Chapter 16

USING SENSOR DIRT FOR TOOLMARK ANALYSIS OF DIGITAL PHOTOGRAPHS

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Abstract Dust particles that collect on the image sensors of digital cameras often leave marks on the pictures taken with these cameras. The question therefore arises whether these marks may be used for forensic identification of the camera used to take a specific picture. This paper considers the question by investigating the impact of various camera and lens factors, such as focal length and recording format. A matching technique involving grid overlay is proposed and the probability of false positive matches is quantified. Initial results indicate that toolmark analysis based on sensor dirt has potential as a forensic technique for camera identification.

Keywords: Digital cameras, sensor dirt, toolmark analysis

1. Introduction

The occurrence of dirt on the optical sensors of digital single lens reflex (DSLR) cameras is a problem that is well known to professional and amateur photographers [6]. These cameras have interchangeable lenses; when a lens is removed, the potential exists for dust to enter the film chamber of the camera. In addition, dust may stick to the rear of a newly-attached lens. Dust particles introduced into a DSLR camera often make their way to the camera sensor, an electrically-charged device that attracts particulate matter.

Dirt typically consists of silica, quartz, metallic, fiber and/or organic particles [4]. The term "dust" is commonly used to refer to these particles, but "dirt" or "contaminants" is arguably a more descriptive term. In the case of photocopier identification, marks left by such particles are referred to as "trash" marks [9]. We prefer to use the term "dirt," but use it interchangeably with the term "dust" in this paper.

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While dirt marks are a nuisance to photographers, they are potentially useful to forensic investigators. Since the marks appear on more or less any picture taken from the time particles stick to the image sensor to the time they are removed, they can help identify the specific camera that was used to take a picture of interest.

It is necessary to consider a number of provisos. Dirt may have been washed from a sensor after a picture was taken – just like fingerprints can be wiped from a murder weapon. Alternatively, the sensor could have been cleaned before a picture was taken, causing the picture to have no distinguishing marks – just like using gloves may prevent fingerprints from being left on a murder weapon. It is possible that the image could have been edited before it was "published," and such editing may have (purposefully or inadvertently) removed the distinguishing marks. Despite these shortcomings, we contend that sensor dirt has the potential to be useful in digital forensic investigations. The fact that it is common knowledge how to avoid leaving fingerprints at crime scenes has not made fingerprint evidence any less useful in criminal investigations.

Some modern cameras have mechanisms that prevent dirt from collecting on image sensors. However, as will be argued below, the problem (or opportunity) persists. In fact, some cameras are delivered with dirt on their sensors. Since removing dirt requires some skill, these cameras may carry the distinguishing marks for the rest of their lives.

This paper is intended as an early analysis of the extent to which sensor dirt may be used to associate a picture with a given camera. Two aspects are considered. The first is the impact of aperture, focal length and related factors on the appearance of sensor dirt in a picture. The second is how artifacts in a picture may be matched with a camera based on the dirt currently present on its image sensor.

2. Background

Toolmark analysis is a well-established branch of forensic science [7]. In the physical world, a tool may impress its form on another object or leave scratch marks as it rubs against the other object [9, 12]. In ballistics, for example, the firing pin impresses a mark on the cartridge that may be used to identify the firearm. As the round travels through the barrel, "striations" are scratched on it by imperfections in the barrel.

It is also important to distinguish between class and individual characteristics [9, 12]. The grooves in the barrel of a firearm produce marks on a round that travels through it; these marks may be shared by other firearms in the class (e.g., firearms of the same caliber or firearms made by the same manufacturer). On the other hand, striations on a round are caused by random imperfections in the barrel of the firearm that fired the round and are, therefore, unique to that firearm.

Digital cameras also leave marks on the images they produce. One example is image resolution (more specifically, image dimensions), which is determined by the sensor. Digital cameras also add metadata about images using EXIF tags [2] that typically include the camera make and model. Another example of a class characteristic is the image file format (usually JPEG). Also, some of the compression parameters may be specific to a class of cameras [10]. In the case of DSLR cameras (and some high-end compact cameras), the image may alternatively (or in addition) be recorded in the proprietary format of the vendor [6]. The term "RAW" is often used to refer to these formats. Since most RAW formats are specific to camera manufacturers, they may also be used to identify the class of camera that took a RAW-format picture.

