AUBE '01

12TH INTERNATIONAL CONFERENCE ON AUTOMATIC FIRE DETECTION

March 25 - 28, 2001
National Institute Of Standards and Technology
Gaithersburg, Maryland U.S.A.

PROCEEDINGS

Editors: Kellie Beall, William Grosshandler and Heinz Luck

NIST
National Institute of Standards and Technology
Technology Administration, U.S. Department of Commerce

Dieter Wieser[1] and Thomas Brupbacher
Siemens Building Technologies AG, Cerberus Products/Alarmcom Division
8708 Männedorf, Switzerland
dieter.wieser@cerberus.ch

Smoke detection in tunnels using video images

Abstract

In the aftermath of the two disastrous fires in the Mont Blanc and the Hohentauern road tunnels, there is a strong trend in Europe to require additional safety installations in tunnels for the detection of fires. Smoke detection based on processing of video images promises fast detection of fires and can complement more traditional techniques such as temperature sensing. Because it uses already required installations (the video system), this video smoke detection system can be deployed at a reasonable cost and, furthermore, it can be retrofitted into already existing installations.

In this paper a new video smoke detection system is described and a report on full scale fire tests in tunnels is given. Furthermore, it is demonstrated that the video smoke detection system correctly processes video sequences prone to give false alarms; no false alarms were given.

1. Introduction

There is a fast-growing infrastructure of video surveillance and monitoring equipment in European tunnels. A standard technique is to connect cameras to a video multiplexing device and to have a human operator judge selected images at a time. This approach has several deficiencies; two of them being the fact that it is inefficient because only a small number of images are observed at a given point in time, and that it is expensive because attentive watching of video images is tiring work and requires the operator to be changed frequently. More and more traffic control systems based on automatic video processing are, therefore, being installed to detect automatically critical conditions and to display to the operator only images of

[1]corresponding author

those situations which must be assessed quickly; it is then up to the operator to take appropriate measures. There are now several products available to automatically measure traffic flow, detect traffic jams, detect wrong-way drivers, etc.

As consequence of several disastrous fires in road tunnels (and in other tunnels, e.g. the Kaprun funicular catastrophe), public tenders in Europe for automatic video surveillance of road tunnels now often also require automatic video smoke detection even though there are other, more traditional techniques, such as the very reliable temperature sensor cables (e.g. the Siemens Cerberus system FibroLaser II), to detect fires in tunnels. This is because video smoke detection promises to alert operators very quickly and display to them images of endangered tunnel sections. Using both systems would, therefore, allow one to combine a very fast but more false alarm prone technique for smoke detection with a slower but more reliable technique that could even be used to control extinguishing.

Previous efforts ([1, 2, 3, 4, 5, 6]) in video smoke detection concentrate on three main techniques:

Histogram based techniques: These approaches calculate the histogram of an acquired image and then use the information in the histogram to detect the presence of smoke/fire. Some approaches in this category compare the computed histogram with pre-computed histograms of typical smoke/fire scenes to make the decision. Other approaches use statistical measures such as the mean and standard deviation to determine the likelihood of the existence of a fire in the scene.

Temporal based techniques: Approaches in this category use the difference(s) between frames to generate growth patterns that could be smoke/fire objects. The number of frames used in calculating the difference image varies depending on the approach.

Once the difference frames are calculated, different techniques are used to segment and identify smoke objects. In some approaches, a number of statistical metrics are calculated from the difference images, then that information is used to infer the presence of smoke/fire. Other approaches use the colour information in the generated patterns to classify and identify smoke objects in the image. Techniques such as color matching filtering are used.

Rule based techniques: A third category of video smoke detection uses domain spe-

cific information coded as rules to infer the presence of fire from a sequence of images. Approaches in this category are in some cases combined with approaches in the first two categories to help during the recognition phase.

In road tunnels, smoke detection algorithms must be able to overcome several difficulties. Moving objects (the vehicles) which may stand for a while (traffic jam) can fill most of the image, making definitions of stable references difficult. In addition, car lights may induce dramatic changes in lighting conditions, especially with oncoming traffic, and near the openings of the tunnel water spray from cars passing by may make detection even more difficult.

