Anti-camera LED Lighting

Xiao Shu
McMaster University
shux@mcmaster.ca

Xiaolin Wu
Shanghai Jiao Tong University
xwu510@sjtu.edu.cn

Qifan Gao
Shanghai Jiao Tong University
gaoqifan@sjtu.edu.cn

ABSTRACT

This work is concerned with the protection of intellectual property rights and privacy against unpermitted uses of digital cameras. A technique of multispectral coded illumination (MSCI) with LED lights is proposed to defeat cameras capturing indoor scenes by inducing annoying color artifacts into the acquired images or video frames. The main idea of MSCI is to temporally modulate LED lights of different colors at certain frequencies so that they interfere with the rolling shutter of the camera, but at the same time the coded illumination appears to human eyes the same as steady white lighting.

CCS CONCEPTS

• **Social and professional topics → Digital rights management**; • **Computing methodologies → Image and video acquisition**;

KEYWORDS

Camcorder piracy, copyright protection, digital right management, display technology, human vision

1 INTRODUCTION

Digital cameras have long become ubiquitous in today's data-rich and highly-interactive societies. They make people's lives, both private and public, more convenient, more enjoyable, and safer in countless ways. However, like any other technology that can profoundly touch humanities, digital cameras can be intrusive to personal privacies, or be downright abused to misappropriate information by taking pictures knowingly or stealthily against others' will. Such risks are real and present as advanced technologies have shaped digital cameras in miniature forms, wearable, and in various disguises.

A telling and familiar example is that museums all over the world are fighting an uphill battle to enforce no-photo policies for the protection of copyrights. Nowadays, with digital cameras accompanying just about everyone, people have an irresistible urge to take pictures of anything of interests, an act that photography critic Jörg M. Colberg describes as "compulsive looking", "the act of photography might have turned into the equivalent of whistling a song, something you do". In this case, rather than monitoring and restricting a habitual behavior of masses, a more effective solution is to make cameras ineffective. If a technology can make the acquired images of museum exhibits so poor a quality that they are practically useless, then it will spoil the appetite of those snatching pictures in museums and eventually rectify a bad habit.

Following the motivation above to defeat cameras, we approach the problem from a new angle, and investigate if and how the light sources that illuminate the exhibited object can be manipulated in ways to introduce severe artifacts into the acquired photographs, but at the same time the manipulated light sources cause no perceivable artifacts to human vision. The main technical challenge is that the anti-camera lighting is not allowed to alter the appearance of the exhibit. The key to conciliate the above two conflicting requirements is to exploit the differences between the optoelectronic camera system and the human visual system (HVS) in the mechanism of image formation. Two critical differences between cameras and eyes (the optoelectronic vs. the physiological mechanisms of imaging) give us a grip on the problem. First, the photoreceptors of human eyes sense optical signals continuously in time, whereas the semiconductor light sensors of digital cameras have to periodically stop sensing during the data read-out cycle. Second, the entire retina of human eyes is exposed to lights, whereas for rolling-shutter cameras (almost all cameras use rolling shutter) the semiconductor image sensors are exposed to lights in successive rows, with a slight delay in time from one row to the next. Working these differences carefully, we craft a novel technique of multispectral coded illumination (MSCI) and develop an MSCI-based anti-camera LED lighting system that can cause malfunctioning of cameras while being perceptually transparent.

Besides in museums, the proposed MEM anti-camera LED lighting system is suited to protect copyrights, intellectual properties and privacy in all indoor venues, or whenever artificial lighting is required in the exhibition. Its applications include live performing arts, court proceedings, demonstration of new products or research prototypes, auctions, etc.

The remainder of the paper is structured as follows. Section 2 is a brief survey of existing techniques for copyright protection against unauthorized using of cameras. In Section 3 we model and analyze the inferences and artifacts caused by flickering lights in camera-acquired images. Based on the above analysis we introduce our MSCI-based anti-camera LED lighting system in Section 4. Section 5 presents and discusses the experimental results. Section 6 concludes.

This research is supported by National Natural Science Foundation of China (NSFC 61331014) and International S&T Cooperation Program of China (ISTCP 2015DAG12050).

MM'17, , October 23–27, 2017, Mountain View, CA, USA.

ACM ISBN ISBN 978-1-4503-4906-2/17/10…$15.00
https://doi.org/10.1145/3123266.3123416

2 PREVIOUS WORK

Although nothing was published, to our best knowledge, on defeating unauthorized cameras in venues of public exhibitions and life performances, a large body of research and patent literature exists on copyright protection and digital right management of displayed image/video contents [2, 5, 6, 11, 13, 15, 21, 23, 25]. In particular, the movie industry has made significant investments in technologies against camera/camcorder piracy in theaters.

As a forensic means in prosecution against privacy, many watermarking methods have been proposed to fingerprint copies of digital multimedia contents for the purpose of identifying the sources of the piracy activities. For instance, visually transparent fingerprint information can be embedded in movies at the stage of production or projection. Although invisible to naked eyes, these fingerprints can be extracted from the recorded copies of the protected movies and used to identify the source screen. The Coded Anti-Piracy (CAP) is such a watermarking approach adopted by movie business to trace individual copies, whether legal or pirated. Kodak, Technicolor, Deluxe Laboratories and Phillips have made significant technical contributions to CAP [1].