The focus of this paper is on individual characteristics. Sensor dirt – like metal particles in the barrel of a firearm – are positioned by chance and should, therefore, be unique to a particular camera.

The identification of imaging equipment from the marks left by particles is not new. The photocopier used to make a specific copy may be identified by the "trash" marks on the copy [9]. However, a DSLR camera, unlike most other imaging systems, has large variations in the manner in which it may be used – in particular, the ability to be used with different lenses at various settings. The impact of a small aperture setting on the visibility of dirt marks is well known. We are not aware of any other work that has considered the impact of other settings in the forensic context.

Our strategy is to empirically determine the impact of various DSLR camera settings on the manner in which dirt marks are recorded. Once the variations are known, it becomes possible to state accurately whether a mark on an image could have been caused by a particle on a sensor or whether it is possible that two marks on two images could have been caused by the same particle. During this second phase, it becomes necessary to locate marks on images, and the work done to locate and eliminate such marks becomes useful. Zhou and Lin [14], for example, have conducted a detailed investigation of the formation and subsequent removal of artifacts caused by sensor dust.

Dirik, *et al.* [5] have proposed an approach for camera identification based on sensor dust. Their approach is to identify possible marks on pictures and then compare the marks on different pictures.

Our approach is closer to that of Zamfir, *et al.* [13], although their primary intention is to correct blemishes rather than to match a photograph to a camera. They have derived a theoretical model that predicts the position and size of artifacts on an image depending on the aperture and focal length. The calculations depend on calibration images to determine certain camera and lens properties. In contrast, we approach these measurements in an empirical manner, which enables us to consider more dimensions, such as image encoding. Our work also does not assume that the suspect lens is available for calibration. Unfortunately, for reasons of space, it is not possible to present a detailed comparison of the theoretical results of Zamfir, *et al.* with our empirical results. Such a comparison, which is clearly important, is left for future work.

Interested readers are referred to the books by Collins [6] and Hedgecoe [8] for additional information about photography, and to the Pentax K10D DSLR manual [11] for details about the camera used in this work.

3. Artifacts

A spot caused by sensor dirt is referred to as a mark or “artifact.” The appearance of an artifact may be influenced by various factors. Photographers are well aware that artifacts are more noticeable at small apertures. However, the largest aperture at which an artifact may be useful for forensic purposes is not yet known. This section presents an empirical study of the effect of aperture size and other factors on artifacts. Key factors that may impact the usefulness of an artifact include lens focal length, sensor sensitivity (or film speed), lens nature (zoom as opposed to fixed focal length), dirt on the rear lens element and the degree of “busyness” of the image in the area of an expected artifact.

It is probable that all these factors are to some extent dependent on one another. For example, the usability of an artifact at a given aperture may depend on sensor sensitivity. This gives rise to a multidimensional problem where a huge number of combinations have to be tested. However, since this is a preliminary study, the factors are considered independently instead of in combination. Also, the results reported in this paper are based on a single camera. Nevertheless, we believe that our study provides some useful insights while containing the complexity.

3.1 Experimental Setup

Our experiments used a Pentax K10D DSLR camera with an SMC Pentax-D FA Macro 50mm F2.8 set at F32 that was manually focused on a sheet of white paper 50cm away. Image quality was set to “best” and shake reduction was turned off. Filtered daylight in a simple light tent was used and the white balance set to daylight. Sensor sensitivity was set to ISO 100. We refer to the camera used in the experiments as the "experimental camera" and the picture of the white sheet as a "sensor shot." In the experiments described below, the base setup was used with all settings kept constant, except for the factor being considered, which was varied over a range of values.

A 20" LCD screen with 1,400 × 1,050 resolution was used to view the images. The resolution of the image sensor in the experimental camera was 3,872 × 2,592; this means that effectively 1,400 × 937 pixels (about 1.3 megapixels) were used to view the approximately 10 megapixels produced by the image sensor. Since each pixel on the screen represented approximately eight sensor pixels, small marks (in the region of eight or fewer pixels) would not have been observed.

