Evaluation of solid-state camera systems in varying illumination conditions

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Abstract. We propose a practical method for the expeditious determination of the performance of imaging CCD and CMOS camera systems. Special attention is paid to the operation of these devices in varying illumination conditions, which is typical to many surveillance and consumer electronics applications. One emerging application utilizing imaging sensors in variable illumination conditions is the third generation mobile phone, which will deliver wirelessly pictures, graphics, and video. In our method, determination of the system performance is based on the imaging of a calibrated gray scale test chart as a function of illuminance. At each level of illumination the system response is characterized by a signal to random noise figure. The signal is calculated as the difference of the system response to the lightest and darkest areas of the gray scale. The random noise is measured as the standard deviation of the gray values in a difference of two successive images of the test pattern. The proposed method is applied in three exemplary cases: 1. comparison of inexpensive CCD and CMOS cameras, 2. analysis of the effect of wireless image transmission, and 3. comparison of the effects of automatic and manual gain controls. [DOI: 10.1117/1.1365937]

Subject terms: evaluation of CCD and CMOS cameras; low light level imaging; surveillance; wireless image transmission.

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1 Introduction

The use of solid-state video cameras is expanding rapidly in various applications. In particular low-cost small cameras are emerging in consumer applications, where production numbers may reach tens of millions. These growing consumer applications include web cameras, video conferencing, mobile phones, toys, and computer game consoles. Also more traditional applications, such as surveillance, are expanding, since decreasing prices and size make video cameras affordable and suitable for places where they used to be too expensive or bulky.

A common feature of many of these new applications is the need to operate properly under widely varying illumination conditions. For example, a camera integrated into a mobile phone is required to operate in both indoor and outdoor conditions without its own illumination. Typically, this must be achieved without the user manually adjusting camera parameters, e.g., iris, or integration time or gain. For these reasons, it is important to have methods for evaluating the performance of solid-state video cameras in varying illumination conditions.

Camera manufacturers give information about their products, but in many cases these data are not easily comparable and the information about the measurement conditions is deficient. Several methods for evaluating the performance of solid-state video cameras as a function of illumination have been presented.[1–3] Janesick's[1] CCD transfer method is well known in the scientific community and it produces results in the form of a CCD transfer curve giving a characterization of the camera in absolute terms. The drawback of this method is its rather laborious nature and need for sophisticated equipment. Other researchers have reported CCD evaluation methods for specific applications such as astronomy[4,5] and real-time photogrammetry.[6] We present a new method for evaluating the performance of standard video cameras in varying conditions, especially in low light level conditions. The method gives information on the dynamic range and signal-to-noise ratio over this range of the camera system. The method is readily realizable with moderate equipment, i.e., a lamp, some optical filters, a PC, and a frame grabber. We present the method and apply it to three cases in which effects of the sensor type, wireless image transmission, and gain control on the system performance are considered. The method, as well as the experimental set-up used, is presented in Sec. 2 and the exemplary cases are discussed in Sec. 3. Conclusions are presented in Sec. 4.

2 Evaluation Method

The determination of the system performance in our method is based on the imaging of a calibrated gray scale test chart in varying illumination conditions. At each level of illumination the system response is characterized by a signal to random noise ratio defined in Eq. (1). The highest illumination level is chosen so that the two lightest areas of the test chart can be distinguished, but increasing the illumination would bring them to saturation level. Similarly, the lowest illumination level is chosen so that the two darkest areas of the test chart can be distinguished in the image. The signal is calculated as the difference of the system response to the lightest and darkest areas of the gray scale according to Eq. (2). We are studying temporal random noise; we are not interested in the pixel response nonuniformity (PRNU) and other permanent phenomena, which can be eliminated, at least in principle, by calibration measures.

