J Forensic Sci, May 2009, Vol. 54, No. 3
doi: 10.1111/j.1556-4029.2009.01017.x
Available online at: www.blackwell-synergy.com

TECHNICAL NOTE

Kenji Kurosawa,[1] Ph.D.; Kenro Kuroki,[1] Ph.D.; and Norimitsu Akiba,[1] Ph.D.

Individual Camera Identification Using Correlation of Fixed Pattern Noise in Image Sensors

ABSTRACT: This paper presents results of experiments related to individual video camera identification using a correlation coefficient of fixed pattern noise (FPN) in image sensors. Five color charge-coupled device (CCD) modules of the same brand were examined. Images were captured using a 12-bit monochrome video capture board and stored in a personal computer. For each module, 100 frames were captured. They were integrated to obtain FPN. The results show that a specific CCD module was distinguished among the five modules by analyzing the normalized correlation coefficient. The temporal change of the correlation coefficient during several days had only a negligible effect on identifying the modules. Furthermore, a positive relation was found between the correlation coefficient of the same modules and the number of frames that were used for image integration. Consequently, precise individual camera identification is enhanced by acquisition of as many frames as possible.

KEYWORDS: forensic science, engineering, image forensic, image analysis, camera identification, fixed pattern noise, correlation coefficient

Camera identification is an advancing new field in image forensics. The technology is useful to determine whether or not questionable images or questionable video sequences were recorded using a specific camera. This type of identification proves useful in the court for establishing the origin of images presented as evidence. Kurosawa et al. (1,2) developed an individual video camera identification method based on fixed pattern noise (FPN) of charge-coupled device (CCD) arrays. The FPN contains characteristic pixels, so-called hot pixels, which have large dark current. Using the proposed method to compare the coordinates of hot pixels in questioned video images of an actual sexual crime scene and the coordinates of hot pixels generated in a suspect's video camera, the video sequence was shown to have been recorded with that camera (2). This kind of individualization method is also useful for examining video-recorded images of kidnapping or child pornography, for showing evidence of video editing, etc. Geradts et al. (3,4) and Saitoh et al. (5) showed that digital photographs are identifiable by comparison of pattern noise caused by pixel defects and the hot pixels. These methods are useful not only for CCD mounted cameras but also for cameras equipped with complementary metal oxide semiconductor (CMOS) image sensors.

Lukáš et al. (6,7) developed a new method to identify digital photographs; it is based on evaluation of the correlation of photo-response nonuniformity noise (PRNU) in image sensors. They extracted the noise pattern from images of natural scenes using a wavelet-based denoising filter. Then, a correlation coefficient between the noise pattern and a reference pattern of a given camera was calculated for identifying the camera. They tested nine digital cameras of eight different camera brands, and their results showed that the method was effective. Their study was practical because photographs of natural scenes were used in their experiments, whereas FPN caused by dark current can be observed only in dark images. They also provided a unified framework for identifying the source digital camera from its images and for revealing digitally altered imaging using PRNU (8).

Another source camera identification method was proposed by Bayram et al. Their method was identifying traces of a color filter array (CFA) interpolation algorithm deployed by digital cameras (9). They used the expectation–maximization algorithm to estimate CFA interpolation algorithm: an interpolation kernel and a probability map. Then, the estimated algorithm was classified with the support vector machine to identify cameras. The method can be used for camera model identification; however, it cannot be used for individual camera identification because cameras of the same model employ the same interpolation algorithm.

Our research interest is "individual video camera identification," which distinguishes a specific video camera from among cameras of the same brand. For this study, five analog video-image sensing modules of the same brand were used to test the camera identification method using the correlation coefficient of FPN. The studies by Lukáš et al. (6,7) used the correlation coefficient of the pattern noise; however, their research did not address video camera identification. In this present paper, experimental results are reported: the correlation coefficient and temporal change of the coefficient.

Methods

Individual Camera Identification

Solid-state image sensors, such as CCD and CMOS image sensors, typically comprise more than hundreds of thousands of pixels, which function as photo detectors. Pixel-to-pixel variations pertain in sensitivity and the amount of dark current (10). Pixel-to-pixel variations in amplifier gain also exist in CMOS detectors. These inconsistent electrical properties of pixels cause FPN (11,12), a stable noise component that is superimposed on image signals and

---

[1] Physics Section, Second Forensic Science Division, National Research Institute of Police Science, 6-3-1, Kashiwanoha, Kashiwa, Chiba 277-0882, Japan.