To reduce the reliance on human observation, Adobe Premiere's fill tool was used to fill the backgrounds of the images with a pure white color. This made it possible to isolate artifacts precisely at the pixel level; the first non pure white pixel after background filling was taken to represent the edge of the artifact. Only artifacts that were visible on the LCD screen when it was initially viewed were considered after filling.

3.2 Dirt Configuration

The dust on the camera sensor was another constant; no dirt was added and no dirt was removed during the experiments. In fact, the camera's dust removal system was switched on for a significant period before the experiments were conducted and it was left on for the duration of the experiments. This meant that the observed dirt was probably stuck to the sensor; any new loose dirt that may have been introduced would, in all likelihood, have been shaken off.

One important issue was how to represent the dirt. A number of options were considered; dividing the sensor into a grid and identifying particles based on their grid positions seemed the most promising. One aspect that was not fully known before the work was started was the accuracy with which particle positions may be determined (this deserves attention in future work). The use of a grid makes it possible to determine the space (in pixels) between grid lines to a degree that is coarse enough to deal with possible imprecision in measurements but fine enough to yield reliable forensic conclusions.

The forensic use of particle positions requires a finely spaced grid; this issue is discussed in more detail in Section 4. However, the focus of this work was to evaluate the utility of the technique, not to make exact measurements. Consequently, a coarse grid of 15 × 10 pixels was employed in the experiments.

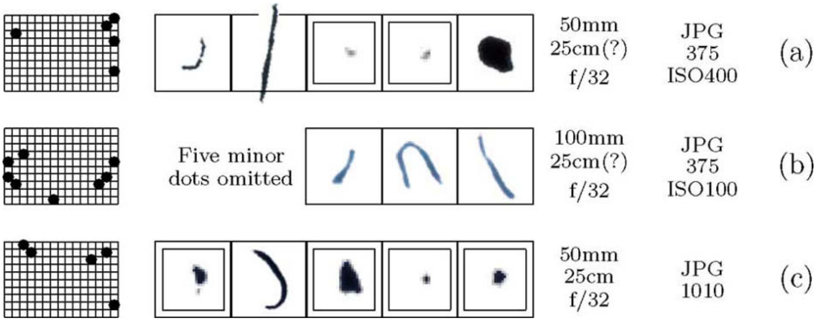

Figure 1. Comparison of three sensors.

Figure 1(c) uses such a grid to show the positions of dust particles in the experimental camera. A dot in a cell position indicates that some dust was observed on the corresponding portion of the sensor. To the right of the grid, individual dust particles are depicted in row-major order. We refer to such a diagram as a "sensor map."

Two scales are used to deal with different sized particles: smaller particles are doubled in size both horizontally and vertically. A double square frame around a particle indicates that doubling has been used. The second particle in Figure 1(c) starts at Row 301 from the top of the sensor and stretches over 54 pixel rows down to Row 355. (The middle row of this range corresponds to Row 2 of the grid.) 54 rows on the sensor correspond to a physical height for the dust particle of about 327μm. In contrast, the fourth particle in Figure 1(c) is much smaller; it occupies only six rows (about 36μm high), and is magnified in the figure to be visible at all.

Figure 1 shows the dirt on the experimental camera as well as dirt on two other sensors for comparison. Figure 1(a) is based on a sensor shot of the experimental camera that was taken some time before the experiments were conducted. The camera sensor was cleaned after this shot was taken and dirt was allowed to build up until the experiments were performed. Figure 1(b) is based on a sensor shot of a Pentax *ist DS also taken some time before the experiments. The sensor of the Pentax *ist DS only contained 6 megapixels; the figure has been adjusted so that similar sized particles are represented using similar sized images even though they cover fewer (but physically larger) pixels.

Figure 1 clearly illustrates that sensor dirt forms characteristic patterns. Even though a very low resolution grid is used, the patterns formed are very different. Moreover, the size and shape of the individual particles demonstrate unique characteristics.

