

# An Empirical Investigation into the Correlation between Vignetting Effect and the Quality of Sensor Pattern Noise

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## Abstract

The sensor pattern noise (SPN) is a unique attribute of the content of images that can facilitate identification of source digital imaging devices. Due to its potential in forensic applications, it has drawn much attention in the digital forensic community. While much work has been done on the applications of the SPN, investigations into its characteristics have been largely overlooked in the literature. In this paper, we aim to fill this gap by providing insight into the characteristic dependency of the SPN quality on its location in images. We have observed that the SPN components at the image periphery are not reliable for the task of source camera identification, and tend to cause higher false positive rates. Empirical evidence is presented in this work. We suspect that this location-dependent SPN quality degradation has strong connection with the so-called *vignetting effect*, as both exhibit the same type of location-dependency. We recommend that when image blocks are to be used for forensic investigations, they should be taken from the image centre before SPN extraction is performed in order to reduce false positive rate.

**Keywords:** Sensor pattern noise, vignetting effect, source device identification, multimedia forensics, digital forensics, multimedia authentication

## 1. Introduction

Attributed to the combined effect of falling prices and increased functionalities, digital imaging devices are as common as watches and wallets in our everyday life in the past two decades. Multimedia manipulations have been made easy with the availability of powerful and easy-to-use multimedia processing software. This has undoubtedly opened up many new opportunities and possibilities for positive purposes. However, the very same set of technologies also provides means for malicious intention to be realised. In response to the challenges posed by the abuse of these technologies, *multimedia forensics* has emerged as a new and fast evolving discipline with the aim of undertaking combat against digital crime. Typical *multimedia forensic* applications include source device identification [1-4], source device linking [5], classification of images taken by unknown cameras [6-8], content integrity verification and authentication [7, 9], etc.

At the centre of these technologies and applications is digital imaging devices, especially digital cameras, and the content they produce. It is therefore useful to have a closer look at how a typical digital camera works and how it produces images. Figure 1 illustrates the simplified digital image acquisition process that a typical digital camera has to go through in order to produce a photo. The light emitting from the scene enters the lens, passes through an anti-aliasing filter, and then reaches a colour filter array (CFA) that is recurrently placed over the semiconductor sensors to capture colour information. Each element of the CFA is only sensitive to a certain light wavelength range such that the corresponding sensor pixel receives only one of the red (R), green (G) and blue (B) components of the light. The missing two colours at each pixel are subsequently interpolated by a de-mosaicking process based on the colour configuration within a neighbourhood of the pixel in question. A sequence of image processing operations, such as colour correction, white balancing, Gamma correction, enhancement and JPEG compression, then take place before the photo is stored in the disk. At each stage of the acquisition pipeline, the hardware and software involved may leave

unique “fingerprints” in the content of the image, which can be exploited to identify the imaging devices. Therefore, researchers have proposed a number of techniques to extract such fingerprints from images for various forensic investigation purposes. Modalities among the fingerprints that have drawn much attention from scientists are sensor pattern noise (SPN) [1, 2, 4, 5, 6, 9, 10], camera response function [11, 12], CFA interpolation artefacts [13, 14], traces of sensor dust [15], JPEG compression [16] and lens aberrations [17, 18].

While many methods [10, 11, 13, 14] can only be applicable when specific assumptions or constraints are satisfied, the sensor pattern noise (SPN) has attracted much greater interest due to its independence of the similar assumptions and constraints. Another desirable feature of the sensor pattern noise is that it cannot only identify camera models, but also individual cameras of the same model [1, 2, 4, 9, 19]. This desirable characteristic of SPN is ironically attributed to manufacturing imperfections and different sensitivity of pixels to light due to the inhomogeneity of silicon wafers [20]. Because of the uniqueness of manufacturing imperfections and the non-uniform sensitivity of each pixel to the light, even sensors made from the same silicon wafer would produce uncorrelated and unique pattern noise, which is not visible to human eyes. The reader is referred to [20] for more details in relation to the sensor pattern noise. Due to its potential in forensic applications, SPN has drawn much attention in the digital forensic community. While much work has been done on the applications of the SPN [1-4, 6, 7, 9, 19], investigations into its characteristics have been largely overlooked in the literature. This has motivated this work and its previous preliminary study [21]. By providing insight into the characteristic dependency of the SPN quality on its location in images, we aim to fill the gap between SPN applications and SPN characteristics in order to avoid the undesirable SPN characteristics in its real-world applications.