However, as forensic means the watermarking techniques cannot directly defeat or discourage unauthorized uses of cameras. In digital cinema applications, various techniques have been developed to jam cameras by emitting interference lights that can degrade the visual quality of unlawfully acquired videos but at the same time are invisible to theater audience. An early and simple solution is to emit infrared lights towards the pirating cameras [7, 19, 22]. The infrared lights, while being unperceivable to human eyes, can ruin the pirated images because they can trigger many semiconductor imaging sensors (e.g., CMOS and CCD). But this simple camera jamming trick can be easily neutralized by installing a suitable filter on the camera lens. A more robust spectrum-based approach is to use with spectral combinations that appear identical to human but different to camera [6]. However, as the gap between the color sensitivities of a camera and a human eye is getting smaller with the latest image sensor technologies, the effectiveness of spectrum-based techniques has become limited.

Another approach of fencing off pirate cameras is spatiotemporal modulation of image signals at the stage of display [3, 4, 8, 10, 12, 14, 18, 20]. One possible attack is to create temporal aliasing artifacts in the pirated videos by adding a sinusoid signal to the displayed videos in temporal domain [5]. If the frame rates of the camcorders mismatch the frequency of the sinusoid, the captured videos will be plagued by flickering artifacts. Zhai and Wu proposed to exploit the difference in image formation mechanism between human eyes and imaging sensors in the development of camera jamming techniques [24]. They developed an anti-piracy technique based on temporal psychovisual modulation [9]. However, as this technique needs to decompose an image into two or more atom frames (basis images) and display them at a frame rate that is at least twice as high as the flicker frequency, it cannot be used in the application scenario of this papers: defeating unauthorized cameras that shoot real world objects or live performances.

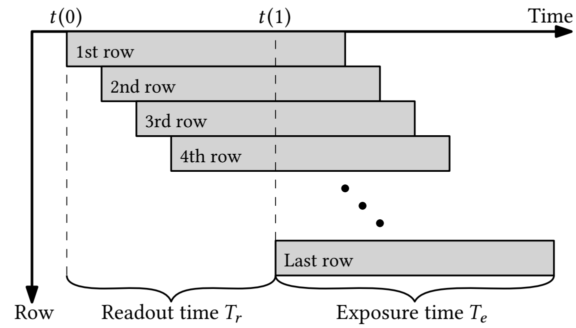


Figure 1: Most digital cameras capture an image by scanning the target progressively row by row from top to bottom.

3 INTERFERENCE MODEL OF FLICKERING LIGHT

It is well known that, despite being largely invisible to human eyes, the flicker of an alternating current (AC) powered lamp could interfere the image formation in a camera and leave trace of horizontal stripes in captured videos. To alleviate this problem, most video cameras ask user for the local power line frequency so that they can adjust exposure parameters accordingly to minimize the adverse effects of a flickering light source. The objective of this study is exactly the opposite; we want to maximize the interference in order to deter the unauthorized uses of digital cameras. In this section, we model the formation of these interference effects mathematically and analyze the factors affecting the strength and appearance of the objectionable artifacts.

3.1 Imaging Model

In an image captured by a digital camera, the intensity $I(i,j)$ of each pixel is the total amount of the light received by the pixel during exposure time T_e, i.e.,

$$I(i,j) = \int_{t(i)}^{t(i)+T_e} L_{i,j}(t)\,\mathrm{d}t, \tag{1}$$

where $t(i)$ is the starting time of exposure for pixel (i,j), and $L_{i,j}(t)$ is the light intensity at time t. During the exposure of an image, most digital cameras scan the scene progressively in a row-by-row fashion from top to bottom as illustrated in Fig. 1. Therefore, for a row indexed by $i \in [0,1]$ on the image sensor, the start time $t(i)$ of exposure are identical for all pixels in the row and can be estimated as,

$$t(i) = t(0) + iT_r, \tag{2}$$

where $T_r = t(1) - t(0)$ is the starting time difference between the exposures of the top and bottom rows. For cameras equipped with electronic shutter, T_r is equal to the time required to read all pixel values from sensor, hence T_r is also commonly referred as readout time [16, 17].

To simplify the analysis, we assume that the imaged object is a large white wall which diffuses light uniformly. Then, the light intensity $L_{i,j}(t)$ of a pixel at time t is determined only by the intensity of the illumination source. If the intensity of the light changes periodically over time with period T, then function $L_{i,j}(t)$ can be

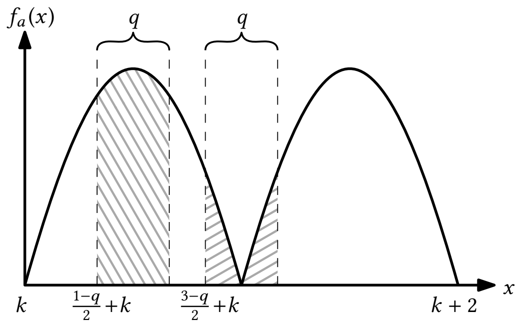


Figure 2: A plot of periodic intensity function f_a, where k is an arbitrary integer. The shaded regions show when the definite integral of f_a over a region of width q reaches the maximum and minimum.