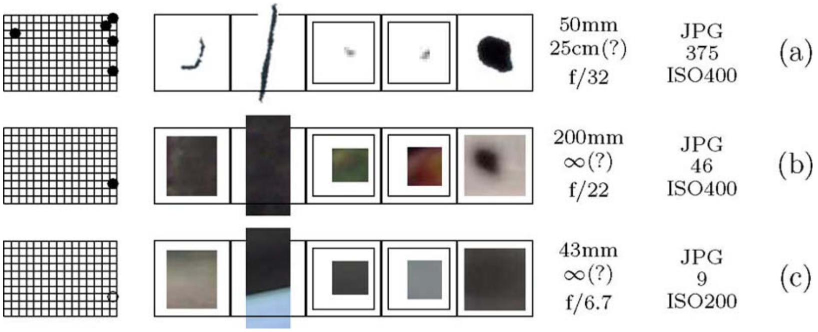

Figure 2. Spot occurrence in pictures.

On the negative side, the fact that two diagrams in the figure originated from the same camera clearly demonstrates that sensor patterns are temporary. Sensors may be cleaned and may accumulate additional dirt over time. Hence, such an analysis will only be useful if the camera was seized soon after the picture of interest was taken. This limitation may not be quite as serious as it seems. Cleaning a sensor requires some dexterity and somewhat specialized tools. Hence, many people will allow sensor dirt to accumulate until the effect becomes unbearable. Moreover, some cameras are shipped with dirt on their sensors [3].

In fact, it is probable that the experimental camera was shipped with dirt on its sensor. One spot, in particular, was visible from almost the first picture taken. The sensor shot in Figure 1(a) was taken when the camera was a few weeks old. Figure 2 repeats the sensor shot of Figure 1(a) and adds the corresponding regions from two early pictures taken with the camera. A region consists of the pixels corresponding to the observed particle and some additional bits around it. In the case of the larger particles, ten additional bits were added on each side and, if space permitted, ten more bits were added at the top and bottom. For smaller particles, five bits were included at the sides, top and bottom. They were then enlarged with the smaller picture, as was the case for the smaller particles discussed earlier. The question is whether the sensor pattern in Figure 2(a) and the corresponding areas from the pictures (contained in Figures 2(b) and 2(c)) prove that they were taken with the same camera.

Figure 2 demonstrates the difficulty of using sensor dirt for camera identification. The first four areas of the picture in Figure 2(b) are simply too dark to observe any spots. The fifth spot is clearly present and has a similar shape. However, it seems to be shifted to the left and is, perhaps, a little higher and a little smaller. Is this enough to declare that the picture matches the sensor? The remainder of this paper attempts to address this question.

Figure 2(c) illustrates additional challenges involved in camera identification. Some of the areas are lighter and may have shown some spots if particles were present at the time the picture was taken. Note that since dirt particles may have collected later, the absence of a spot does not prove that the camera was not used. The area in the extreme right of Figure 2(c) does indeed contain a spot, but it is enlarged to the extent that it almost fills the displayed area. Furthermore, the differences between the tone of the spot and the surrounding area are so subtle that the spot disappears in the printed version. When displayed on a screen (and with some imagination) the spot is discernible. However, it becomes clearer when a larger area is considered and when it is displayed more densely. This suggests that our choice to use a border of five or ten pixels may be too conservative. Nevertheless, it is not clear that a larger area would be sufficient to link the picture positively to the sensor.

Some details about the camera settings appear to the right of the sensor maps in Figure 2. Clearly, there are several differences between the various cases, e.g., different focal lengths (50mm, an 18–200mm zoom lens at 200mm and a 28–70mm zoom lens at 43mm), different sensor speeds (ISO 200 and ISO 400) and different apertures (f/32, f/22 and f/6.7). The impact of these factors on sensor shots is discussed below.

3.3 Encoding

The first issue to consider is the encoding format used to record an image. Most high-end digital cameras offer a lossy compression encoding (typically JPEG abbreviated as JPG), and a format in which all the pixels (and some other information) are recorded without loss. While TIFF was used in the past, most current cameras use a proprietary RAW format. The experimental camera offers a RAW format known as PEF. It also supports Adobe's DNG format, which may be used without paying royalties and could lead the drive towards standardization [1].

The recording format must be considered because a lossy compression technique (e.g., that used by JPG) may lose information about sensor dirt, which may not be desirable. We say "may" because it is not clear if it is best to use the same compression technique that was used to create the suspect picture.