Our system analyzes the contrast in the image and uses special procedures to overcome the above difficulties. The aim of this paper is not to explain the algorithm being used (the system will soon be commercialized), but to illustrate for an audience more oriented towards indoor fire detection the possibilities of and difficulties in this tunnel application.

2. Estimation of the loss of contrast

As mentioned above, our approach to the detection of smoke in a tunnel is based on a loss of contrast in the image caused by the presence of smoke. For simplicity, we consider only the luminance contrast. The contrast C of an isolated object viewed against a uniform, extended background is defined by [7]

$$C = (L_{\mathrm{o}} - L_{\mathrm{b}})/L_{\mathrm{b}} \tag{1}$$

L_{o} and L_{b}, respecively, are the luminance of the object and of the background. If a light extincting medium, such as smoke, is present, then the contrast after passing for a distance R through the medium is reduced to

$$C_R = C \exp(-K\,R) \tag{2}$$

The extinction of light caused by smoke can be expressed through the particle concentration in the smoke as

$$K = 2.3\,D = 2.3\,D_m \frac{\Delta M}{V_c} \tag{3}$$

with D being the optical density per metre, D_m the mass optical density, ΔM the mass loss of the burning sample, and V_c the volume of the chamber containing the

fire. Values for D_m are tabulated and can be found e.g. in Mulholland [7]. In tunnels, Equation (3) has to be modified to account for the wind

$$K = 2.3\, D_m \frac{\dot{M}}{\dot{V}} \tag{4}$$

For an estimate of $\dot{V}$, the volume flow of air in the tunnel, both the effects of the fire and of the forced air flow (natural and forced convection) have to be taken into account. By looking at the relevant combustion reactions, the volume of exhaust gases can be put into relation with the mass loss in the fire.

In the early stage of a typical fire in a tunnel, e.g. a burning car, mostly organic matter (in the chemical sense) is decomposing. This means that we can restrict the discussion to the most common elements occurring in organic substances, namely carbon (chemical symbol C), hydrogen (H), and oxygen (O), and to sulphur (S), which is often contained in fossile fuels as an impurity. Because of the superposition principle for chemical reactions, it also suffices to look at the combustion reactions of the elements.

$$\mathrm{C} + \mathrm{O_2} = \mathrm{CO_2} \tag{5}$$

$$2\,\mathrm{H} + \frac{1}{2}\mathrm{O_2} = \mathrm{H_2O} \tag{6}$$

$$\mathrm{S} + \mathrm{O_2} = \mathrm{SO_2} \tag{7}$$

In the case of oxygen deficiency, carbon monoxide, CO, is additionally formed and at the same time the reaction of CO with water has to be taken into account:

$$\mathrm{C} + \frac{1}{2}\mathrm{O_2} = \mathrm{CO} \tag{8}$$

$$\mathrm{CO} + \mathrm{H_2O} = \mathrm{CO_2} + \mathrm{H_2} \tag{9}$$

This last reaction, the reduction of water to hydrogen, is endothermic and is thus strongly dependent on the temperature in the reaction zone. If the substances involved in the fire also contain halogens (fluorine F, chlorine Cl, bromine Br, iodine I), these react preferentially with hydrogen to form acids. Halogens are largely being replaced in todays materials (e.g. PVC is being replaced by other compounds) and are, therefore, neglected in the following discussion.

Assuming the above stoichiometric reactions (5 – 9), the mass of oxygen, m_{O}, needed for complete combustion of 1 kg of burning material can be calculated from

$$m_{\mathrm{O}} = 2.664\, w_{\mathrm{C}} + 7.937\, w_{\mathrm{H}} + 0.998\, w_{\mathrm{S}} - w_{\mathrm{O}} \tag{10}$$

Where w_{X} denote the mass fraction of the elements in the burning substance. Using the ideal gas equation, this mass can be transferred into an equivalent volume at any given pressure, temperature, and composition of the burning material.

