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Video-based Cargo Fire Verification System for Commercial Aircraft

Abstract

The Cargo Fire Verification System was developed to address the problem of frequent false smoke alarms that are of particular concern in long range flights of passenger aircraft. The system uses low-cost CCD cameras operating in the near infra red range to directly detect fire and hotspots. In addition, LED illumination units are appropriately switched on and off, and the obtained images are analyzed to detect smoke. Fusion of image processing results with temperature and humidity readings allows reliable detection of true fires and elimination of false alarms due to fog and dust.

Introduction

Development of the Cargo Fire Verification System (CFVS) was motivated by the need to reduce the incidence of false alarms and to improve detection of "smokeless" fires over conventional smoke detection systems used in cargo bays of commercial aircraft. Upon an alarm, the crew is typically required to release fire suppressant and to divert to the nearest airport. Each emergency landing due to a false alarm incurs significant cost to the air carrier. In addition, diversion to a small remote airport may itself pose significant danger to the passengers or the aircraft. In case of long range flights over polar regions, the nearest airport may lack the necessary facilities, so safe take-off may be questionable in harsh weather environment. It is therefore desirable to reduce the false alarm rate and give the crew a method to assess the state of the cargo compartment prior to and after fire suppression. Optical spot smoke detectors do not detect smokeless fire quickly. The CFVS was designed to address these issues in long range Airbus A340 wide body aircraft.

The CFVS was designed as a verification system, intended to confirm or identify false alarms (unconfirm) issued by the primary system. While suppression would still be performed following a smoke alarm, the decision to divert would be based on the actual state of the cargo bay. The digital video recording function of the CFVS allows visual inspection of the bay to check the fire conditions that existed at the time of the alarm. It also allows the pilot to view the cargo bay, back in time, and prior to the alarm to see the situation as it developed. Visibility in a fully loaded cargo hold may be restricted to very narrow gaps between containers and the bay's ceiling and walls, thus making such visual assessment of difficult. To address this difficulty, the CFVS uses image processing to detect and differentiate phenomena invisible to the naked eye in raw video feed. Image features calculated from multiple frames are fused with non-video data to obtain a final diagnosis that maximizes rejection of false fire alarms without affecting true ones.

As suggested by Airbus, the CFVS was developed to meet performance requirements based on EN54 fire detection standard, which are significantly more demanding than the usual smoke detection tests used for aircraft certification purposes.

The use of computer vision constitutes a breakthrough in aircraft fire detection. From the performance standpoint, the CFVS can be used as a stand-alone system. Its smoke detection capability matches, and fire detection surpasses, that of traditional smoke detectors. It is also much less sensitive to such common false alarm sources as fog or dust. It also gives the crew greater confidence by presenting the diagnosis in a visual form overlaid over the actual images of the cargo bay. Installed either in new aircraft or as a retrofit, it offers greatly improved detection and false alarm immunity.

System architecture

The cores of the CFVS are CCD cameras operating in the near infrared (NIR) band. Two cameras are located in opposite corners of each cargo bay, providing full visibility of the entire bay. In order to make them immune to external illumination sources, the cameras use optical filters that block visible light. Typically, cargo bays are equipped with fluorescent lighting with no emissions in the NIR band. Therefore, the CFVS operation does not depend on whether the cargo bay light is on or off. Each camera is equipped with its own controlled NIR LED illumination source. Additional NIR illumination units are installed in the ceiling of the bay. Through appropriate switching of those illumination sources, the system obtains different views of the scene, as described in a following section. An example of placement of cameras and overhead illumination sources in A340 cargo bays is shown in Figure 1.

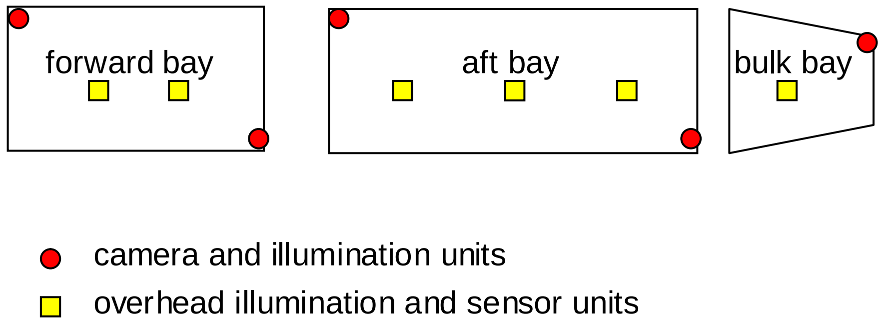

Figure 1. Example of camera and illumination placement in cargo bays; top view

Each camera is equipped with a DSP processor to analyze captured images and to calculate their various numerical features, which are then sent to the central control module. Additionally, the CFVS collects temperature and humidity measurements from sensors placed within cameras and overhead illumination units. These values are used to assess possibility of a false alarm-inducing scenario such as ascent-related fog. The central processing unit analyzes video and non-video data and upon an alarm issued by the primary system produces confirmation or unconfirmation diagnosis, together with the appropriate highlighting of the images sent to the cockpit video display.