Received 21 Mar. 2008; and in revised form 10 June 2008; accepted 21 June 2008.

which is independent from the image signals. Each image sensor is considered to have a unique FPN because the pixel-to-pixel inconsistencies are formed during manufacturing; furthermore, the distribution pattern of the variation is not controllable during fabrication. Consequently, if FPN can be extracted from the images, it is expected that individual camera identification is possible by evaluating similarities of FPNs among images.

Experiments

In our experiments, five analog color CCD modules of the same brand (MTV-54K0N) were used to examine FPN similarity. Moreover, the temporal change of the similarity was examined. The module is 32 × 32 × 32 mm. We used the CCD modules in our experiment because small camera modules of this type can be used in criminal situations. The modules have 542(H) × 496(V) effective pixels, which output the NTSC video standard signals. The serial numbers of each module were G08047659, G08047663, G08047665, G08047668, and G08047670.

To simplify the experimental conditions, blank images were recorded by covering the camera lens with a lens cap at room temperature. Therefore, FPN results mainly from heterogeneity of the dark current under this condition. The imaging modules were warmed for at least 30 min after power-on to stabilize the experimental condition. The images were captured using a 12-bit monochrome video capture board (PC-Visionplus; Dalsa Corp., Waterloo, Ontario, Canada) and stored in a personal computer. The capture board was introduced in our experiments because of its high amplitude resolution of 12-bit. As signal amplitude of FPN is quite low, high amplitude resolution is important for analyzing FPN involved in video images. In the experiments, authors placed priority on the amplitude resolution rather than color information. Therefore, the 12-bit monochrome video capture board was used because no 12-bit color video capture board was available in our laboratory. The resolution of captured images was 640 × 480 pixels. For each module, 100 frames (i.e., video images) were captured. In general, FPN was hardly detected from a single captured frame because of the random noise component involved in video signals. This is because the power of FPN is less than that of the random noise component. To suppress the power of the random noise component, the 100 captured frames were integrated. The integrated image was considered as FPN in our experiments. It was obtained six times every 10 min for each module (day 0). After leaving the devices switched off for 10 days, FPN was re-obtained using the same procedure (day 10).

Here, $\mathrm{FPN}^{i}_{k,\mathrm{Day}=j}$ is defined as k-th obtained FPN ($k = 1, 2, \ldots, 6$) for CCD module i ($i = 1, 2, \ldots, 5$) at Day j ($j = 0, 10$). The similarity of FPN was evaluated using the normalized correlation coefficient r given as

$$r(X,Y) = \frac{E_{X,Y}[(X-\mu_X)(Y-\mu_Y)]}{\sqrt{E_X\left[(X-\mu_X)^2\right]}\sqrt{E_Y\left[(Y-\mu_Y)^2\right]}}\,(-1 \le r \le 1)$$

where X and Y are FPN, and where μ denotes the average of pixel values. The center region of FPN (the resolution: 540 × 380 pixels) was used for calculating the normalized correlation coefficient. Edge region was trimmed for calculating r because the captured frames contained blank pixels at their frame edge; i.e., the pixel value was always zero in the region, and because the influence of the blank region was serious for precise calculation of r. All normalized correlation coefficients for every combination of i, j, and k were calculated. For this study, $r(\mathrm{FPN}^{i1}_{k1,\mathrm{Day}=j1}, \mathrm{FPN}^{i2}_{k2,\mathrm{Day}=j2})$ is defined as the "intra-module" correlation coefficient when $i1 = i2$; that is, the coefficient for the same modules. Furthermore, r is defined as the "inter-module" correlation coefficient when $i1 < >i2$; that is, the coefficient for different modules.

Results

All the normalized correlation coefficients $r(\mathrm{FPN}^{i1}_{k1,\mathrm{Day}=j1}, \mathrm{FPN}^{i2}_{k2,\mathrm{Day}=j2})$ for every combination of $i1$, $i2$, $k1$, and $k2$ are depicted in Fig. 1. These are the results when 100 frames were integrated for obtaining FPN. The horizontal axis shows the CCD module number; the vertical axis shows the normalized correlation coefficient r. The plots on the left-hand side for each module are the correlation coefficients between FPN (day = 0) and FPN (day = 0); the plots on the right-hand side are the coefficients between FPN (day = 0) and FPN (day = 10). The intra-module correlation coefficients (i.e., for the same modules) were 0.55–0.8, as portrayed in this graph. The inter-module correlation coefficients (i.e., for different modules) were < 0.4, which indicated a positive correlation between different individuals. The inter-module correlation coefficients were smaller than the intra-module values. Therefore, it was considered that individual camera identification is possible by evaluating r. Some intra-module r values decreased markedly after 10 days (e.g., module no. 4). The other values changed slightly after 10 days. However, the change was small. It can be inferred that individual camera identification is possible even after 10 days because differences remained between the inter- and intra-module correlation coefficients. In general, temporal changes of FPN are negligible. An example is the study of Lukáš et al. (7), which mentioned stability of pattern noise over 5 years. A video image acquisition system with high amplitude resolution and high signal-to-noise ratio is necessary to obtain a clear FPN because the signal level of FPN is low and FPN is contaminated with random noise. Although we used a 12-bit video image capturing system, some improvement is necessary for more stable observation of FPN. We assume that the change of r resulted from not enough frame integration to rule out the stochastic noise component.