In [21], we focused on studying an anomaly in the changes of false positive rates with respect to the size of image blocks in source device identification when two SPN-based methods reported in

[1] and [2] are used. Our findings suggested that this anomaly may well be due to the so-called *vignetting effect*, because it exhibits a similar location-dependent characteristic as the quality of the sensor pattern noise. In this work, we extend the empirical investigation of [21] with two new contributions. First, we evaluate the effective location dependency of the quality of SPN, by measuring the similarity of SPN from different cameras, when they are taken from changing locations of the image. Secondly, we evaluate the impact of such location dependency in the performance attained by the method of [1] in the task of source camera identification. We point out that the aim of the latter analysis is similar to that of [21]. However, in [21] our investigations involved only a small set of clear sky images without any high frequency details because we would like to assess the SPN location-dependent quality without the influence of scene details. Instead, in this work we use a bigger dataset containing images of various scenes, both indoor and outdoor, in order to evaluate the influence of the location dependency of SPN quality in a more realistic setting. In addition, in [21] we considered only a small subset of locations of the block from which the SPN is extracted, while in this work we consider all the possible locations with an exhaustive analysis.

The rest of this work is organised as follows. We first review two SPN-based source device identification methods [1, 2] in Section 2. The anomaly is then discussed in Section 3. In Section 4, we provide a brief insight into the vignetting effect. Empirical investigations into the location-dependent quality of SPN are presented in Section 5. Finally, conclusions and further research directions are drawn in Section 6.

## 2. Previous Work

Most SPN-based image forensic techniques [2, 4, 5, 8, 9, 19] extract the SPN by exploiting the additive noise model in [1] or its variant [5]. Denoting  $n$  as the SPN in an image  $I$ , the model proposed in [1] (when used in the Discrete Wavelet Transform domain) can be formulated as

$$n = DWT(I) - F(DWT(I)) \quad (1)$$

where  $DWT$  is the Discrete Wavelet Transform and  $F$  is a de-noising filter. Because of the high-frequency nature of the sensor pattern noise,  $F$  is usually a low-pass filter. Subtracting the de-noised version of  $I$  from the original version leaves the high-frequency components of  $I$  to be used as the sensor pattern noise,  $n$ . As one can easily see, the de-noising function  $F$  plays a major role in determining the reliability of the sensor pattern noise. Although different de-noising filters can be used as  $F$ , the wavelet-based de-noising filter presented in the Appendix A of [1] has been known as effective in producing good results. As such, it is used in this work.

Once SPN is extracted, it can be used in a variety of forensic applications, for instance identifying the source camera of an image [1-4, 19], clustering images according to their source devices [6] and content integrity verification [9]. To these ends, a metric for evaluating the similarity between SPNs is necessary. A common distance metrics for measuring the similarity between the SPNs  $n_i$  and  $n_j$  of images  $i$  and  $j$  is the Normalised Cross-Correlation defined as

$$\rho(i, j) = \frac{(n_i - \bar{n}_i) \cdot (n_j - \bar{n}_j)}{\|n_i - \bar{n}_i\| \cdot \|n_j - \bar{n}_j\|} \quad (2)$$

where  $\bar{n}_i$  and  $\bar{n}_j$  are the means of  $n_i$  and  $n_j$ , respectively. In source device identification,  $n_j$  is a template SPN, usually obtained by averaging different SPNs extracted from a number of images

taken by the same device. If the similarity  $\rho(i, j)$  is greater than a given threshold, image  $i$  is classified as taken by device  $j$ . A commonly adopted threshold is 0.01 [1, 2, 5, 7, 9].

A challenging issue that affects the quality and reliability of SPN is the presence of edges and details in the scene, e.g., brick walls, tree leaves and other types of textured surfaces. Such details appear as high-frequency components in the *DWT* domain of the image, whose magnitude is typically greater than that of sensor pattern noise by many orders of magnitude, thus distorting the quality of the extracted SPN. Figure 2 illustrates a good example. Figure 2(a) is an image without details and Figure 2(b) is the sensor pattern noise extracted from Figure 2(a) using the method of [1]. Because there is no significant details in Figure 2(a), the intensity of the extracted SPN is minute. However, if the image contains significant details such as Figure 2(c), the extracted SPN, as shown in Figure 2(d), will contain those details (i.e., the SPN is contaminated by those details). Therefore, forensic investigations based on contaminated SPNs are likely to be questionable. We addressed this issue in a previous work [2] using an effective SPN enhancer that attenuates the interference of scene details. The enhancer is based on the underlying hypothesis that strong SPN signal components are not trustworthy, as it is more likely that they are created by high-frequency details. Following this hypothesis, an enhanced SPN can be obtained by assigning weighting factors inversely proportional to the magnitude of the signal components. The reader is referred to [2] for further details about the SPN enhancer.