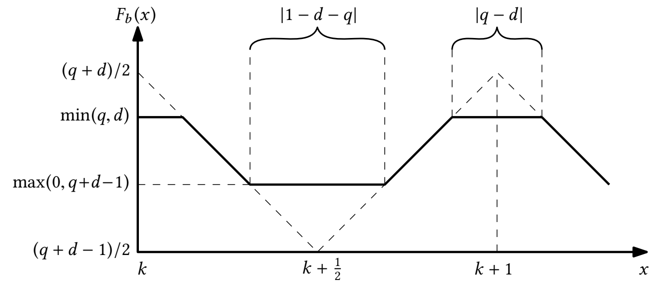


Figure 3: A plot of function F_b, where k is an arbitrary integer. Function F_b is a clipped triangle wave whose maximum and minimum values are $\min(q,d)$ and $\max(0,q+d-1)$, respectively.

formulated using a periodic intensity function f of unit period and amplitude as follows,

$$L_{i,j}(t) = A \cdot f(\varphi + t/T), \tag{3}$$

where A, φ are the amplitude and phase of the light source, respectively. By combining Eqs. (1), (2) and (3), we can calculate the intensity $I(i,j)$ of a pixel as,

$$\begin{aligned} I(i,j) &= \int_{t(i)}^{t(i)+T_e} A \cdot f(\varphi + t/T)\,\mathrm{d}t \\ &= A \int_0^{T_e} f(\varphi + t(i)/T + t/T)\,\mathrm{d}t \\ &= AT \int_0^{T_e/T} f(\hat{\varphi}(i) + x)\,\mathrm{d}x, \end{aligned} \tag{4}$$

where $\hat{\varphi}(i) = \varphi + t(0)/T + iT_r/T$. Now let p, q be the integer and fractional parts of the ratio of camera exposure time T_e to light flickering period T, respectively, i.e.,

$$p = \lfloor T_e/T \rfloor, \tag{5}$$

$$q = T_e/T - p. \tag{6}$$

Since f is a periodic function of period 1, we have

$$\begin{aligned} I(i,j) &= AT \int_0^{p+q} f(\hat{\varphi}(i) + x)\,\mathrm{d}x, \\ &= ATp\bar{f} + AT \int_0^q f(\hat{\varphi}(i) + x)\,\mathrm{d}x, \end{aligned} \tag{7}$$

where $\bar{f}$ is the mean of function f, i.e.,

$$\bar{f} = \int_0^1 f(x)\,\mathrm{d}x. \tag{8}$$

3.2 Interference by AC Powered Lamp

For an AC powered incandescent Lamp, its periodic intensity function $f_a(x) = |\sin(\pi x)|$ is a full-wave rectified sinusoid. In a scene illuminated by such a light source, a camera with exposure time T_e captures $p+q$ periods T of the rectified sinusoid, where integer p and fraction q are defined in Eqs. (5) and (6). As shown by a plot of $f_a(x)$ in Fig. 2, the maximum intensity of any pixel in a captured image is,

$$\begin{aligned} \max_{i,j} I(i,j) &= ATp\bar{f}_a + AT \int_0^q \left|\sin\left(\frac{1-q}{2}\pi + x\pi\right)\right| \mathrm{d}x \\ &= \frac{2}{\pi}ATp + \frac{2}{\pi}AT\sin\left(\frac{\pi q}{2}\right), \end{aligned} \tag{9}$$

which occurs at pixels in row i such that $\hat{\varphi}(i) = (1-q)/2 + k$ for some integer k. Similarly, the minimum intensity of any pixel is,

$$\min_{i,j} I(i,j) = \frac{2}{\pi}ATp + \frac{2}{\pi}AT\left[1 - \cos\left(\frac{\pi q}{2}\right)\right], \tag{10}$$

when $\hat{\varphi}(i) = -q/2 + k$ for some integer k. As the mean intensity of the flickering light is $AT_e\bar{f}_a = AT(p+q)\bar{f}_a$, the intensity difference between the brightest and darkest pixels in relative to the mean intensity is,

$$\begin{aligned} D_a &= \left[\max_{i,j} I(i,j) - \min_{i,j} I(i,j)\right] \Big/ \operatorname*{mean}_{i,j} I(i,j) \\ &= \frac{1}{p+q}\left[\sin\left(\frac{\pi q}{2}\right) + \cos\left(\frac{\pi q}{2}\right) - 1\right]. \end{aligned} \tag{11}$$

Since the imaged subject is a uniform white wall, an ideal image of the scene should be uniform as well with the relative intensity difference $D_a = 0$, while images captured under a flickering light source might have extra interference patterns, resulting a non-zero D_a. In general, the larger the difference D_a is, the more prominent the interference effects become in the captured image. As the relative intensity difference D_a is 0 when $q = 0$ by Eq. (11), a camera can easily prevent the adverse effects caused by AC powered lamp by setting the exposure time T_e to be a multiple of flickering period T. For example, if the power line frequency is 60 Hz and the flickering frequency of AC powered lamp is 120 Hz, then the captured image is free of artifacts as long as the exposure time T_e is a multiple of 1/120 s.

3.3 Interference by Strobe Light

Half-wave rectified sinusoid like f_a is not the most effective periodic intensity function for inducing artifacts; a pulse train can lead to larger difference between the brightest and darkest pixels in the captured image due to its more concentrated energy in each period.

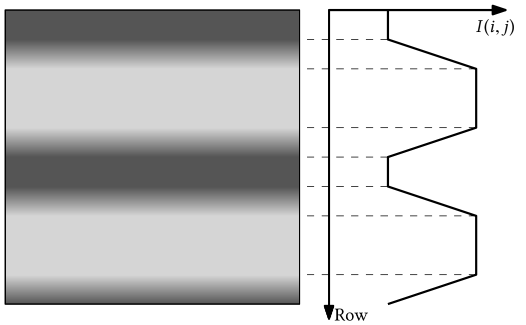


Figure 4: The interference artifacts in an image caused by strobe light are horizontal stripes with waveform like function F_b.