As described in the experimental method, 100 frames were integrated for obtaining FPN to decrease the random noise component involved in the captured frames. Figure 2 depicts the intra-module correlation coefficients when the number of frames for integration

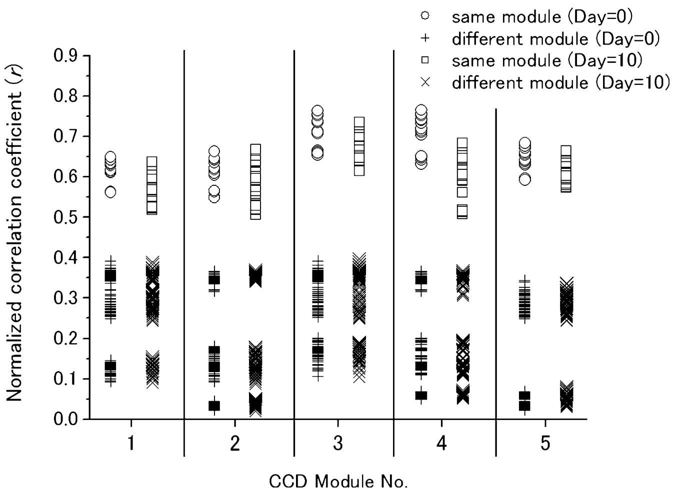

FIG. 1—*Normalized correlation coefficients of fixed pattern noise (FPN) when 100 frames were integrated. Plots on the left-hand side for each module show correlation coefficients between FPN (day = 0) and FPN (day = 0); plots on the right-hand side are coefficients between FPN (day = 0) and FPN (day = 10).*

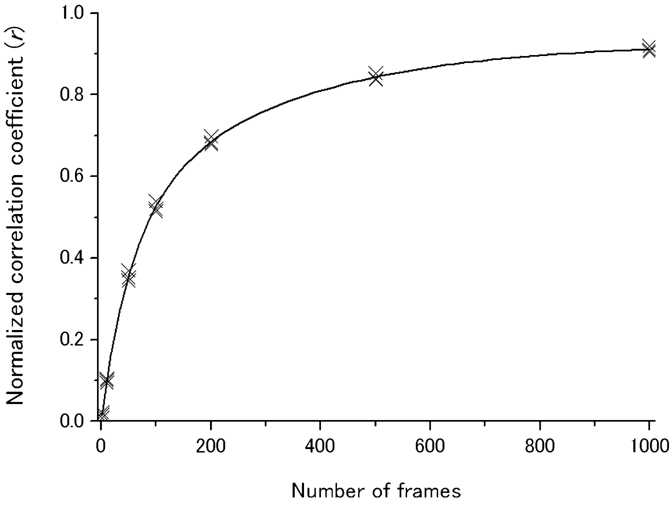

FIG. 2—*Intra-module correlation coefficients when the number of frames for integration was changed. Module no. 2 was used. Data were collected three times.*

was changed from 10 to 1000. The horizontal axis represents the number of frames, and the vertical axis represents *r*. The *r* value increased concomitantly with the numerical increase of frames, and exceeded 0.9 at 1000 frames. This result indicates that the module outputs contained a non-negligible random noise component, which decreased the intra-module *r* when the number of frames was small. Figure 3 shows the intra-module and inter-module correlation coefficients when 1000 frames were integrated. Under these conditions, the intra-module correlation coefficients were >0.9, whereas the inter-module correlation coefficients were <0.4. Therefore, these results show that the modules can be identified clearly using *r* because of the large gap. Furthermore, these results underscore that numerous frames, as many as possible, are required for precise video camera identification. One thousand frames are equivalent to 33.3 sec in the NTSC video format.

Conclusion

Individual video camera identification using the correlation coefficient of the FPN was studied in this paper. The experimental results show that a specific CCD module can be distinguished among five modules of the same brand by analyzing the normalized correlation coefficient of FPN. The coefficients changed slightly after 10 days. However, the change was generally small. It was considered that the temporal change of the coefficient during several days is negligible for camera identification. In addition, a positive relation was found between the correlation coefficients of the same modules and the number of frames that were used for image integration. Consequently, it is desirable to acquire as many frames as possible for precise video camera identification.