### **3. Anomaly Reported in Previous Work**

Matching two SPNs through Eq. (2) can be performed by considering only a block of the image, e.g. a block of  $256 \times 256$  or  $512 \times 512$  pixels. Using bigger blocks leads to higher performance, while the use of smaller blocks reduces the computational complexity and speeds up the matching

process. In [2], the performance of the SPN enhancer was compared to that of the method in [1] in the task of source camera identification, with various block sizes considered. On one hand, results reported in [2] confirm the effectiveness of the SPN enhancer-based approach and its superiority to the method in [1]. On the other hand, both methods show an anomaly in the changes of false positive rates with respect to block sizes (See Table 1). Table 1 reports the device identification performance of both methods. We use M1 to stand for the method of [1] and M2 to stand for our proposed SPN enhancer [2]. It can be seen that the false positive rate initially decreases as the size of the image block is greater, reaches the minimum when the block size is  $1024 \times 1024$  pixels, then increases significantly afterwards. This anomaly (i.e., the decreasing false positive rates with respect to the decreasing block size when the blocks sizes are greater than  $1024 \times 1024$  pixels) is particularly clearer for the case without enhancement (i.e., M1). After applying other values of the similarity threshold (0.005, 0.015, 0.02, 0.025 and 0.03), we still observed the same anomaly.

We could not explain the cause of this anomaly at the time of writing [2]. But our recent study into the *vignetting effect* (i.e., reduction of brightness at the peripheral areas of images) in optics and photography [20 - 22] has pointed us to the possibility that vignetting may have a role in distorting the sensor pattern noise in a *location-dependent* manner. Our experiments, to be presented in Section 5, reveal that source camera identification based on SPN blocks taken from locations near the centre of the image produce lower false positive rates, while blocks from the periphery lead to significantly higher false positive rates. This fact has confirmed that the quality of the sensor pattern noise exhibits the similar location-dependent characteristic as that of the vignetting effect. Although without further in-depth research, it is difficult to definitively conclude that such a location-dependent SPN quality variation is due to the vignetting effect, we would like to

- 1) present our finding of this location-dependency of SPN quality and

- 2) recommend that the image borders be avoided if only portions / blocks of the full-size images are needed for forensic applications.

We also hope that this work will facilitate further discussions over the possible connection between the vignetting effect and the location-dependent SPN quality degradation in order to gain better understanding of SPN characteristics. A brief review of the vignetting effect is presented in the next section.

## 4. Vignetting

Vignetting is the location-dependent reduction of brightness in optics and photography at the peripheral areas of photos. Brightness is higher in the centre of the images and falls off gradually towards the edges (see Figure 3 for an example). Vignetting can often be seen in photographic portraits that usually are clearer in the centre and fade off at the periphery. It may also be added in post-production, as it is perceived as pleasant in certain kinds of photographs. However, camera settings and lens design are the main physical causes of the vignetting effect. Four main types of vignetting exist, each due to a different reason [24]:

- **Optical vignetting.** This type of vignetting is inherent in the lens design and is due to the physical aperture of a multiple element lens. Because the lens has a length, the on-axis light from the scene (corresponding to the image centre) impinges the lens spot-on while the off-axis light (corresponding to image periphery) may be blocked by the lens body. As a result, the effective entrance pupil for the off-axis incident light is reduced, making the image edges appear darker than the image centre.

- **Natural vignetting.** Also known as natural illumination falloff, natural vignetting is caused by the different angles at which the light strikes on different locations of the sensor array. The path from the rear end of the lens (the exit pupil) to the edges of the sensor is longer than to the centre of the sensor. Therefore, light has to travel longer. The longer the journey is, the greater the loss of light intensity. According to the so-called "cosine fourth" law of illumination falloff, the loss of intensity is proportional to  $\cos^4 \theta$ , where  $\theta$  is the angle of the incident light on the sensor array. With a zoom lens, the natural vignetting effect is generally inversely proportional to the focal length.
- **Pixel vignetting.** It is caused by the differences in the incident angle of the photons in respect to pixels sensor elements. Photons striking perpendicularly on a sensor element produce stronger signals than photons hitting it at an oblique angle. This angle-dependence of the sensor response also contributes to the falloff of brightness towards the edges of images.
- **Mechanical vignetting.** This is due to the use of inappropriate attachments to the lens, such as thick or stacked filters, secondary lenses and misaligned lens hoods that partially block the light path.

Based on the above discussions, we can see that both vignetting effect and false positive device identification rates increase with respect to the distance of the sensor elements / image pixels from the centre of images. As such, we expect that the vignetting effect is likely to be the cause (or one of the main causes) of the location-dependent SPN quality variation.

## 5. Empirical Investigations

We conducted a series of experimental investigations to assess: i) the location dependency of SPN quality and ii) its implications in a practical task: source camera identification. The results are presented in Sec. 5.1 and Sec. 5.2, respectively. Note that, as we can see from Table 1, the anomalous changes of false positive rates are more evident when M1 is applied and thus can better facilitate our discussions. Therefore, we will use M1 in our experiments to extract the SPN.