The random noise is measured as the standard deviation of the gray values in the difference of two successive images of the test pattern. The standard deviation is calculated from digitized images for a small group of pixels (typically 36×36) corresponding to the different areas of the gray scale in the test pattern images according to Eq. (3).

$$\text{signal to random noise} = \frac{S}{N_r}, \tag{1}$$

$$S = g_{\text{light}} - g_{\text{dark}}, \tag{2}$$

$$N_r^2 = \frac{1}{n-1} \sum_{i=1}^{n} (g_{i1} - g_{i2})^2. \tag{3}$$

Here S is the signal, g_{light} is the average system response to the lightest area of the gray scale, g_{dark} is the average system response to the darkest area of the gray scale, N_r is the random noise, n is the number of pixels used in calculation (in a typical case $60^2 = 3600$), g_{i1} is the i'th pixel in the first image and g_{i2} is the i'th pixel in the second image. When the random noise is plotted as a function of signal [encoded in digital numbers (DN)] for small group of pixels, a photon transfer curve is obtained.[3] This is one of the basic performance standards for CCD sensors.

The gray scale test chart used is shown in Fig. 1(a) and its structure in Fig. 1(b). Figures on the outer rows contain the optical reflection density D_r which is related to reflectance R in the way given in Eq. (4). In the case of the test chart this means that ratio of light reflected from the darkest square (1.2) to the light reflected from the lightest square (0.2) is 1 to 10. Respectively, the optical density D_t of a neutral density filter is related to transmittance T as given in Eq. (5).

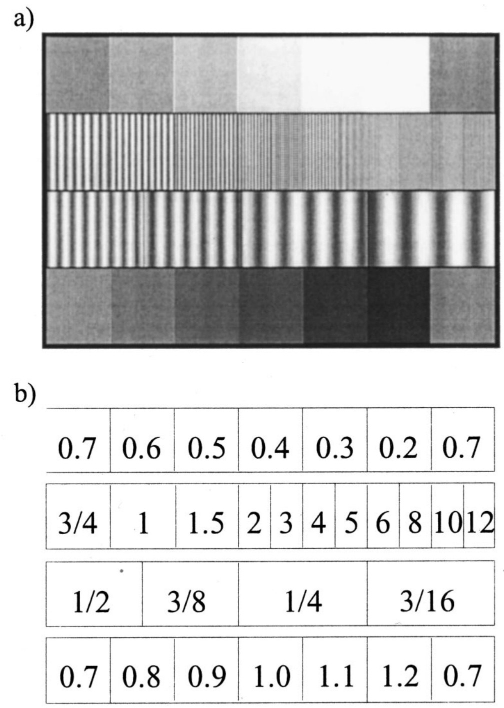

Fig. 1 (a) Sine patterns M-13-60 reflection sinusoidal test pattern and (b) the structure of the pattern. The outer rows contain the gray scale (numbers indicate approximate reflection density) and the inner rows the sinusoidal areas (number indicate spatial frequencies in cycles/mm). The size (1×) of the target is 47×70 mm.

$$D_r = -\log R, \tag{4}$$

$$D_t = -\log T. \tag{5}$$

A general test environment for the evaluation of imaging cameras using the proposed method is depicted in Fig. 2. The calibrated test chart is illuminated diffusively by a 500 W DC regulated tungsten-halogen filament lamp. The short term stability of high power thermal light sources is excellent because, due to the large mass, the changes in temperature are slow. The light output is flattened by a ground glass diffuser.

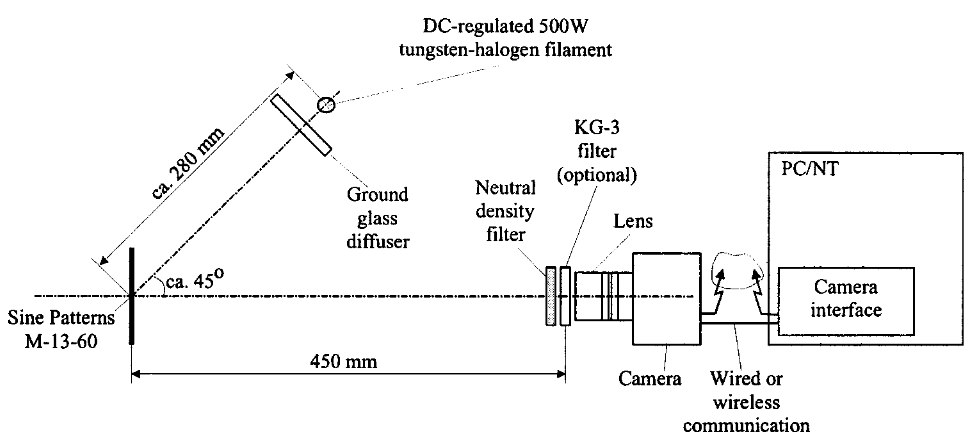

Fig. 2 Experimental set-up.