A pulse train $f_b(x)$ of duty cycle $d \in [0, 1]$ can be defined as follows,

$$f_b(x) = \sum_{k=-\infty}^{\infty} \mathrm{rect}(k + x), \tag{12}$$

where,

$$\mathrm{rect}(x) = \begin{cases} 1 & \text{if } |x| \le d/2 \\ 0 & \text{otherwise.} \end{cases} \tag{13}$$

The mean of function f_b is equal to its duty cycle d by Eq. (8). The definite integral of $f_b(x)$ from x_0 to $x_0 + q$ is a clipped triangle wave function F_b of x_0 as follows,

$$\begin{aligned} F_b(x_0) &= \int_0^q f_b(x_0 + x)\,\mathrm{d}x \\ &= \max(\min(g(x_0)+(q+d-1)/2, q, d), \\ &\qquad 0, q+d-1), \end{aligned} \tag{14}$$

where,

$$g(x) = \sum_{k=-\infty}^{\infty} \mathrm{tri}(k + x), \tag{15}$$

$$\mathrm{tri}(x) = \max(1/2 - |x|, 0). \tag{16}$$

The waveform of function F_b is shown in Fig. 3.

By Eq. (7), the intensity $I(i, j)$ of a pixel illuminated by a light source with periodic intensity function f_b is,

$$\begin{aligned} I(i, j) &= ATp\bar{f}_b + AT \int_0^q f_b(\hat{\varphi}(i) + x)\,\mathrm{d}x \\ &= ATpd + ATF_b(\hat{\varphi}(i)). \end{aligned} \tag{17}$$

This result implies that the interfered image has horizontal stripes with waveform like function F_b, as demonstrated in Fig. 4. In such an image, the maximum intensity of any pixel is,

$$\begin{aligned} \max_{i,j} I(i, j) &= ATpd + AT \max_{i,j} F_b(\hat{\varphi}(i)) \\ &= ATpd + AT \min(q, d), \end{aligned} \tag{18}$$

when $\hat{\varphi}(i) = k$ for some integer k; and likewise, the minimum intensity of any pixel is,

$$\min_{i,j} I(i, j) = ATpd + AT \max(0, q + d - 1), \tag{19}$$

when $\hat{\varphi}(i) = k + 1/2$ for some integer k. Thus, as in Eq. (11), the relative intensity difference between the brightest and darkest pixels can be calculated as follows,

$$\begin{aligned} D_b &= \left[\max_{i,j} I(i, j) - \min_{i,j} I(i, j)\right] \Big/ \operatorname*{mean}_{i,j} I(i, j) \\ &= \frac{\min(q, d) - \max(0, q + d - 1)}{(p + q)d}. \end{aligned} \tag{20}$$

Similar to the previous discussion on the interference effects of a sinusoidal light source, the relative intensity difference D_b of the brightest and darkest pixels is also 0 when $q = 0$. Therefore, the trick of setting the exposure time T_e to be a multiple of flickering period T can still effectively remove the artifacts when the light source emits a train of pulses. However, this is under the premise that the camera has the knowledge of the flickering period T. If T is unknown to the camera, then q can be any real number in $[0, 1)$. Unless q is exactly 0, the relative intensity difference D_b is greater than 0, implying the existence of interference artifacts.

Now we analyze the average relative intensity difference D_b for different values of q. Suppose T_e/T is uniformly distributed between p and $p + 1$ for some non-negative integer p, then by the definition of D_b in Eq. (20), the expected value of D_b is,

$$\mathrm{E}[D_b] = \int_0^1 \frac{\min(q, d) - \max(0, q + d - 1)}{(p + q)d}\,\mathrm{d}q \tag{21}$$

Since,

$$\min(q, d) - \max(0, q + d - 1) = \begin{cases} q & \text{if } 0 \le q < \hat{d} \\ \hat{d} & \text{if } \hat{d} \le q < 1 - \hat{d} \\ 1 - q & \text{if } 1 - \hat{d} \le q < 1, \end{cases} \tag{22}$$

where $\hat{d} = \min(d, 1 - d)$, it can be shown that,

$$\begin{aligned} \mathrm{E}[D_b] &= -\log d - \frac{1 - d}{d} \log(1 - d) && \text{if } p = 0; \\ \mathrm{E}[D_b] &\approx \frac{1 - d}{p + 1/2} && \text{if } p \ge 1. \end{aligned} \tag{23}$$

In either of the two cases, the expected relative intensity difference $\mathrm{E}[D_b]$ is a monotonically decreasing function of duty cycle d, suggesting that d should be as small as possible to achieve the best interference effects. But decreasing duty cycle d adversely affects the overall brightness of the scene, forcing the camera to compensate by increasing exposure time T_e. As a result, $p = \lfloor T_e/T \rfloor$ must increase as well, canceling the benefit of a small d in boosting the expected relative difference $\mathrm{E}[D_b]$. For instance, if a camera adjusts exposure time T_e to keep the mean intensity $AT_e d$ a constant, say C, then for the case $p \ge 0$, $\mathrm{E}[D_b]$ is approximately,

$$\mathrm{E}[D_b] \approx \frac{1 - d}{T_e/T} = \frac{AT}{C}(1 - d)d, \tag{24}$$

which reaches the maximum at $d = 1/2$ rather than $d = 0$. In practice, the choice of d is subject to other factors such as the cost of the lighting system and the flicker fusion threshold of HVS.