A common and time-proven estimate of the development of a fire with time is given by

$$\frac{\mathrm{d}}{\mathrm{d}t}q = \dot{q} = A\,b\,t^2, \tag{11}$$

with $\frac{\mathrm{d}}{\mathrm{d}t}q$ being the rate of heat release, A the area of the fire, b a constant, and t the time since ignition. The rate of heat release increases until it reaches a maximum $\dot{q}_{\mathrm{max}}$ that is dependent on the geometry of the fire and on the nature of the combustant. With the reaction enthalpies of the chemical reactions ((5 – 9), the rate of heat release $\dot{q}$ can be linked to the rate of mass loss of the combustant $\dot{M}$. The combustion enthalpy can be caclulated as

$$h = (338 \times 10^5\, w_{\mathrm{C}} + 1004 \times 10^5\, w_{\mathrm{H}} + 95 \times 10^5\, w_{\mathrm{S}} - w_{\mathrm{O}})\frac{\mathrm{J}}{\mathrm{kg}}, \tag{12}$$

using reaction enthalpies from [8]. Using $\dot{q} = h\dot{M}$, the rate of mass loss in the combustant can be calculated to

$$\dot{M} = \frac{Abt^2}{h}. \tag{13}$$

As an example, consider the scenario of a simple model calculation for a burning car in a tunnel with a cross-section $A_{\mathrm{tunnel}} = 60\ \mathrm{m}^2$: The combustable mass is assumed to have a composition of $w_{\mathrm{C}} = 0.78$, $w_{\mathrm{H}} = 0.12$, and $w_{\mathrm{O}} = 0.1$, typical for plastics and hydrocarbons. Using equation (10), the mass of oxygen needed to combust 1 kg of substance equals to 0.852 kg, corresponding to approximately 26.7 mol of atomic oxygen, or a volume $V = 0.33\,\mathrm{m}^3$ at standard conditions. The relative composition of oxygen in air is 21 volume percent, thus this corresponds to roughly 1.5 m^3 air. This is a relatively small volume compared to a convection of 120 m^3/s at a wind speed of 2 m/s; it becomes clear that, at least in the early stages of the fire, convection a) can feed the fire with enough oxygen, and b) dominates the mass flow. It is, therefore, justified to set $\dot{V}$ to the wind speed times the tunnel cross-section area. From this simplification, the time needed to raise an alarm can be now estimated: Using equations (4) and (13), the extinction factor can be calculated to

$$K = 2.3\,D_m\,\frac{Abt^2}{h\dot{V}}. \tag{14}$$

After ingnition of the fire, there will be a certain time delay until the smoke enters the detection zone over which the extinction KL will be integrated. During this

time nothing is detected. Then the extinction KL will increase until it reaches a maximum.

Example: Assume the geometry of the tunnel as above, a distance between the camera and the fire of 150 m, and a distance L over which we integrate of 10 m. The fire is given by $\dot{q}_{\max} = 5$ MW, $A = 2$ m^2, $b = 30$ W/m^2/s^2, a composition as above and thus $h = 12$ MJ/kg, and $D_m = 0.5$ m^2/g. The smoke of the fire enters the detection path 70 s after ignition of the fire; at this point in time K approximately equals 23%/m. So already a short optical path lenght suffices to detect the smoke.

3. Test results

3.1. Fires in the fire test laboratory

The development of the video smoke detection method was based on experiences with test-fires, done according to the European norm EN-54, performed in the fire test laboratory at Siemens Cerberus. The dynamic contrast analysis algorithm was developed so far that smoke is detected within seconds in normal office rooms. Long term tests in hallways were also performed; these showed that the system gave no to false alarms when running for weeks at a time.

3.2. Tests at the test tunnel Hagerbach

Siemens Cerberus have a tunnel fire laboratory installed in the ventillation section of the "Versuchsstollen Hagerbach" near Sargans (Switzerland) and have been performing weekly tests with fires for the last two years. Figure 1 shows a schematic of the setup. In collaboration with "Vereinigung deutscher Schadensversicherer" (VdS) in Köln, a simulation program to describe tunnel fires is developed to allow for a scaling up or scaling down of arbitrary fires in tunnels. Test fires with heat releases of up to 5 MW can be produced under controlled conditions using different combustants; the wind speed can be varied between 0.5 and 5 m/s. All fires are monitored using several video cameras.