Table 1 Comparison of CMOS and CCD sensors.

	CMOS	CCD
Spatial resolution	Same	Same
Image quality	8–10 bits gray	Up to 14 bits gray
Power consumption	10's of mW	100's of mW
Power supply	Single 3.3 or 2.5 V supply	Multiple 5–15 V supplies
System integration	Logic integration	Needs multiple chips
Windowing	On-chip function	Not possible

A suitable combination of neutral density filters is used in front of the camera lens to achieve the desired illumination level without changing the power feed of the lamp and thus the spectral content of the optical radiation. An IR cut-filter (e.g., KG3) can be included in the system if only the visible range is important for the intended application.

The signal from the camera can be either digital or analog. In the latter case the digitization is done by the A/D converter of the interfacing frame grabber board in the PC. All the image processing is performed in the PC using commercial image processing software, like MATLAB. The image data transfer from the camera to the PC can be wired or wireless. An example of a system in which wireless image transmission is applied is given in Sec. 3 (Case 2).

3 Experimental Cases

3.1 *Case 1: Comparison of Inexpensive CCD and CMOS Cameras*

The use of video cameras is growing rapidly in applications like video conferencing and surveillance.[7] It is expected that new fast growing markets will open in automotives, mobile phones and toys. This expensive use of video cameras is due to the decreasing size and sinking prices of the cameras. All standard video cameras today employ solid-state components, either more traditional charge coupled device (CCD)[8] or newer complementary metal oxide semiconductor (CMOS)[9] technology. The advantages of CMOS are the need for only one low supply voltage, usually +3.3 V, compared to two or more voltages needed for CCD operation; and the possibility to integrate auxiliary circuitry, e.g., timing electronics on to the same chip with the actual sensor. The latter feature enables, at least in principle, pixelwise illumination control, signal amplification, and image processing on a chip. A general comparison of CCD and CMOS sensor characteristics is shown in Table 1.

Two typical inexpensive video cameras, a CCD and a CMOS, were chosen to be evaluated with the method presented in Sec. 2. Standard fixed aperture video lenses ($f = 12$ mm) were used as imaging optics. The analog video signals from the cameras were digitized using a 10 bit Matrox Pulsar digitizer board. The technical specifications for the cameras are given in Table 2. Note that both cameras have an automatic gain control (AGC) function which cannot be turned off.

The signal and random noise characteristics for the two cameras are given in the graphs of Fig. 3. The abscissa represents the different optical densities of the test pattern. Figure 3(a) represents the behavior of the CMOS camera in very good illumination conditions, whereas Fig. 3(b) is measured in low light level conditions. In similar fashion, Figs. 3(c) and 3(d) represent the signal and random noise behavior of the measured CCD camera.

The measured signal to random noise ratios S/N_r for the two cameras are shown in Fig. 4. The S/N_r behavior of the CCD camera is consistent, i.e., it improves with increasing illumination. The same is true for the CMOS camera, except for the anomalia due to the poorly performing AGC.

In addition to the measured results, we visually evaluated the quality of images produced by the cameras when restricting the incident illumination with neutral density filters applied in front of the lens. It can be seen from the images in Fig. 5 that the visual quality of the images produced with the CCD camera is better. The CMOS camera suffers from poor behavior at a certain illumination level [see Fig. 5(b)], as mentioned before, and high visible noise in low light levels [Fig. 5(d)]. It should also be noted that in this case the CCD camera not only produced better visual quality but it also operated in a wider illumination range than the CMOS camera. The optical densities $D=0$ and $D=4.5$ (CCD) correspond to an illumination change of

Table 2 Specifications of the exemplary cameras.

