controlled areas

In order to introduce the concept of difference image monitoring (DIM), consider Fig. 2. For the sake of clarity Fig. 2**a** shows the DI camera module itself with its lens facing a candle in front of a uniform piece of cardboard. Fig. 2**b** and **c**, on the other hand, com-

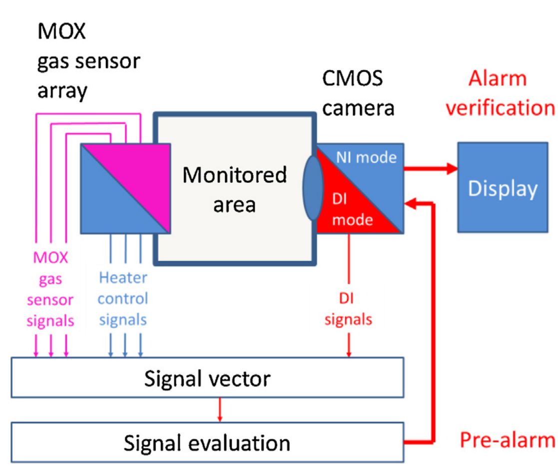

Fig. 1. Schematics of the DI fire monitoring and verification concept.