In addition to decision making, the central unit acts as a digital video recorder. Output of each camera is recorded at a lower frame rate, so that it can be viewed at any time at push of a button. This allows the crew examining the state of a cargo bay before and after a primary alarm. In the present implementation, the CFVS stores the most recent 10 minutes of video from each camera. With addition of memory chips or adjustment of recorded frame rate, the length of this time window may be modified as needed.

Light switching sequences

To detect various visual aspects of fire and smoke and to differentiate it from non-fire aerosols such as fog and dust, the CFVS analyzes different views obtained under different illumination conditions. In the current implementation, four distinct views are used. Figure 2 shows examples of these four views through a simulated 4.3 cm gap above a container, acquired in University of Duisburg Fire Detection Laboratory.

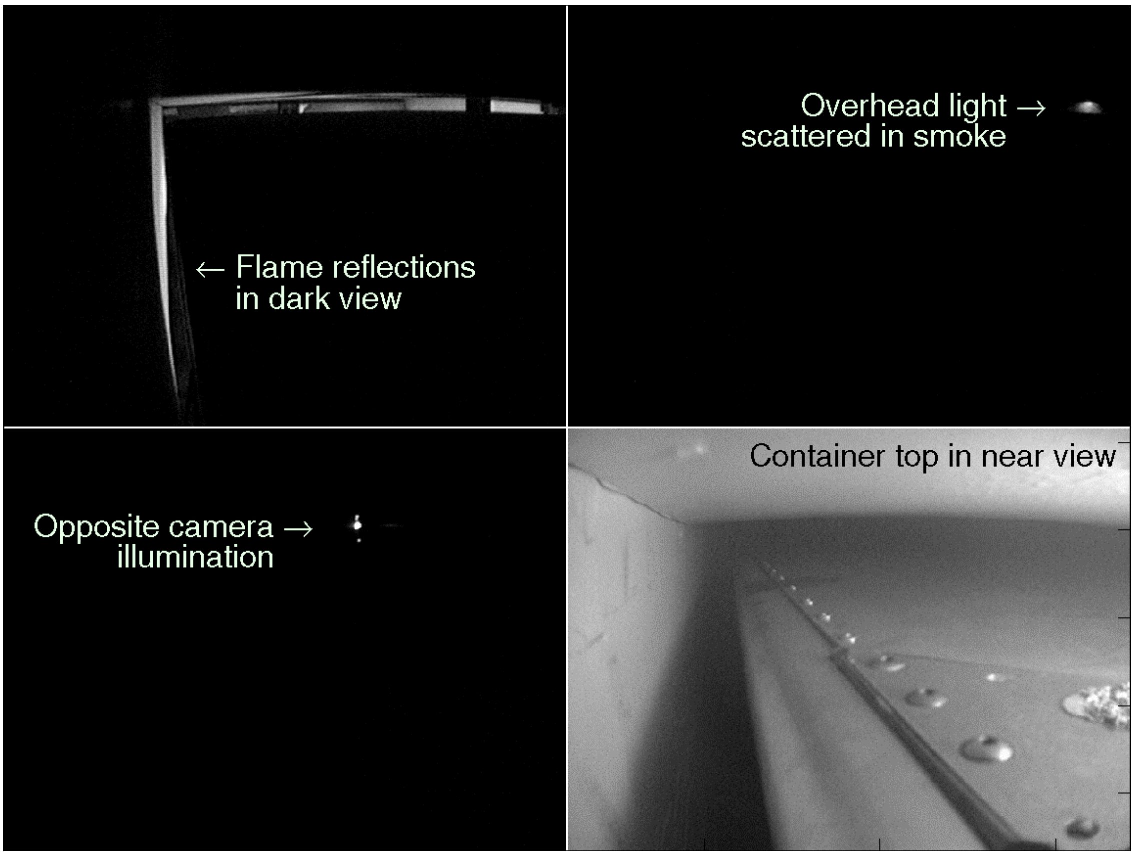

Figure 2. Four views with different illumination, same geometric configuration

In the dark view, all illumination sources are turned off, so that the presence of any high intensity image areas indicates a heat source, as illustrated in the upper-left part of Figure 2. This view is used for flame and hotspot detection, which is sufficient in majority of fire cases. However, in a fully loaded cargo bay, flames may be hidden behind containers. Similarly, for smoldering fires similar to EN54 fires TF2 and TF3 no flames may be visible. In such cases, the system must use the alternate smoke detection mode. For this, the remaining three illuminated views are used.