	MONACOR TVCCD-40MC	Vision VC5400R001
Sensor	CCD 1/3″, $4.4\times 3.3\ \mathrm{mm}^2$	CMOS 1/3″, $4.66\times 3.54\ \mathrm{mm}^2$
Pixels	512 (h)×582 (v)	384 (h)×287 (v)
AGC	automatic	automatic
S/N	>45 dB	>38 dB
DC supply voltage	12 V DC/ca. 150 mA	7.. 12 V DC
Video	CCIR	CCIR

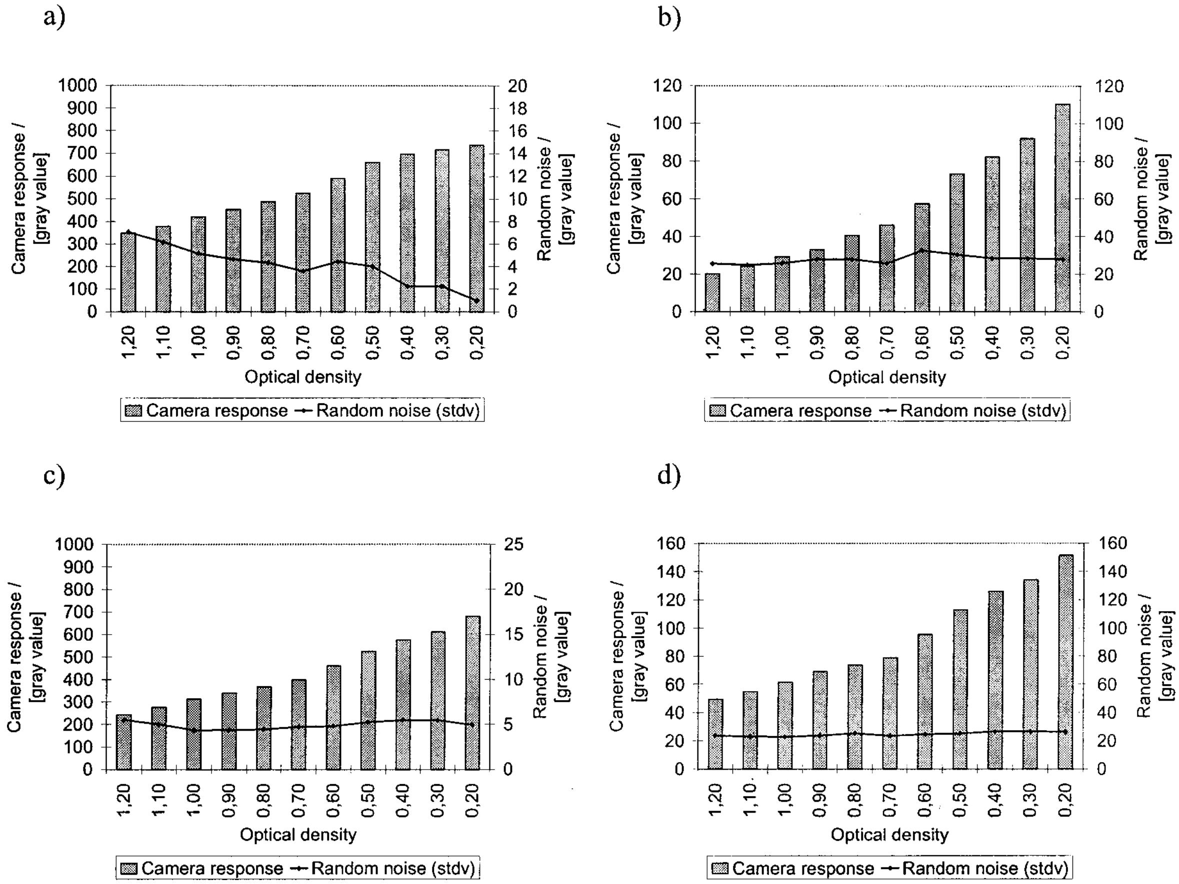

Fig. 3 Signal and random noise characteristics for the two exemplary cameras under various illumination: (a) CMOS, $D_t=0.3$, (b) CMOS, $D_t=3.0$, (c) CCD, $D_t=0$, and (d) CCD, $D_t=4.5$. Here D_t refers to the optical density of the neutral density filter in front of the imaging lens.

1:31622, and $D=0.3$ and $D=3.0$ (CMOS) correspond to an illumination change of 1:500. These figures correspond to the dynamic ranges of 45 dB (CCD) and 27 dB (CMOS). The latter number should not be directly compared to the value given in Table 2 (S/N>38 dB), because the width of the region of anomalous operation was not determined accurately.