4 ANTI-CAMERA SYSTEM

In this section, we present the design of our MSCI-based anti-camera LED lighting system. As discussed in the previous section, image captured by a digital camera can be interfered by an illumination source like a simple AC powered incandescent lamp or

LED strobe light, resulting horizontal patterns in the image. The key challenge in the design of the our lighting system is how to make the interference more effective and difficult to remove while keeping the emitted light natural and completely indistinguishable from the light of a regular lamp for human viewers. Furthermore, as it is impossible to know the exact exposure parameters of the camera or even whether an unauthorized camera is currently being used, the anti-camera system has extremely limited information to work with. Thus, with the same set of configurations, the system should be robust and able to work for as many different conditions as possible.

4.1 Design of Control Parameters

The proposed anti-camera lighting system illuminates the protected scene using high power LEDs driven by a pulsing signal. As LEDs are turned on and off almost instantly, the intensity of the light emitted by the LEDs can match the driving signal exactly. To achieve the desired interference effects, there are three control parameters that can be utilized: pulse amplitude A, period T and duty cycle d.

To a human viewer, the perceived brightness of the pulsing light source is positively correlated with Ad; to a camera, the mean intensity of light received by the image sensor is $AT_e d$, if the exposure time is T_e and the imaged subject is a uniform white wall. In most application environments that require an anti-camera system, such as, theater, museum, etc., the desired brightness setting of the light is governed by the preference of human viewers rather than the requirement of the system for maximizing its effectiveness. Therefore, although the proposed system is allowed to manipulate the pulse amplitude A and duty cycle d, it must maintain the product, Ad, a constant. Since more powerful LEDs and power supplies are required to realize large amplitude A, it is more cost-effective to increase duty cycle d first instead of A to achieve the same level of brightness.

With regard to the pulse period T of the proposed system, its design space is constrained by several factors. First, the flicker of a light source is imperceptible to human eyes only if the flickering frequency is above the flicker fusion threshold, which is about 60 Hz for the average human observer. Thus, to make the light source appear to be completely steady, the pulse period T must be always less than 1/60 s.

Second, the pulse period T must be small enough in order to corrupt the captured image with sufficient number of interference stripes. As the periodic intensity function f defined in Eq. (3) is of period 1, by the definition of $\hat{\varphi}(i)$ in Eq. (4),

$$\begin{aligned} f(\hat{\varphi}(i + T/T_r) + x) &= f(\varphi + t(0)/T + (i + T/T_r) \cdot T_r/T + x) \\ &= f(\hat{\varphi}(i) + 1 + x) \\ &= f(\hat{\varphi}(i) + x), \end{aligned} \tag{25}$$

where T_r is the readout time of the camera. Then by the formula of pixel intensity in Eq. (7), $I(i + T/T_r, j)$ is identical to $I(i, j)$, which means that the horizontal interference stripes repeat themselves every T/T_r rows. In other words, there are T_r/T stripes in the corrupted image. Thus, given the flickering period T of the light source and an image with interference stripes, we can estimate the readout time of the camera that takes the image by counting the number of stripes. For example, the readout times of iPhone 6s and 7 are about 1/51 s and 1/60 s, respectively, estimated by this method. Since T must be less than 1/60 s to hide the flicker from human eyes, an image captured by either of the two iPhones must have at least one complete stripe.

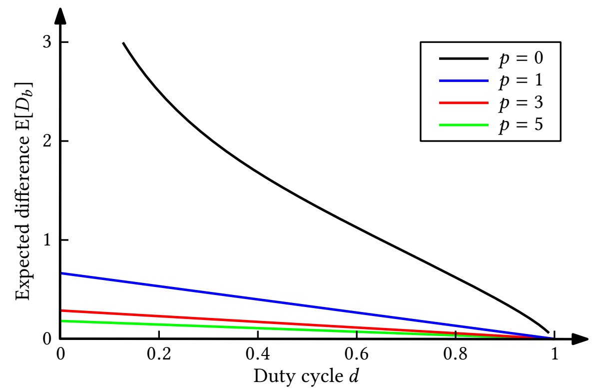


Figure 5: The expected relative difference E[D_b] between the brightest and darkest pixels caused by a pulse light source as a function of d, the duty cycle, and p, the ratio of T_e to T.

Cameras equipped with mechanical focal-plane shutter, like most digital single-lens reflex cameras (DSLRs), have much smaller rolling-shutter effect; their equivalent readout time, the exposure start time difference between the first row and last row as defined in Eq. (2), is commonly less than 1/400 s, half of the X-sync time. If the pulse period T is much longer than that, an image taken by a DSLR might capture only a flat part of the interference stripes as shown in Figs. 3 and 4, resulting no artifacts at all. Thus, T must be less than 1/400 s in order to defeat DSLRs. For video capture, as most consumer cameras and smart phones use electronic shutter in video mode, the readout time T_r is relatively long and is less of a constraint for the period T.