### 5.1. Location-dependent quality of sensor pattern noise

In the first set of experiments, we evaluated the *inter-camera* (i.e., *inter-class*) similarity of the SPN with respect to the location of the block from which the SPN is obtained. The rationale behind this set of experiments is that higher quality SPNs should exhibit a lower *inter-camera* similarity, i.e. they should be more different from each another.

To analyse the quality of SPN without the influence of scene details, we used 300 photos of blue sky in JPEG format taken by 6 different cameras, each responsible for 50. The JPEG quality factors of the images range approximately from 93% to 97%. The 6 cameras ( $C_1$  to  $C_6$ ) are Canon IXUS 850IS, Canon PowerShot A400, Canon IXY Digital 500, FujiFilm A602, FujiFilm FinePix A902 and Olympus FE210. The size of the images of all the cameras are  $1536 \times 2048$  pixels. The SPN of each camera was obtained as the average of 50 SPN, each from one image taken by the camera.

We divide each image into 192 ( $= 12 \times 16$ ) non-overlapping blocks of  $128 \times 128$  pixels. We then extracted the SPN from each block. For each camera  $C_i$ , and for each block location in the grid, we evaluated the average similarity between the SPN block extracted from  $C_i$  and the SPN block extracted from the other cameras  $C_j, j \neq i$ . The similarity between SPN blocks was obtained via the Normalized Cross-Correlation of Eq. (2). The average SPN similarity with respect to the block

position is shown in Figure 4 for all the cameras. In Figure 5, we also show the average inter-camera similarity with respect to the block position, as the average of the six plots in Figure 4.

As can be seen from Figure 4 and Figure 5, the SPN similarity shows a noticeable location-dependent behaviour. In particular, the average similarity between the SPN of different cameras tends to be higher when SPN blocks are taken near the borders, while it goes lower moving towards the centre of the image; in other words, the SPN tend to loose its “uniqueness” in peripheral locations of the image. This behaviour suggests that the SPN quality is distorted in a manner similar to the change of brightness of images due to vignetting effect as show in Figure 3. The degradation is particularly evident in the corners, where the highest inter-camera similarities are attained. This is consistent to our hypothesis that the location-dependent quality of SPN is caused by the vignetting effect, as the corners are the most affected locations of the image with respect to vignetting. Note that the inter-camera similarity of camera  $C_6$  shows a different behaviour: in fact, this camera shows low inter-camera similarities even in the borders, with the exception of the *upper-left* corner. This is most probably due to a better constructive quality that possibly allows  $C_6$  to handle vignetting better than the other cameras.

It is worth noting that, on average, the inter-camera similarity (Figure 5) is higher in the *upper* and *left* borders than in the *lower* and *right* ones (see Table 2, which shows the average inter-camera SPN similarity in the four borders), and maximum in the upper corners. This suggests that the quality degradation of the sensor pattern noise components is asymmetrical with respect to the centre of the image. Thus, the SPN quality does not necessarily vary isotropically.

The location-dependent behaviour shown above is likely to impact in all the forensics tasks involving SPN. In the next Section, we focus on the influence of the SPN block location in the task of [2], i.e. source camera identification.

## 5.2. Impact of SPN location dependency in source camera identification

Following the first set of experiments of Sec.5.1, in this Section we evaluate the impact of the location-dependent behaviour of SPN quality, in the task of source camera identification [1, 2, 5, 7, 9]. We used the same six cameras of Sect 5.1, and the same 300 photos, to extract a reference SPN block  $n_c$  of each camera  $c$ . As in Sec.5.1, the reference SPN of each camera was obtained by averaging 50 SPN, each from one image taken by the camera. We then extracted an SPN block  $n_i$  from each image  $i$  of a different data set of 1200 photos, taken by the same six cameras (each camera was responsible of 200 photos). These images contain various indoor and outdoor scenes and were shot at different hours of the day. The Normalised Cross-Correlation defined in Eq. (3) was used to measure the similarity between SPNs  $n_i$  of images  $i$  and the reference SPNs  $n_c$ :

$$\rho(i,c) = \frac{(n_i - \bar{n}_i) \cdot (n_c - \bar{n}_c)}{\|n_i - \bar{n}_i\| \cdot \|n_c - \bar{n}_c\|}, \quad c \in (1,6) \quad (3)$$

where  $\bar{n}_i$  and  $\bar{n}_c$  are the means of  $n_i$  and  $n_c$ , respectively. For each image block, if its similarity with any camera's reference SPN block was greater than 0.01, this image was deemed as taken by the camera. Note that each image could be labelled as taken by more than one camera depending on  $\rho(i,c)$ .

Similarly to the experiments of Sec.5.1, we changed the location at which the reference SPNs blocks  $n_c$  and the probe SPNs  $n_i$  blocks were extracted, by means of a regular grid. We carried out two experiments. In the first experiment (denoted as EXP\_512 in the following), we used a block of size 512 x 512 pixels, and moved the block from left to right and from top to bottom, with a displacement of 64 pixels. In total, 425 ( $= 17 \times 25$ ) different blocks were cropped. In the second experiment (denoted as EXP\_256 in the following), we set the block size to 256 x 256 pixels and

the displacement step to 32 pixels. In total, 2337 ( $41 \times 57$ ) different blocks are obtained from different locations.