One insight gained from the experiments in the Hagerbach tunnel is that the wind speed is critical to the constrast observed in the video image; reliable detection at wind speeds above 2.5 m/s, where the smoke is turbulently mixed with air and

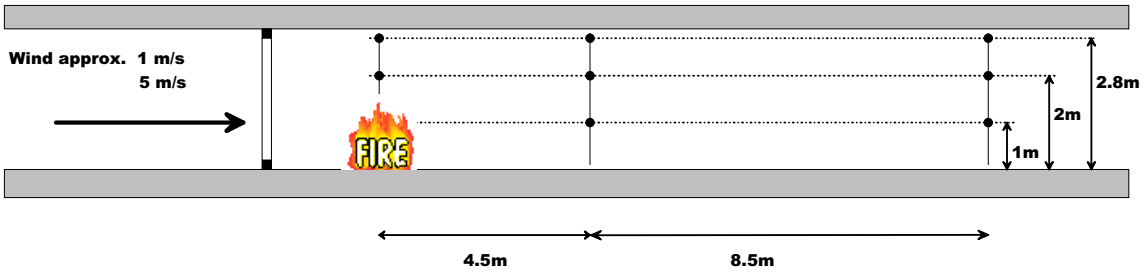

Figure 1: Schematic setup in the Hagerbach tunnel

diluted by the tunnel wind, is very important.

3.3. Calibration in a smoke box

Based on the results and experience gained from the Hagerbach experiments, realistic smoke densities were able to be reproduced in a "smoke box" sized $1\text{m} \times 1\text{m} \times 1\text{m}$. Figure 2 shows this box equipped with an aerosolgenerator (PALAS AGF2.0), ventilator (generates the turbulence), extinction mesurement device (MIREX, according to EN54), video camera, and several light sources.

A fire with hydro carbons (gasoline, diesel, plastic) generates aerosols and soot particles with diameters of less than 1000 nm. For the simulation of smoke, aerosols with a Sauter-diameter of 500–1000 nm were produced from Di(2-ethylhexyl)-Seabacte (Merck 1263). Using the above mentioned experimental setup, the contrast-algorithm was calibrated to raise an alarm at a total extinction $KL = 12\%$ over a path-length L.

3.4. Alarm tests with large scale tunnel fires

Tests with open gasoline fires conducted on the 22$^{\text{nd}}$ September 1999 in the road tunnel "Schönberg" near Salzburg were recorded using standard video cameras. These recordings were afterwards used to test the calibrated smoke detection algorithm. The series of images in figure 3 illustrate this test; the image labelled with "!!!Fire!!!" is taken as a screen shot from a computer running the video smoke detection algorithm.