In the overhead view, the cameras' LED sources are switched off, while the overhead illumination units are turned on. In presence of smoke, their light is scattered, resulting in brighter image areas, as illustrated in the upper-right part of Figure 2. In many cases, the overhead light provides quickest smoke detection.

In the opposite view, all illumination sources are turned off, except for the LED of the opposite camera. In absence of smoke the opposite light is well visible, as seen in the lower-left part of Figure 2. With smoke, the light gets absorbed and the image becomes smaller and dimmer until it may disappear completely. It may be noted that the CFVS operating in opposite view mode acts as a very long optical smoke detector, whose length comprises the entire bay. A pair of cameras placed on opposite ends of the bay replaces, and offers detection superior to, an entire set of multiple conventional point smoke detectors. For this mode to work, however, there must be a clear gap between the top of the cargo (containers) and the ceiling, e.g. as stated in Airbus loadability conditions. Presence of any cargo obstructing visibility of the opposite light may make this view useless from the detection point of view. However, the system may analyze such situation prior to take-off and switch to alternate backup detection modes.

The last of the illuminated views is the so-called near view, in which the only light turned on is the one collocated with the camera that is acquiring images. It is the near view that is fed to the central unit and recorded for later use by the crew. An example of a near view image is shown in the lower-right portion of Figure 2. Smoke may be visible in the near view through scattering of light by an aerosol cloud.

Performance requirements

The main challenge in design of the CFVS image processing and decision making algorithms was to specify clear and verifiable performance criteria. On one hand, the CFVS must always detect true fire or smoke prior to the primary system, so that when the latter issues its alarm the CFVS is ready with a confirmation decision. On the other hand, the common false alarm scenarios should be recognized as such. This required detailed characterization of the most common false alarm causes. We used available public domain studies such as [1], as well as proprietary false alarm statistics provided by Airbus. In addition, an advisory group of university and industrial experts was formed and asked to determine which false alarm scenarios are prevalent in practice and may be successfully distinguished from true smoke or fire. A conclusion of this study was that the overwhelming majority of false alarms are most likely caused by fog. For example, fog may form through super-saturation of humid air due to rapid pressure decrease and adiabatic cooling during take-off and ascent. Fog may also form during the flight near moisture-emitting cargo such as vegetables or animals. The second most probable false alarm cause was determined to be dust lifted from dirty containers, or perhaps produced by cargo such as pollinating plants or agitated animals.

In view of these findings, the CFVS was designed to address fog and dust as primary non-fire false alarm scenarios. For performance in fog, the system was tested in a pressure chamber, in which rapid depressurization was used to produce quite uniform dense fog almost instantaneously. A fog generator was also used to test fog emanating from a point source. For performance in dust, a specialized dust generator was used with standardized ISO dust.

Densities of both fog and dust were chosen such that they caused the conventional smoke detectors to alarm. The success criterion for the CFVS was to diagnose a non-fire case and to provide false alarm information prior the primary system's alarm.

For fire detection, it was agreed that a super-set of EN54 test fires would be useful. Since the EN54 tests were originally designed for point smoke detectors with focus on building environment, they had to be appropriately adapted and scaled, so that they more closely correspond to cargo bay conditions. These modifications are described in detail in the accompanying paper [2]. The CFVS was required to reach a confirmation decision for each test fire prior to the primary system's alarm.

Detection and discrimination algorithms

Image processing is performed by DSP chips located within each camera. Therefore, it is done on a single frame basis – i.e. each frame is analyzed independently. Then the calculated values of image features are sent over a low-bandwidth digital link to the control unit which then performs data fusion and makes a fire/non-fire decision.