In both experiments EXP\_512 and EXP\_256, for each block position, we evaluated the source camera identification performance. In particular, we measured the *false positive* rate (i.e., the percentage of incorrect assignments), since the anomaly reported in Sec.3 affected the number of false positives. The false positive rates with respect to the block position at which the SPN is extracted are shown in Figure 6 and Figure 7 for EXP\_512 and EXP\_256, respectively. As one can easily see, the same location-dependent behaviour that affects the inter-camera similarity of SPN (See Figure 4 and 5) arises in camera identification performance. This again demonstrates the close relationship between the vignetting effect and SPN quality.

The above results have conformed to our expectation that the SPN quality is indeed location-dependent and it is degraded to a greater extent at the image periphery. Furthermore, we showed that this behaviour influences the performance of source camera identification. As such, we can conclude that

- *This explains the anomaly reported in Table 3 of [2] (duplicated as Table 1 in this work).* When full-size images ( $1536 \times 2048$  pixels) are used for device identification, although more data is involved to help with the identification, the SPN components of poor quality along the image borders are also included, which out-weigh the benefit of using the whole image. By comparing the figures in Table 1, we can see that when only blocks of  $1024 \times 2048$  pixels taken from the image centre are used, the false positive rate drops from 12.03% (when the full-size images are use) to 2.4%. This is because the 256 rows at the top edge and the 256 rows at the bottom edges have been excluded. So even though only 66.67 % ( $= 1024 / 1536$ ) of the original pixels are used, the exclusion of the SPN

components of poorer quality at the periphery allows better performance to be gained. This trend continues as the blocks size is further reduced down to  $1024 \times 1024$ . This time not only the 512 rows at the periphery, but also the 1024 columns at the image periphery are excluded. However, when the block size is further reduced down to  $512 \times 1024$ , the false positive rates start to increase, indicating that the SPN components of poor quality have been sufficiently excluded and the identifier is starting to suffer from the lack of useful data (i.e., SPN components of better quality).

- In forensics applications wherein smaller image blocks are required (e.g., blind classification of large image datasets [6-8]), *it is advisable that blocks are taken from the image centre.*

## 6. Conclusions

Sensor pattern noise carries a high potential in digital forensic applications. Therefore, it is important to better understand its characteristics and their impact on the accuracy of the information / evidence drawn from forensic analysis. In a previous work, we observed a counter intuitive situation that full-size images or image blocks closer to the image periphery tend to give rise to higher false positive rates when used for source camera identification. In this work, starting with the assumption that this anomaly might be related to the vignetting effect due to the lens/sensor design and/or camera settings, we have carried out a series of experiments to see if significant performance discrepancy can be found when the SPN from peripheral blocks and inner blocks are used. The experiments have confirmed that, like the vignetting effect, the SPN quality is indeed location-dependent and explained the cause of the anomaly. Based on the experimental results, our recommendations for the digital forensics communities are:

- Excluding the peripheral pixels of images before the SPN is extracted for source camera identification and linking,
- Taking the blocks from the centre when only small blocks are needed in the applications (e.g., image classification),
- Exercising cautions when dealing with blocks along the image periphery, when block-based integrity verification is to be carried out.

It is our aim in this work to facilitate further discussions and in-depth study into the characteristics of the SPN. Our future work will include a more thorough investigation into the relationship between the vignetting effect and SPN quality, as well as devising models and methods to quantitatively assess the quality of the components of sensor pattern noise.

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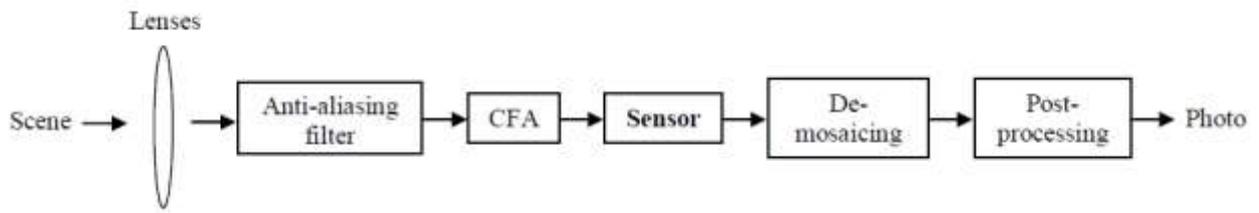


Figure 1. The process of image acquisition that takes place in a typical digital camera.