Considering the transfer time needed for the smoke to reach the position of the

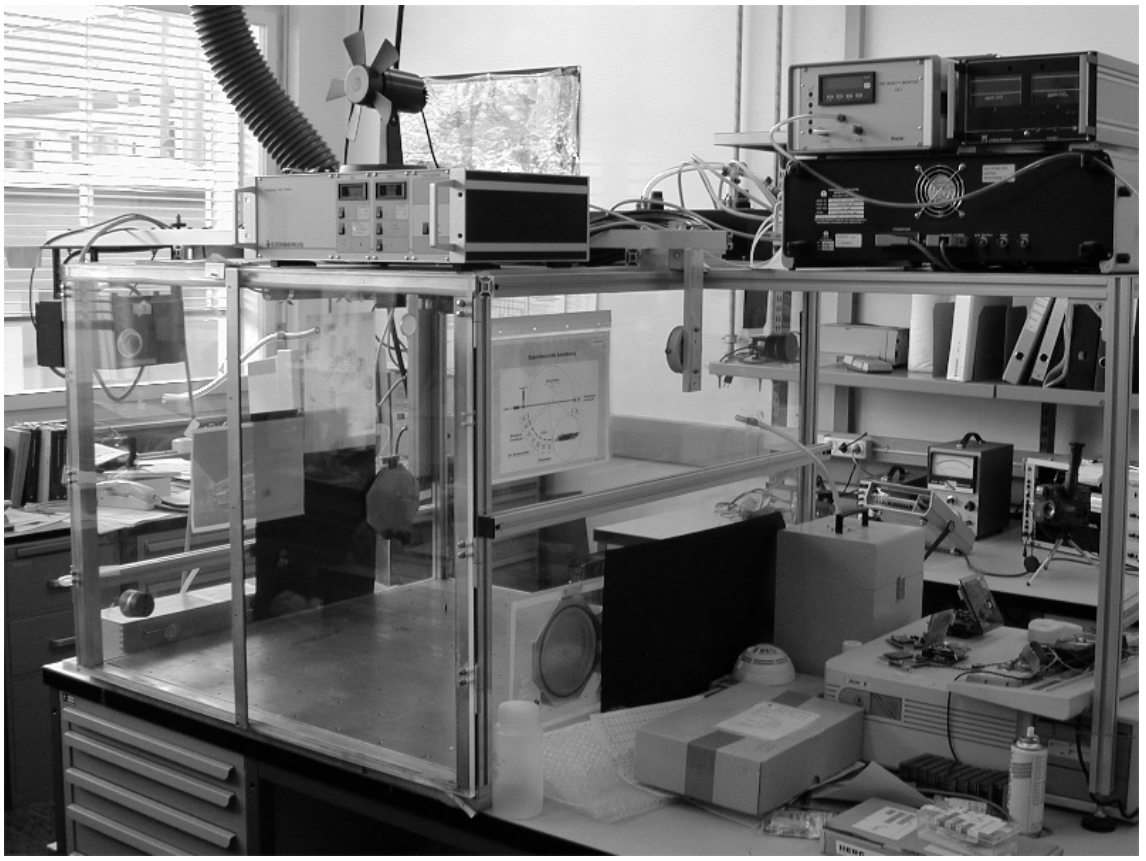

Figure 2: The smoke box used to develop and calibrate the algorithm.

camera (60 m distance, wind speed of 1 m/s), the algorithm triggered an alarm four seconds after the smoke could have reached the position of the camera. The smoke density at the position of the camera was at this point in time far below that found in the case of a fully developed fire. The calibration to $KL = 12\%$ set from measurements in the laboratory was adequate to trigger the alarm in the early stages of a real, fullscale fire. It should be noted that the visibility decreases rapidly with time after the alarm was given and quickly approaches 0 m. At this point, it is impossible to monitor the fire with the camera raising the alarm.

3.5. Long term tests

To test the long term stability of the contrast algorithm under realistic conditions, several cameras in the Gubrist tunnel in the greater Zürich area were monitored. This allowed for a test of the algorithm under difficult conditions, such as traffic line ups, accidents and ensuing line ups, switching of the lights from day to night mode,

Figure 3: Screen shots of the large scale test in the Schönberg tunnel near Salzburg. Width of tunnel = 10 m, height = 6 m. Wind speed 1.0 – 1.2 m/s. Area of fire 1 m^2, 20 L gasoline with 5 L diesel added. Distance between camera and fire 60 m

and combinations of the above. Figure 4 shows a schematic of the system setup.