The third factor that affects the choice of T is the camera exposure time T_e. In the previous section, we analyze the expected relative difference $\mathrm{E}[D_b]$ between the brightest and darkest pixels due to the interference from a pulse light source as in Eq. (24). Plotted in Fig. 5 is $\mathrm{E}[D_b]$ as a function of duty cycle d for different floored ratios p of T_e to T. As shown by the figure, when $p = 0$ or $T_e < T$ by the definition of p as in Eq. (5), there is a large average relative difference $\mathrm{E}[D_b]$ between pixels, indicating outstanding interference patterns. In fact, some pixels might be captured in complete darkness if $q + d < 1$, as suggested by periodic intensity function $F_b(x)$ in Fig. 3, making the damage to resulting image unrecoverable. However, in a common indoor environment, the exposure time T_e set by the automatic exposure function of a camera is often greater than 1/60 s. Therefore, T_e is likely greater than T in our application scenario. In such a case where $p \geq 1$, if we want the expected relative difference to be greater than a threshold M, then by Eq. (24),

$$\begin{aligned} \mathrm{E}[D_b] = \frac{1 - d}{p + 1/2} &> M \\ 1 - M(p + 1/2) &> d. \end{aligned} \tag{26}$$

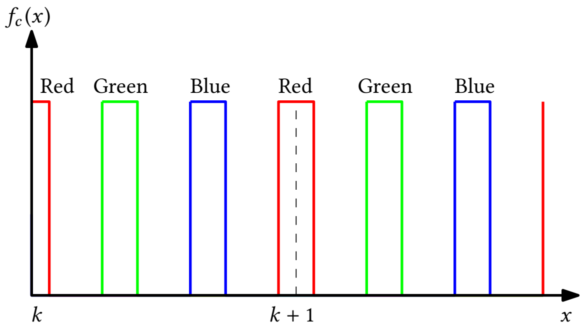


Figure 6: Period intensity function f_b is a pulse function with multiple colors. It switches the lights on and off in turns by their colors.

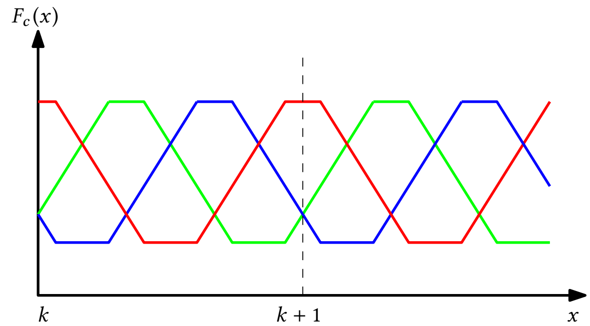


Figure 7: A plot of F_c, which is a definite integral function of f_c over range from 0 to 1.

For instance, if the expected relative difference must be greater than $M = 0.1$, and T_e can be 5 times greater than T, i.e., $p > 5$, then we should set the duty cycle d to be less than 45%.

4.2 Improving Robustness

With the growing popularity of LED lights driven by pulse width modulation (PWM), some cameras, like iPhone 7, have come with flicker detection sensor for reducing the interference caused by those flickering LED lights. If the pulse period T of the proposed anti-camera system is held constant as well, then the camera can easily detect its frequency. As discussed previously, once T is known, the camera can simply adjust exposure time T_e to be a multiple of T to eliminate the interference effects. To counter this countermeasure, the proposed system changes the pulse period within a given range randomly every second to prevent T being detected accurately. As a sudden large change of flickering frequency can be perceivable, the amplitude of each period change is limited within 20% of the previous T. Using this method, the transition between different periods is fully transparent to human viewers.

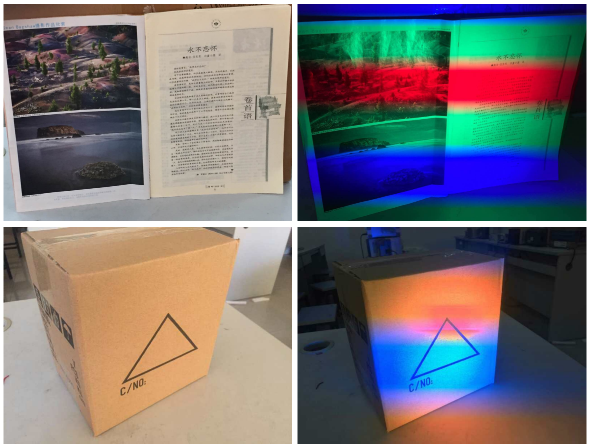
Another improvement to the proposed system is to employ RGB color LED lights in place of white light. By using a pulse signal of the same period but different phase to drive each of the three colors, the RGB lighting system switches the lights on and off in turns by their colors as in Fig. 6. Suppose for each color, the pulse period is T and duty cycle is d, then for all lights, the overall flickering period and duty cycle are $T/3$ and $3d$, respectively, hence the light intensity of the system is $3Ad$. To achieve the same level of light intensity using white lights, we need either more powerful LEDs and power supply that can support a pulse amplitude of $3A$, or a longer duty cycle of $3d$, which induces weaker interference effects than a duty cycle of d by Eq. (24). Therefore, with color lights, we can get strong interference effects in each color channel of the captured image without extra investment on the power supply hardware in comparison with the white lighting system.