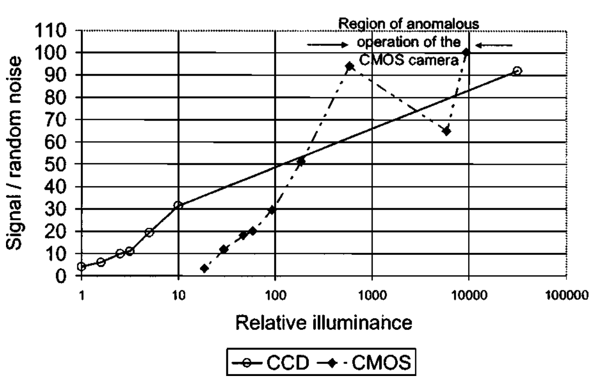

Fig. 4 Signal/random noise as a function of relative illumination for the exemplary cameras.

3.2 *Case 2: Analysis of the Effect of Wireless Image Transmission*

Wireless transfer of imagery, both still and video, is expanding rapidly. Applications include remote surveillance, wireless local area networks, web cameras with laptops, and perhaps most importantly, third generation mobile phones. In all of these applications it is important to know what the dynamic range and signal to random noise ratio of the images is and what, if any, is the effect of wireless transmission on these parameters. To demonstrate the applicability of the evaluation method presented, a wireless camera system case is given.

The exemplary wireless system consists of a JAI CV-M10BX monochrome progressive scan camera with an interline transfer CCD sensor of 1/2″ format. The specified signal to noise ratio for the CV-M10BX camera is 55 dB or more (AGC off, gamma=1.0). In our measurements AGC was ON and gamma=1. A Nikon AF Nikkor 24-mm 1:2.8D camera lens (35 mm format) was used as imaging optics. The analog video signal was transmitted both by wires and wirelessly approximately for a 5-m distance in free space. In the wireless transmission mode a Hung Chang HTR2400 2.4 GHz FM transmission system was

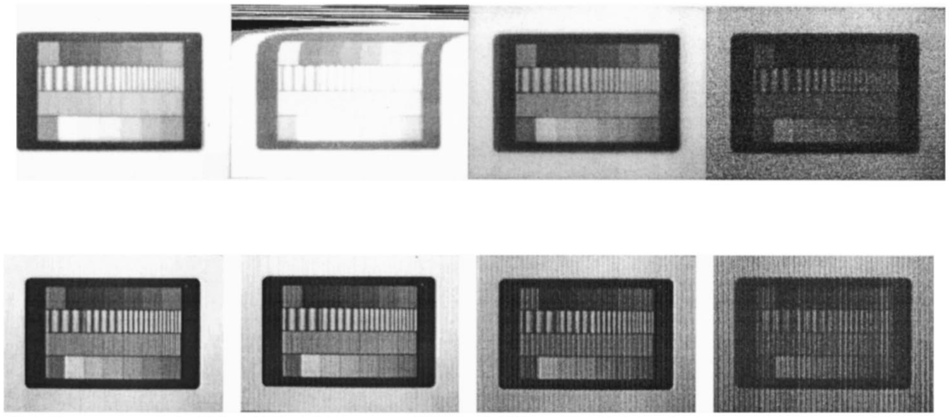

Fig. 5 Images of the M-13-60 test pattern. CMOS camera with neutral density filter $D=$(a) 0.3, (b) 1.0, (c) 2.5 and (d) 3.0. CCD camera with neutral density filter $D=$(e)0, (f) 3.0, (g) 4.0 and (h) 4.5. The anomaly of the CMOS camera operation at a certain illuminance range is apparent.

utilized. The signal was digitized with a Matrox Meteor II board in the PC.

The measured signal to random noise ratios S/N_r for the wired and wireless image transmission are shown in Fig. 6. It is interesting to notice that in this case the wireless image transmission tends to slightly increase the signal to random noise ratio at low light levels compared to the wired transmission. At the upper end of the illuminance range the situation is reversed. The optical densities of the neutral density filters varied in this test from $D=0$ to $D=4.2$. In addition to the neutral density filters, the illuminance was adjusted by the aperture of the lens. The combined effect of neutral density filters and aperture changes corresponds in both cases approximately to an illumination change of 958860:1. The dynamic range is respectively $\approx$60 dB, which is a reasonable value compared to the specified 55 dB.