In fact, the situation is even more complex – cameras offer different compression levels, with higher compression levels typically yielding lower quality images and vice versa. Our experiments did not test the effect of different compression levels, but simply used the highest quality level offered by the camera. Any differences seen between the JPG and RAW images should be significantly more pronounced when lower qual-

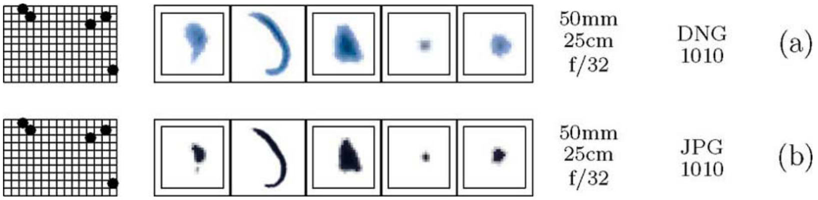

Figure 3. Comparison of JPG and DNG images.

ity levels are used. Since it did not seem to matter which RAW format was used (all RAW formats record all pixels), we decided to use DNG in our experiments.

Figure 3 shows the results of an experiment performed in this regard. As expected, JPG compression smoothed the transition between the blank sensor and the dark dirt, resulting in smaller – albeit apparently darker – marks on the image (Figure 3(b)). JPG compression removed between two and six pixels from the height or width of the mark. This is rather significant given the fact that the marks (in JPG) ranged in length dimension from four pixels to 51 pixels. Given the fact that the JPG encoding modifies the observed particles, we decided to use DNG in the remainder of our work.

3.4 Focus Distance

The second experiment with encoding in the previous section suggests another issue that needs to be considered: Does focus distance have an impact on how marks are rendered? In fact, focus distance had a minor effect on the rendering of the artifacts. However, space limitations do not permit a full discussion in this paper.

A more important observation was that the positions of the marks were affected by focus distance. This observation is predicted by the model of Zamfir, *et al.* [13]. The observation suggests that the sensor shot should ideally be taken with focus distance set to the same range as that for the suspect picture. Further study is required to determine whether marks recorded at different focus distances can be matched reliably. This could determine the finest grid resolution that may be used to match mark positions.

3.5 Lighting

Lighting was considered as a possible reason for mark size variations in the previous section. Artificial lighting can be better controlled than natural light that was used in that particular case. Hence, that part

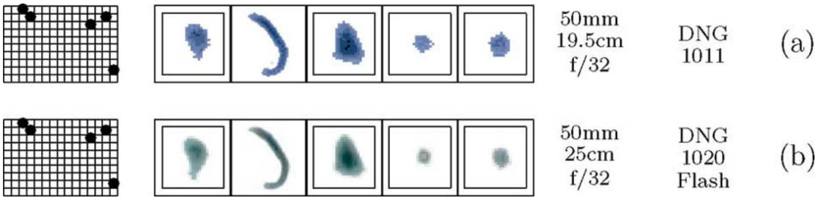

Figure 4. Comparison of flash and daylight photography.

of the experiment was repeated using an electronic flash. The results are presented in Figure 4. Note that the differences appear to be more pronounced than they were in reality. The sizes of most marks differed by zero, one or two pixels; one differed by three pixels. These variations did not seem to be significant enough to warrant further investigation. We assumed natural light suffices, which is useful when longer lenses are tested (as discussed below).

3.6 Aperture

As suggested earlier in the paper, focal length may affect the rendering of marks. Many of the lenses available for the experiments could not be set to an aperture of f/32 – as was used in the testing procedure up to this point. Hence, the smallest common aperture setting of f/22 was used. Before discussing the impact of focal length, we examine the effect of aperture on the experimental observations.

It is well known that sensor dirt causes the most problems at small apertures, primarily because dirt is most visible at small apertures. Consequently, small apertures were chosen in the experimental study (f/32, in general, and f/22 for the tests involving focal lengths). Experience has shown that sensor marks quickly become less defined at larger apertures, but they remain observable and their positions are clearly marked. Filling the background with white helped us to conduct the experiments in a repeatable manner and enabled precise measurements of the position, size and shape of dirt marks down to the pixel level.

Since it was known that larger apertures would not provide such precision, aperture testing was scheduled as the last test in the current series. However, we were surprised at the rate at which precision was lost.