As mentioned previously, the pulse period T needs to be short to defeat the very short readout time T_r of a DSLR, but small T also limits the strength of the interference effects as shown by Fig. 5. The RGB lighting system can greatly alleviate this dilemma. As the overall flickering period is only $T/3$, the RGB lighting system induces more stripes in the captured image than a flickering white light with pulse period T does, thus a camera with short readout time T_r can still be affected by this type of artifacts. Furthermore, in addition to intensity changes, the RGB lighting system also causes color shifting artifacts. As demonstrated by the definite integral of $f_b(x)$ over range from 0 to 1 in Fig. 7, there is no point in the integral function $F_b(x)$ where RGB three channels have the same intensity. Thus, even if there is no horizontal stripes due to $T_r = 0$, the color of the captured image is still corrupted by the interference.

Figure 8: The test platform for our experiments on the anti-camera lighting system.

5 EXPERIMENTAL RESULTS

To evaluate the design of our anti-camera lighting system, we implement the proposed technique with an array of high power RGB LED lights as shown in Fig. 8. The driving pulse signal for the LED lights is provided from a micro-controller. We use several different smart phones from various manufactures, including Apple iPhone 6s, 7, Samsung S6 and Xiaomi Mi5, to test the effectiveness of our technique. A mirror-less camera, Nikon 1 V3, is also used for the test. Fig. 9 presents a quick comparison of images of the same objects illuminated by an ordinary light and our anti-camera lighting system. As shown by the figure, the images captured under the proposed lighting system are plagued with colorful stripes. Short video clips of these two scenes are available in the supplementary material.



(a) Normal light **(b) Proposed system**

Figure 9: A comparison of images illuminated by an ordinary light and our anti-camera system.

Table 1: Flicker fusion threshold

	White			RGB
Duty cycle	30%	50%	70%	17%
Fusion frequency (Hz)	65.11	67	63.56	56.35
Standard deviation	3.06	3.16	2.96	2.26

To human observers, the flickering light from our system appears to be steady and is not different from the light emitted by an ordinary LED lamp. To find the design limits of our system, we invited 9 college students to look at a scene illuminated by our lighting system. The scene contains some small objects placed on a desk in front of a white wall. We programmed the system to change its pulse period T gradually and we asked the test subjects to report immediately if they notice any trace of flickering. Frequencies at which the test subjects start to notice flickering were then recorded. Table 1 shows the results. When the duty cycle changes from 30% to 70%, the flicker fusion threshold does not change much. Thus, as long as the pulse period is less than 1/70 s, the system can use any duty cycle in that range. For RGB lights, the frequency is measured in each color channel, hence the overall fusion frequency is three times of 56.35 Hz.

Shown in Figs. 10, 11, 12 and 13 are images captured under different light and camera settings, such as pulse period T, duty cycle d and exposure time T_e. The proposed anti-camera system can induce severe interference artifacts especially when the camera exposure time T_e is short. However, when T_e is a multiple of T as in Figs. 11a, 12g and 13g, the capture image is completely free of horizontal stripes.

6 CONCLUSION

The main technical challenge in the design of an anti-camera lighting system is that the lighting is not allowed to alter the appearance

(a) $d=10\%$, $T_e=1/60s$ **(b)** $d=30\%$, $T_e=1/60s$ **(c)** $d=50\%$, $T_e=1/15s$

(d) $d=50\%$, $T_e=1/30s$ **(e)** $d=50\%$, $T_e=1/60s$ **(f)** $d=50\%$, $T_e=1/125s$

(g) $d=50\%$, $T_e=1/250s$ **(h)** $d=70\%$, $T_e=1/60s$ **(i)** $d=90\%$, $T_e=1/60s$

Figure 10: Images of a white wall illuminated by the proposed system with white light flickering at period $T = 1/80s$.

(a) $T=1/120s$ **(b)** $T=1/220s$ **(c)** $T=1/350s$

Figure 11: Images of a white wall illuminated by the proposed system with white light, where $d=50\%$, $T_e=1/60s$

of the target. By exploiting the differences between the optoelectronic camera system and the human visual system (HVS) in the mechanism of image formation, our proposed lighting system can successfully interfere with the rolling shutter of the camera, but at the same time the coded illumination appears to human eyes the same as steady white lighting.

REFERENCES

[1] Darcy Antonellis, Jeffrey J Bartley, Margit Elisabeth Elo, Jean Pierre Gagnon, William B Hogue Jr, and Edward J Price. 2007. Motion picture anti-piracy coding. (April 17 2007). US Patent 7,206,409.

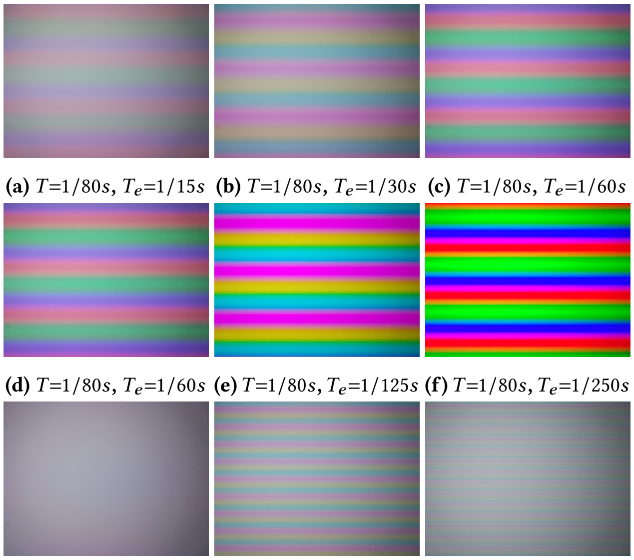
[2] SS Bedi, Rakesh Ahuja, and Himanshu Agarwal. 2013. Copyright Protection using Video Watermarking based on Wavelet Transformation in Multiband. *International Journal of Computer Applications* 66, 8 (2013).