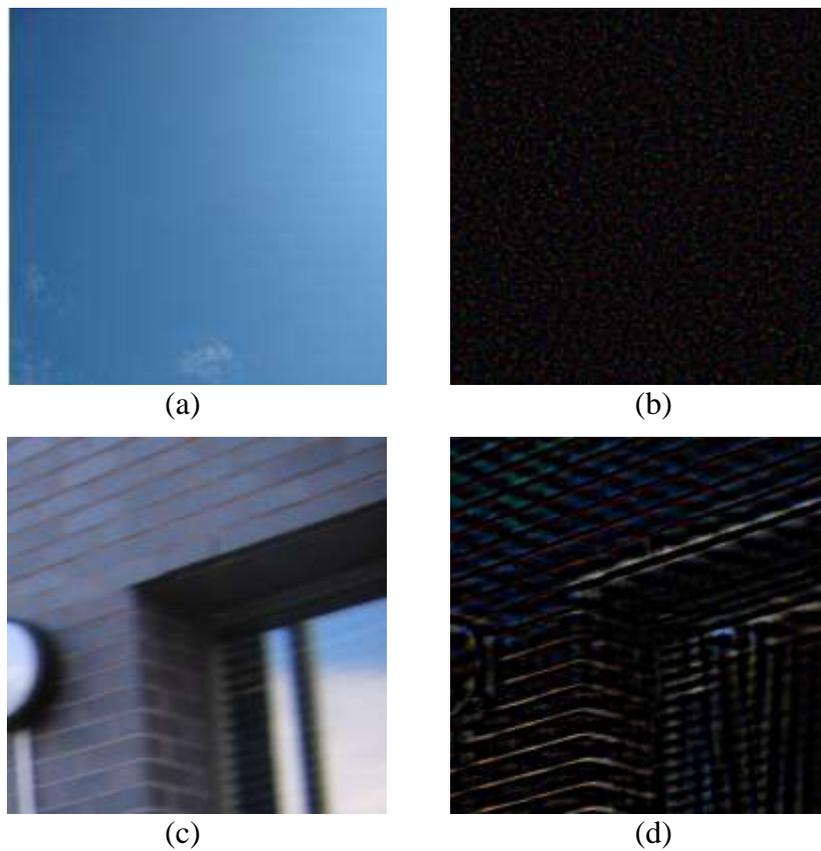
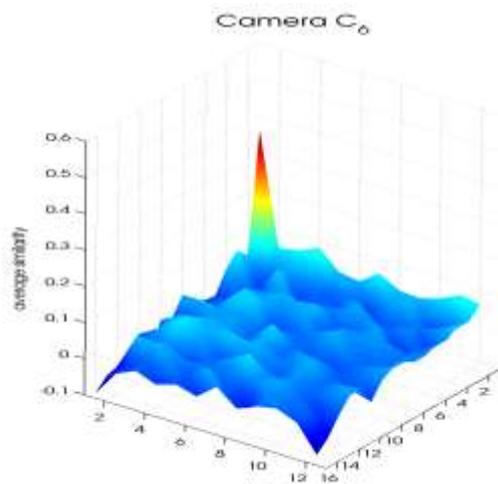
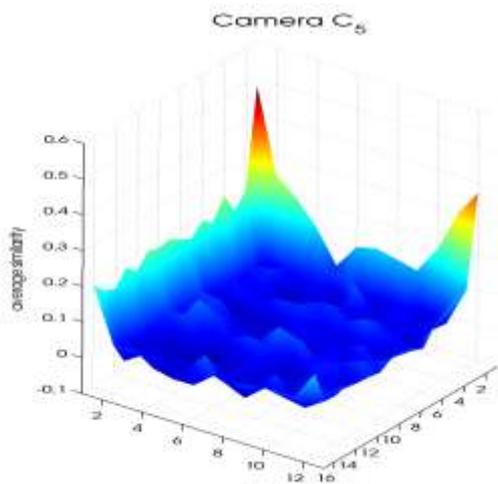
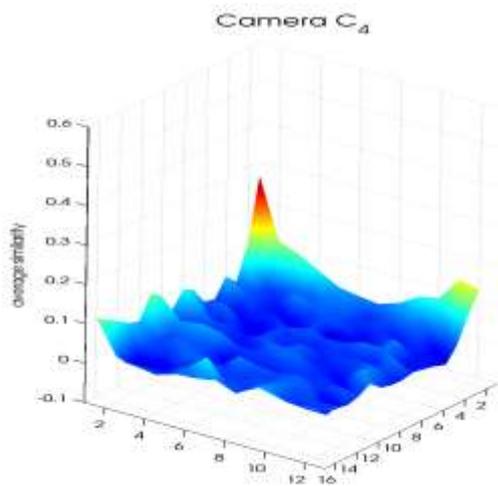
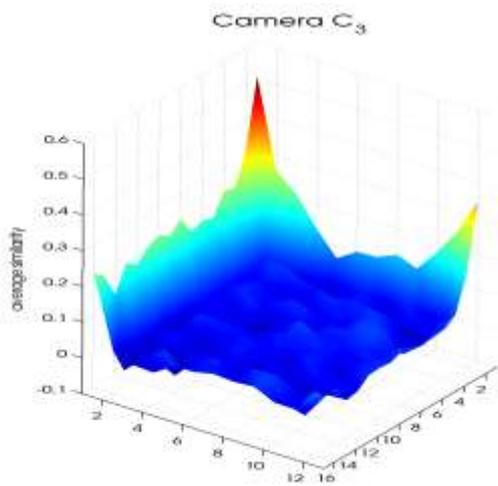
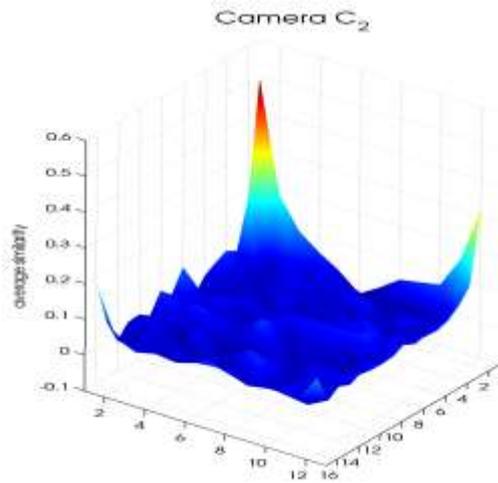
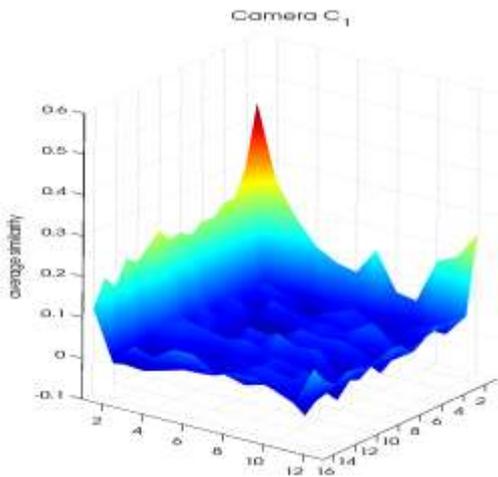