The 50mm lens focused at infinity was still used in the aperture tests; it was set to apertures of f/32, f/22, f/16, f/11, f/5.6, f/4 and f/2.8. As expected, the dirt marks became "softer."

At the f/22 setting, all five sensor marks were visible in the original image; however, filling the background with white erased the two smaller marks and drastically reduced the size of the three remaining marks. At aperture settings larger than f/22, filling the background erased all the marks, which rendered exact comparative testing impossible.

The three larger marks remained visible up to f/5.6, and some at f/4. Even at f/5.6, the color variation between mark and background was so subtle that observability depended on specific screen settings. At f/4, it was only possible to observe the marks after “tweaking,” which, of course, touches on the fundamental premises of experimentation. Obviously, a specialized tool that could identify marks more objectively would be very useful in future experiments.

The shape of the most distinctive mark was still recognizable at f/16 and, perhaps, even f/11; the other marks lost their distinctive shapes at f/22. The sizes of the marks were (according to a subjective assessment) significantly affected by aperture. Consequently, it appears that mark position is the most useful attribute. Size may have to be adjusted depending on various factors in order for it to be useful. Shape offers, perhaps, the most convincing proof, when it is observable, especially when smaller apertures are used.

In summary, larger apertures cause a loss of shape and an increase in the size of marks, and may cause some marks to disappear. Many marks remain discernible up to fairly large apertures (even f/4). Moreover, the marks that remain visible do not change their position. These observations are interesting, but their quantification requires a tool that can objectively isolate marks.

3.7 Focal Lengths

The following focal lengths were tested: 500mm, 170mm, 100mm, 50mm, 40mm, 17mm and 10mm. The first two and last two used zoom lenses at their extreme settings; the others used fixed focal length lenses. The fisheye zoom lens was used for the 17mm and 10mm settings.

Observations were harder to make than expected. One difficulty stemmed from the fact that an aperture of f/22 was used. In all cases this eliminated the smaller two marks once the background was filled with white. (Subjectively, all marks were initially present.) Another problem arose because the white plane used in the experiments proved to be too small at the shorter focal lengths. This was easily remedied in the case of the 40mm lens However, for the 10mm lens, the field of view across the diagonal was 180° and it was not possible to obtain an evenly lit white background. The same problem occurred for the 17mm setting. While the marks were clearly visible, the edges introduced by the borders of the light tent and the fact that all the sides of the light tent were not evenly lit caused the background filling to fail.

For some reason, only one mark remained for the 500mm lens after filling. Its position moved 16 pixels horizontally and 13 pixels vertically between the 500mm and 50mm settings, with most of the movement (12 and 12 pixels, respectively) occurring from 500mm to 170mm. The other marks that were present from 170mm down, showed very little movement (up to four pixels horizontally and six pixels vertically) until the point where measurement became an issue given the background edge marks. Size remained virtually unchanged (with a four pixel change in one case). However, as mentioned above, comparing these results with others in the paper is questionable given the impact of the f/22 aperture used.

4. Camera Identification

It was argued earlier in the paper that matching an image to a sensor may be based on the position, shape and size of dirt marks. We have pointed out that particle shape requires a suitable aperture and further investigation of the effects of particle size is required. Consequently, the primary attribute for matching at this point is particle position.

As discussed above, a grid is very useful for comparing the positions of dirt particles. We propose that the grid be placed so that a mark does not move from one grid cell to another due to the focal length or focus distance or other factors. Having assumed that an $m \times n$ grid has been overlaid in such a manner, the question is: Given some marks on the image and given some marks on the sensor, what is the probability that the image has been produced by the sensor? To quantify the probability, we assume that a dirt particle will stick to any part of the sensor with equal probability.

In the following calculations, for $k, j \in I\!N$, the term $k^{!j}$ denotes $k \times (k-1) \times (k-2) \times (k-j+1)$, i.e., the product of the j successive integers ranging from k to $k-j+1$. Note that $k^{!j} = \frac{k!}{(k-j)!}$.

Assume that the picture displays p marks and that there are s (visible) particles on the sensor. Further, assume that c of these marks are in corresponding cells of the overlaid grid.

The probability of a Type I (false positive) error is given by:

$$P(c) = \binom{s}{c} \frac{(mn-p)^{!(s-c)} \cdot p^{!c}}{(mn)^{!s}}.$$

The derivation of this probability expression is not provided due to a shortage of space. Interested readers may contact the author for the derivation.