Different image processing algorithms are used for the four different views. Although state of the art DSP chips are used, the processor cycles are still at premium, which is a typical situation in image analysis applications. Therefore the priority was given to computationally inexpensive image features well known in literature [3]. Among those, mean pixel intensity and its standard deviation were found particularly useful.

$$\mathrm{mean}(X) = \frac{1}{MN}\sum_{i=1}^{M}\sum_{j=1}^{N} X(i,j)$$

$$\mathrm{stdev}(X) = \sqrt{\frac{1}{MN}\sum_{i=1}^{M}\sum_{j=1}^{N}\left(X(i,j) - \mathrm{mean}(X)\right)^2}$$

These two image statistics provide useful information about global intensity level and its variability, but do not allow any inference about its spatial distribution. This maybe achieved by analyzing second order moments

$$\mathrm{M}_{20}(X) = \frac{1}{MN}\sum_{i=1}^{M}\sum_{j=1}^{N}(i - \mathrm{X}_c)^2 X(i,j)$$

$$\mathrm{M}_{02}(X) = \frac{1}{MN}\sum_{i=1}^{M}\sum_{j=1}^{N}(j - \mathrm{Y}_c)^2 X(i,j)$$

$$\mathrm{M}_{11}(X) = \frac{1}{MN}\sum_{i=1}^{M}\sum_{j=1}^{N}(i - \mathrm{X}_c)(j - \mathrm{Y}_c) X(i,j)$$

where X_c and Y_c are the center of mass coordinates for the intensity field, given by

$$\mathrm{X}_c(X) = \frac{1}{MN}\sum_{i=1}^{M}\sum_{j=1}^{N} i\, X(i,j) \qquad \mathrm{Y}_c(X) = \frac{1}{MN}\sum_{i=1}^{M}\sum_{j=1}^{N} j\, X(i,j)$$

The above image statistics may be applied to raw images, as captured by the camera, or after suitable transformations designed to extract the specific aspects of interest. For example, edge detection transformation may be performed. Then, mean intensity of the edge image describes "edginess" or detail level of the original image. A fairly simple transformation that describes image sharpness is gradient norm, given by:

$$G_1(i,j) = X(i+1,j) - X(i,j)$$

$$G_2(i,j) = X(i,j+1) - X(i,j)$$

$$G_N(i,j) = \sqrt{G_1^{\,2}(i,j) + G_2^{\,2}(i,j)}$$

The mean value, standard deviation and second order moment statistics may be applied to the gradient image. For example, a decrease in mean gradient norm may indicate decrease in contrast associated with presence of fog.

For hotspot analysis we applied standard image segmentation algorithms to detect connected, space- and time-wise, regions of elevated intensity.

To reduce influence of spurious noise effects on detection, each feature is appropriately filtered. The simplest option is to use a first order filter

$$y_{filt}(t) = (1-\alpha)y_{filt}(y, t-\Delta) + \alpha y(t)$$

where $y(t)$ is the most recently calculated image feature, $y_{filt}(t)$ is its filtered value, α is the filtering constant, and Δ is the time interval between acquisition of consecutive images. Setting of initial conditions and possible re-initialization of image feature filters had to be carefully considered.