Figure 2. a) An image without details; b) the sensor pattern noise extracted from a); An image with significant details; d) sensor pattern noise extracted from c).



Figure 3. An image affected by vignetting effect. The brightness at the centre of the image is greater than that at the periphery.



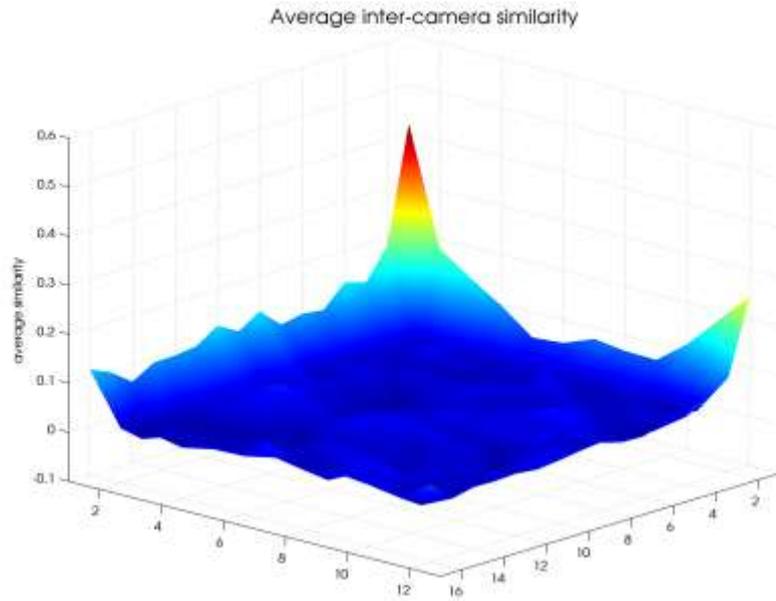


Figure 5. Average inter-camera similarity, measured in terms of Normalised Cross-Correlation, of the SPN, as a function of the SPN block position. The  $x$  and  $y$  axes represent the block position with respect to a 12 x 16 regular grid used to subdivide the image.