Type II errors (false negatives) are expected to occur frequently. A dust particle may be deposited on the sensor, appear in a single picture and then fall from the sensor. Alternatively, the sensor may be cleaned between pictures. Also, camera settings, such as aperture, may cause some particles not to appear in the picture.

Given these considerations, what do the formulas in this section mean in practice? The marks observed in this study suggest that a 300×200 (or finer) grid may be practical. A match of exactly one cell on such a grid implies false positives for 0.0017% of such cases based on position alone. A false positive match of exactly two cells ($s = p = c$) occurs with a frequency of 2.7×10^{-8}%. Partial matches may not be as convincing, but may be perfectly adequate. In fact, our experiments indicate that a sensor with two marks that matches the position of one mark correctly links a picture to a camera in more than 99.996% of test cases.

5. Conclusions

Dirt particles on a camera sensor can be used as toolmarks to link a picture to the camera. Several factors, including focus distance and aperture, affect the rendering of dirt marks on camera images. A matching technique involving grid overlay was proposed and the probability of false positive matches was quantified. The results indicate that toolmark analysis based on sensor dirt is a promising technique for camera identification.

More work needs to be done to fully understand the effects of individual factors and combinations of factors on image rendering. Experiments should also be conducted on multiple cameras and dirt configurations. Additionally, some of the assumptions used in this preliminary work, e.g., the random distribution of dirt particles, should be verified empirically.

Camera dust removal systems are being continuously improved. However, because a few isolated marks appear to be more useful than myriad marks, sensor cleaning may, in fact, have a positive impact on the potential of the technique, as long as dust removal systems are not 100% effective.

References

[1] Adobe Systems, Digital Negative (DNG) Specification (version 1.1.0.0), San Jose, California (www.adobe.com/products/dng/pdfs /dng_spec.pdf), 2005.

[2] P. Alvarez, Using extended file information (EXIF) file headers in digital evidence analysis, *International Journal of Digital Evidence*, vol. 2(3), pp. 1–5, 2004.

[3] Anonymous, Pentax K10D, *Practical Photography*, pp. 110–113, February 2007.

[4] Delkin, *SensorScope and Digital Duster System Cleaning Guide*, Inglewood, California, 2006.

[5] A. Dirik, H. Sencar and N. Memon, Source camera identification based on sensor dust characteristics, *Proceedings of the IEEE Workshop on Signal Processing Applications for Public Security and Forensics*, pp. 1–6, 2007.

[6] J. Freeman, *Collins Digital SLR Handbook*, Collins, London, United Kingdom, 2007.

[7] N. Genge, *The Forensic Casebook: The Science of Crime Scene Investigation*, Ballantine Books, New York, 2002.

[8] J. Hedgecoe, *The New Manual of Photography*, DK Publishing, New York, 2003.

[9] S. James and J. Nordby (Eds.), *Forensic Science: An Introduction to Scientific and Investigative Techniques*, CRC Press, Boca Raton, Florida, 2005.

[10] J. Lukas, J. Fridrich and M. Goljan, Digital camera identification from sensor pattern noise, *IEEE Transactions on Information Forensics and Security*, vol. 1(2), pp. 205–214, 2006.

[11] Pentax Corporation, *K10D Operating Manual*, Tokyo, Japan (www.pentaxslr.com/files/scms_docs/K10D_Manual.pdf), 2006.

[12] R. Saferstein, *Criminalistics – An Introduction to Forensic Science*, Prentice-Hall, Englewood Cliffs, New Jersey, 2007.

[13] A. Zamfir, A. Drimbarean, M. Zamfir, V. Buzuloiu, E. Steinberg and D. Ursu, An optical model of the appearance of blemishes in digital photographs, in *Proceedings of SPIE (Volume 6502) – Digital Photography III*, R. Martin, J. DiCarlo and N. Sampat (Eds.), SPIE, Bellingham, Washington, 2007.

[14] C. Zhou and S. Lin, Removal of image artifacts due to sensor dust, *Proceedings of the IEEE Conference on Computer Vision and Pattern Recognition*, pp. 1–8, 2007.