3.3 *Case 3: Comparison of the Effects of Automatic and Manual Gain Controls*

Most cameras have an AGC feature available. In many cameras it is not even possible to turn the AGC off, so it is of interest to study the effect of the AGC when compared with manual gain control. For the third case we chose a Pulnix TM9701 camera with selectable AGC.

The TM9701 camera has a 2/3″ progressive scan interline transfer CCD sensor and an internal 8-bit A/D converter. The specified signal to noise ratio for the camera is 50 dB min (AGC off). A Nikon AF Nikkor 35-mm 1:2 camera lens (35 mm format) was used as the imaging optics. The digital data from the camera was transferred to the PC via a Mikrotron Inspecta-2 PCI frame grabber.

The measured signal to random noise ratios S/N_r for the automatic (AGC) (gamma$=1$) and manual (MGC) (gamma$=1$) gain control are shown in Fig. 7. The manual gain was adjusted to its maximum to adapt to the low light level operation range. The differences in system response between the manual and automatic operation are negligible in this case. As in Case 2 the illuminance level was adjusted by a combination of the lens aperture and neutral density filters. The optical densities varied in this test from $D=0$ to $D=4.2$. The combined effect of neutral density filters and aperture changes corresponds approximately to an illumination change of 1917720:1. The dynamic range is respectively $\approx$63 dB, which is a considerably higher value than the specified 50 dB min.

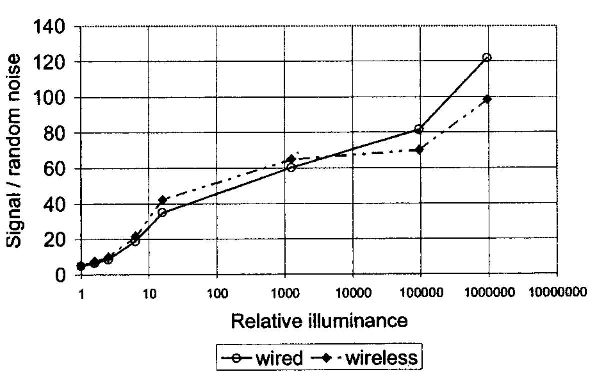

Fig. 6 Signal/random noise as a function of relative illumination for the wired and wireless image transmission.

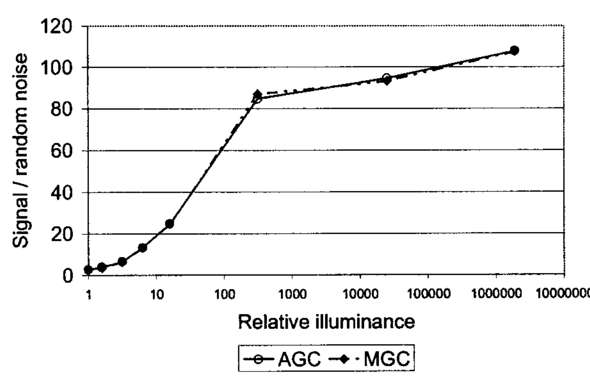

Fig. 7 Signal/random noise as a function of relative illumination for the manual and automatic gain control modes of a Pulnix TM9701 camera. The manual gain was adjusted to its maximum to adapt to the low light level operation range.

4 Conclusions

We have presented a new method for evaluating the signal to random noise of a video camera over the whole dynamic range. The method is based on the imaging of a known gray level chart under varying controlled illumination. The random noise is determined from the pixelwise gray value differences of two successive digitized images. Random noise figures are calculated for small (e.g., 36×36) subimages corresponding to a certain gray level of the test chart.

The method is easy to implement even with moderate equipment, and it gives reproducible results. We have demonstrated the use of the method in three cases involving low-cost small CCD and CMOS cameras, wireless and wired transmission with a CCD camera, and a high-end CCD camera with AGC on and off. The results given by the method were consistent with observations and manufacturer information.

The method presented can be used for evaluating the performance of different cameras for applications where high dynamic range and signal to random noise ratio are important due to varying illumination conditions. At the moment, the method has been applied for b/w cameras, but we plan to develop it also for the evaluation of color video cameras.

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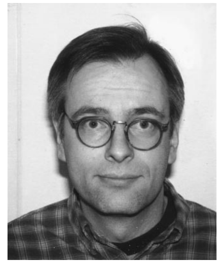

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