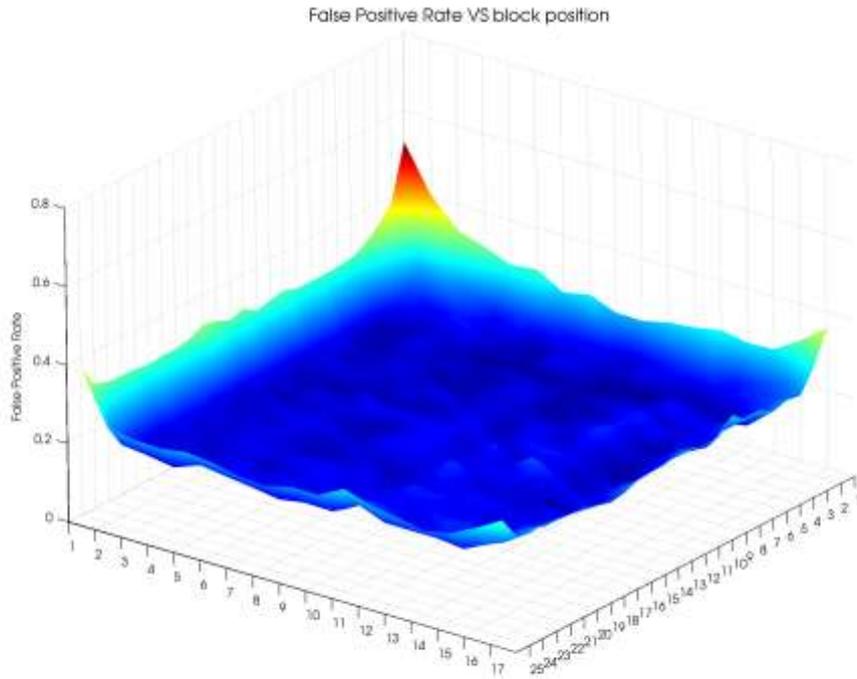


Figure 6. EXP\_512: false positive rate as a function of the position at which the SPN block is extracted, with respect to a 17 x 25 regular grid, and blocks of 512 x 512 pixels.

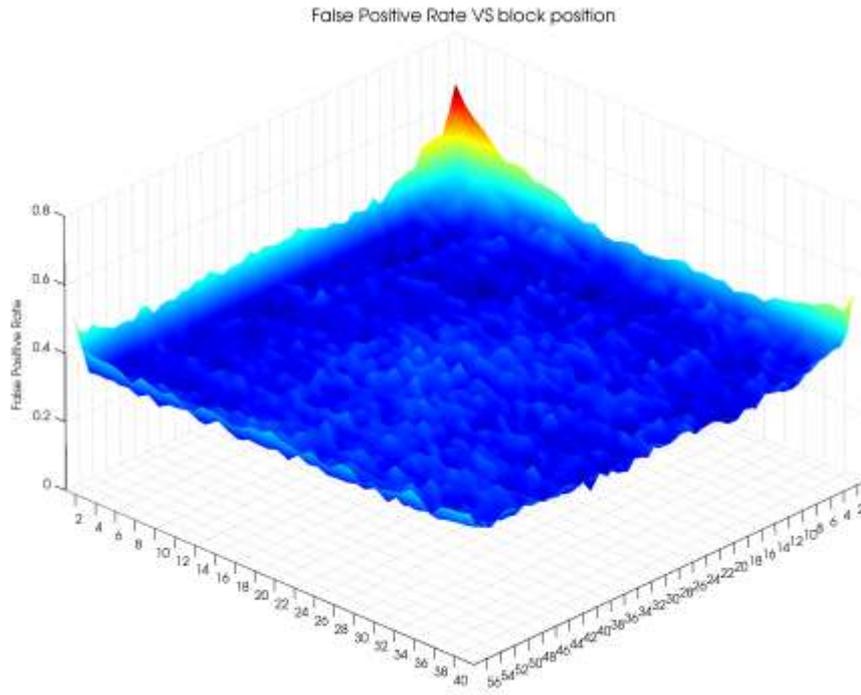


Figure 7. EXP\_256: false positive rate as a function of the position at which the SPN block is extracted, with respect to a 41 x 57 regular grid, and blocks of 256 x 256 pixels.

Method	False positive rate (%) associated with blocks of various sizes								
	128 ×128	128 × 256	256 × 256	256 × 512	512 × 512	512 ×1024	1024 ×1024	1024 ×2048	1536 ×2048
<b>M1</b>	41.68	38.68	32.60	25.71	16.28	6.75	1.90	2.40	12.03
<b>M2</b>	8.33	3.22	0.95	0.15	0.03	0	0	0.03	0.4

Table 1. False positive rates with (M2) and without (M1) applying the SPN enhancer of [2] to the sensor pattern noises extracted with the model proposed in [1]. Note that, in this experiment, the image is deemed as taken by the cameras that are not the source camera if their similarity values are greater than a threshold 0.01. The photos contain a variety of natural indoor and outdoor scenes taken during holidays, around campus and cities, in offices and laboratories, etc.

Average SPN similarity (Normalised Cross-Correlation)				
upper border	left border	lower border	right border	Centre
0.1278	0.1404	0.0498	0.0301	0.0047

Table 2. Average inter-camera similarity of SPN in the four image borders, and in the image centre.