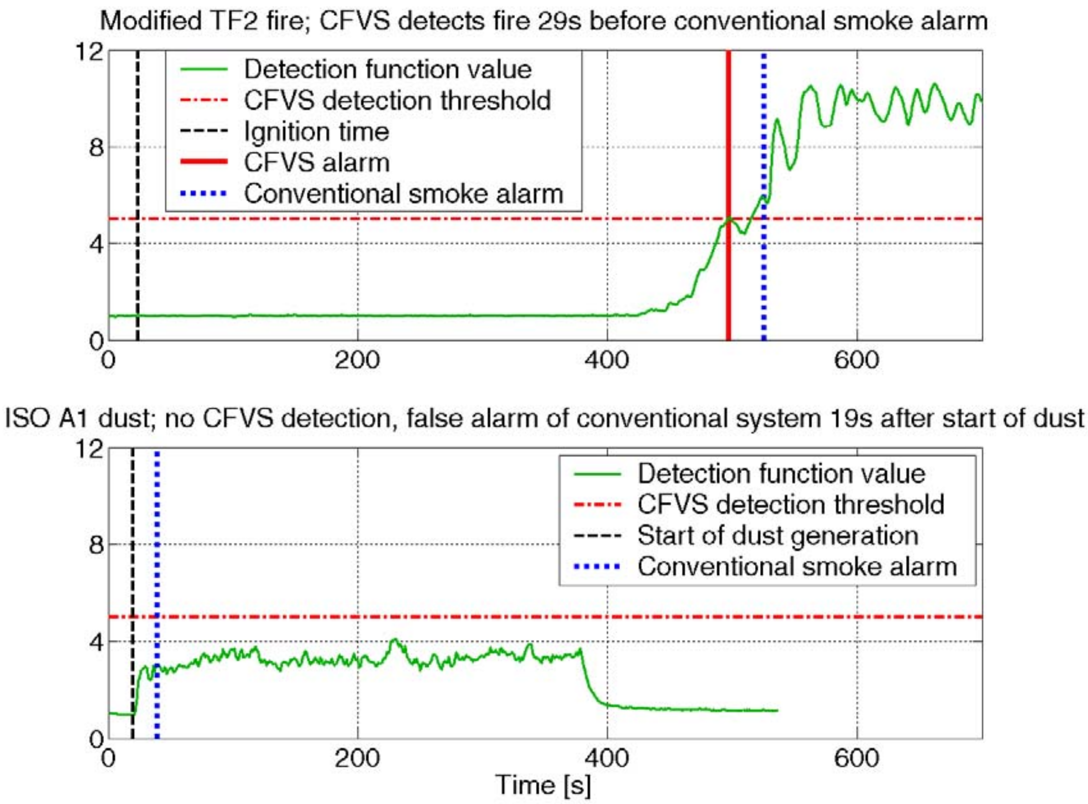

Figure 3. CFVS performance compared to conventional A340 detectors

The filtered image features are sent by the cameras to the central processing unit, which compares them and their most recent values against detection thresholds and performs final decision making. In its simplest form, a decision function may involve checking whether a filtered image feature crossed its associated threshold

$$D_i = \left(y_{filt\,i} > t_i \right)$$

A more complicated form may involve a linear combination of image features

$$D_i = \left(\sum_{j=1}^{k} a_j y_{filt\ j} > t_i \right)$$

Then the final decision may be a Boolean function of multiple elementary decisions D_i.

Other more involved decision making methods may also be used, such as optimal Bayesian reasoning. They fuse image data with non-image measurements such as temperature, humidity or flight phase status to obtain the best decision.

The choice of the particular image features and decision functions is based on experimental video database. While certain guidance may be gathered from the general nature of the observed images, such as fading, loss of contrast, or light blooming, the final selection can only be made based on the actual video data. The decision functions and their thresholds are chosen in such a way so that correct classification of all true fire cases is always assured, but the incidence of false alarms is minimized.

Figure 3 shows two typical examples of CFVS performance compared to actual behavior of production A340 smoke detectors. The decision function shown is based on analysis of the overhead view. For a smoldering fire, the CFVS is ready to confirm almost half a minute prior to the conventional smoke alarm. In the dust test, the CFVS detection threshold is never crossed, while the conventional system issues an alarm only 19 seconds after start of smoke generation. In this case the CFVS would unconfirm the smoke alarm as false. This illustrates the improved immunity of the CFVS to common false alarm causes.

System development status

The CFVS image processing algorithms and their specific parameters were developed based on a large video database, derived from over 300 tests involving smoke, fog, dust and other aerosols. The primary experimental location was in University of Duisburg Fire Detection Laboratory. Fire and smoke experiments were also conducted in a cargo bay mock-up in Trauen, Germany, for accurate simulation of a fully loaded cargo bay. Fog and smoke data in simulated take-off conditions were collected in a National Technical Systems pressure chamber in Boxborough, Massachusetts, USA. Finally, smoke experiments were also conducted on the ground in an A340 aircraft made available by Airbus. The collected database was used to define the exact image features, filtering constants and detection threshold values to be used in the CFVS software.

At present, the CFVS camera and overhead illumination units are fully developed and packaged, meeting all Airbus and FAA/JAA requirements. The control unit along with its software is also fully developed. The system is currently ready for certification and deployment.

Conclusions

The CFVS constitutes a major advancement in the state of the art of aircraft of fire detection. While the concept of video-based detection is well known and was practically used in buildings or tunnels [4], [5], the CFVS is the first vision system suitable for actual deployment in a commercial aircraft. In performance tests, the CFVS detected all fire cases 20 to 350 seconds before the conventional A340 smoke detection system. The hardware meets all DO-160D environmental specifications and software has been developed according to DO-178B guidelines. As such the CFVS is fully certifiable. Although it was developed with Airbus A340 in mind, it may be modified for other aircraft as well – either as original equipment or as a retrofit option.

The advantage of the CFVS over conventional smoke detection is twofold. Firstly, it is able to detect flames and hotspots directly from NIR images. Therefore, it may detect low-smoke fires much faster than traditional smoke detectors. Secondly, the system makes use of the distributed nature of video information. Instead of a small number of discrete points, a camera image integrates data from a large volume, which enables earlier detection. Use of switched lighting allows analysis of different features of smoke and non-smoke aerosols, thereby providing means of fire/non-fire differentiation absent in conventional detectors. The result is a detection system that meets or exceeds all fire detection requirements with greatly improved false alarm immunity.

References

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