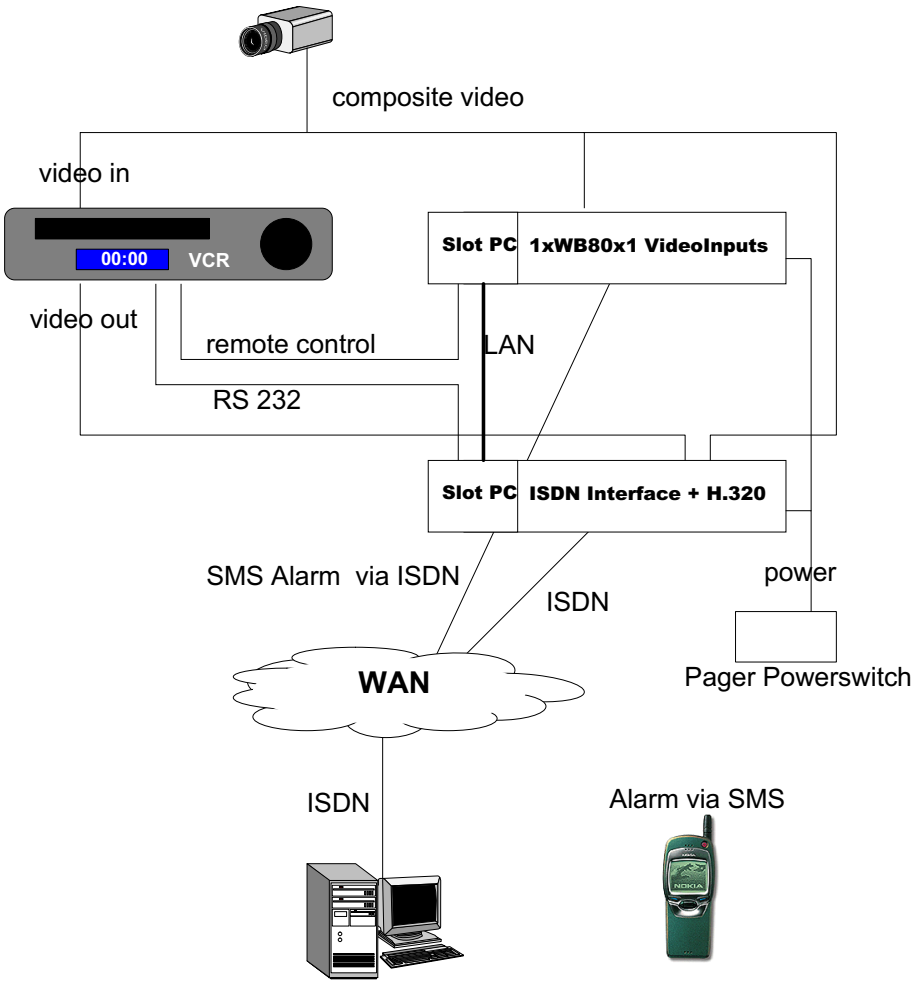

Figure 4: Schematic of the setup for the long term tests in the Gubrist tunnel.

Four cameras were installed at the side-wall of the tunnel, and four cameras were installed in the centre of the ceiling in the tunnel. Cameras on the side were installed at a height of 2.75 m, ceiling cameras at 4.3 m. The video smoke detection algorithm was run on a computer, and video recorders were installed that would be controlled by a second computer. The whole system can be controlled through an ISDN link so as to allow for critical sequences to be recorded.

Sequences of three hours duration each were recorded and especially critical situations were analysed. These sequences are now being used to test modifications of the video smoke detection algorithm for false-alarm proofness. So far, situations with solid line-ups, beginning line-ups, changing lighting conditions at the entrance of the tunnel, and of changing lighting due to the changes between night and day in the tunnel have been analysed. The algorithm has not produced a false alarm and

because there was no fire during the test period, also no fire was detected.

4. Conclusions

Results from a contrast-analysing video smoke detection algorithm have been given. Experience so far indicates that the algorithm is quick to detect smoke in video sequences and at the same time immune to false alarms. In the near future, the system will be installed in several road tunnels to gain experience with non-stop operation.

To judge a video smoke detection system, one has not only to consider response times, but also how the system deals with effects which could induce false alarms such as car lights, motion, blooming, reflexes and other disturbing effects. Unfortunately customers are often not aware of the importance of the above effects. In order to establish video smoke detection as a new technique, system providers should, therefore, define a standard test procedure which takes into account the above mentioned effects as well as real fire situations. At Siemens Cerberus we are working towards such a standard.

References

[1] B. Aird and A. Brown, "Detection and Alarming of the Early Appearance of Fire Using CCTV Cameras", Nuclear Engineering International Fire & Safety conference, London, 24–26 Feb. 1997.

[2] T. Oikawa, M. Tomizawa and S. Degawa, "New Monitoring System for Thermal Power Plants Using Digital Image Processing and Sound Analysis", pp. 221–224, IFAC Control of Power Plants and Power Systems, Cancun, Mexico, 1995.

[3] V. Cappellini, L. Mattii and A. Mecocci, "An Intelligent System for Automatic Fire Detection in Forests", University of Florence, Italy.

[4] S. Noda and K. Ueda, "Fire Detection in Tunnels Using an Image Processing Method", Vehicle Navigation & Information Systems Conference Proceedings, pp. 57-62, Yokohama, Japan, 1994.

[5] G. Healy, D. Slater, T. Lin, D. Drda and D. Goedeke, "A system for Real-Time Fire detection", IEEE computer Vision and Pattern Recognition, pp. 605–606, New York, N.Y., 1993.

[6] S. Y. Foo, "A Rule-based machine vision for fire detection in aircraft dry bays and engine compartments", Knowledge-Based Systems, Vol. 9, No. 8, pp. 531–540, 1996

[7] George W. Mulholland, "Smoke Production and properties" in DiNenno et al. SFPE Handbook of Fire Protection Engineering, 2nd Edition, Chapter 15, Section 2, pp 217–227

[8] H. D. Baehr, Thermodynamik, Springer, 1973.