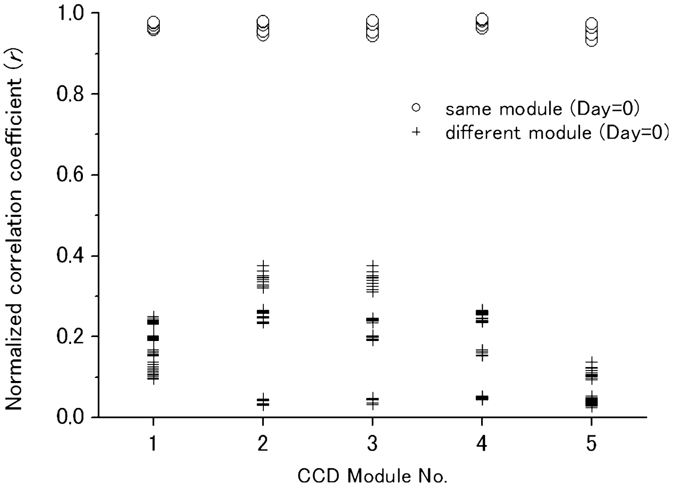

FIG. 3—*Normalized correlation coefficients of fixed pattern noise when 1000 frames were integrated.*

In the experiments, blank images were recorded to simplify the experimental condition. Our future work will include video camera identification using FPN caused by photo-response nonuniformity in image sensors and development of a practical method to extract FPN from images of natural scenes. Furthermore, experiments on the temporal change of the correlation coefficients during several years will be necessary.

Acknowledgments

This study was supported in part by the Ministry of Education, Culture, Sports, Science and Technology of Japan and by the Japan Society for the Promotion of Science under a Grant-in-Aid for Scientific Research.

References

1. Kurosawa K, Kuroki K, Saitoh N. CCD fingerprint method—identification of a video camera from videotaped images. Proceedings of IEEE International Conference on Image Processing '99; 1999 Oct 24–28; Kobe. IEEE 1999;3:537–40.
2. Kurosawa K, Kuroki K, Saitoh N. An approach to individual video camera identification. J Forensic Sci 2002;47(1):97–102.
3. Geradts Z, Bijhold J, Kieft M. Methods for identification of images acquired with digital cameras. Proceedings of 52nd Annual Meeting of the American Academy of Forensic Sciences; Reno, NV. Colorado Springs, CO: American Academy of Forensic Sciences, 2000;VI:68.
4. Geradts Z, Bijhold J, Kieft M, Kurosawa K, Kuroki K, Saitoh N. Methods for identification of images acquired with digital cameras. Proceedings of SPIE; 2000 Nov 5–8; Boston, MA: SPIE, 2001;4232:505–12.
5. Saitoh N, Kurosawa K, Kuroki K, Akiba N, Geradts Z, Bijhold J. CCD fingerprint method for digital still camera. Proceedings of SPIE; 2002 Apr 1–5; Orlando, FL. SPIE 2002;4709:37–48.
6. Lukáš J, Fridrich J, Goljan M. Determining digital image origin using sensor imperfections. Proceedings of SPIE—IS&T Electronic Imaging; 2005 Jan 18–20; San Jose, CA. SPIE 2005;5685:249–60.
7. Lukáš J, Fridrich J, Goljan M. Digital camera identification from sensor pattern noise. IEEE Trans Inf Forensics Security 2006;1(2):205–14.
8. Chen M, Fridrich J, Goljan M, Lukáš J. Determining image origin and integrity using sensor noise. IEEE Trans Inf Forensics Security 2008;3(1):74–90.
9. Bayram S, Sencar H, Memon N, Avcibas I. Source camera identification based on CFA interpolation. Proceedings of ICIP 2005: 12th IEEE International Conference on Image Processing; 2005 Sep 11–14; Genova. IEEE 2005;III:69–72.
10. Chuang SL. Physics of optoelectronic devices. New York City, NY: John Wiley & Sons, 1995.
11. Van Santen JG. Invited: Solid state image sensors using the charge transfer principle. Proceedings of the 8th Conference (1976 International) on Solid State Devices; 1976 Sep 1–3; Tokyo. Tokyo: Japanese J Appl Phys, 1977;16 Suppl 16-1:365–71.
12. Takemura Y. CCD camera technologies. Tokyo: Corona, 1997.

Additional information and reprint requests:
Kenji Kurosawa, Ph.D.
National Research Institute of Police Science
6-3-1 Kashiwanoha, Kashiwa
Chiba 277-0882
Japan
E-mail: kurosawa@nrips.go.jp