[3] Laurent Blondé, Virginie Hallier, and Jonathan Kervec. 2011. Methods of processing and displaying images and display device using the methods. (March 1 2011). US Patent 7,899,242.

[4] Laurent Blondé, Olivier Le Meur, and Jonathan Kervec. 2006. Method and device for displaying images. (Sept. 5 2006). US Patent App. 11/991,189.

[5] Pascal Bourdon, Sylvain Thiebaud, and Didier Doyen. 2008. A theoretical analysis of spatial/temporal modulation-based systems for prevention of illegal recordings in movie theaters. In *Electronic Imaging 2008*. International Society for Optics and Photonics, 68190U–68190U.

[6] Pascal Bourdon, Sylvain Thiebaud, Jean-Jacques Sacré, and Didier Doyen. 2010. A metamerism-based method to prevent camcorder movie piracy in digital theaters. In *Multimedia and Expo (ICME), 2010 IEEE International Conference on*. IEEE,

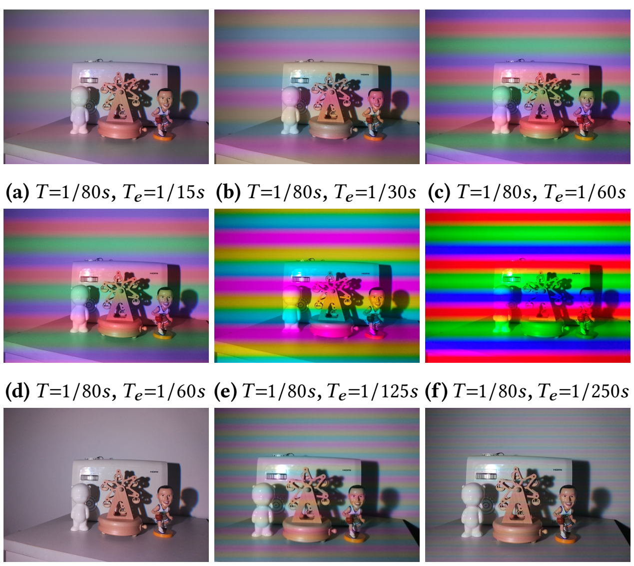


(a) T=1/80s, T_e=1/15s **(b)** T=1/80s, T_e=1/30s **(c)** T=1/80s, T_e=1/60s

(d) T=1/80s, T_e=1/60s **(e)** T=1/80s, T_e=1/125s **(f)** T=1/80s, T_e=1/250s

(g) T=1/120s,T_e=1/60s **(h)** T=1/220s,T_e=1/60s **(i)** T=1/350s, T_e=1/60s

Figure 12: Images of a white wall illuminated by the proposed system with RGB light, where d = 17%



(a) T=1/80s, T_e=1/15s **(b)** T=1/80s, T_e=1/30s **(c)** T=1/80s, T_e=1/60s

(d) T=1/80s, T_e=1/60s **(e)** T=1/80s, T_e=1/125s **(f)** T=1/80s, T_e=1/250s

(g) T=1/120s,T_e=1/60s **(h)** T=1/220s,T_e=1/60s **(i)** T=1/350s, T_e=1/60s

Figure 13: Images of some small objects illuminated by the proposed system with RGB light, where d = 17%

468–473.

[7] Herschel Clement Burstyn, George Herbert Needham Riddle, Leon Shapiro, and David Lloyd Staebler. 2008. Method and apparatus for film anti-piracy. (Jan. 29 2008). US Patent 7,324,646.

[8] Michael Epstein and Douglas A Stanton. 2003. Method and device for preventing piracy of video material from theater screens. (March 4 2003). US Patent 6,529,600.

[9] Zhongpai Gao, Guangtao Zhai, Xiaolin Wu, Xiongkuo Min, and Cheng Zhi. 2014. DLP based anti-piracy display system. In *Visual Communications and Image Processing Conference, 2014 IEEE*. IEEE, 145–148.

[10] Hiromi Harada, Terumasa Kayashima, and Tatsuhiro Nozue. 2000. Apparatus and method for displaying images. (June 6 2000). US Patent 6,072,476.

[11] Frank Hartung and Friedhelm Ramme. 2000. Digital rights management and watermarking of multimedia content for m-commerce applications. *IEEE communications magazine* 38, 11 (2000), 78–84.

[12] Louis S Horvath, James E Roddy, and Robert J Zolla. 2004. Imaging apparatus for increased color gamut using dual spatial light modulators. (May 18 2004). US Patent 6,736,514.

[13] Kensei Jo, Mohit Gupta, and Shree K Nayar. 2016. DisCo: Display-Camera Communication Using Rolling Shutter Sensors. *ACM Transactions on Graphics (TOG)* 35, 5 (2016), 150.

[14] Jonathan Kervec, Didier Doyen, and Laurent Blondé. 2006. Anti-copy image display device and method. *Eur. Patent EP* 1, 737 (2006), 224.

[15] Deepa Kundur and Kannan Karthik. 2004. Video fingerprinting and encryption principles for digital rights management. *Proc. IEEE* 92, 6 (2004), 918–932.

[16] Mingyang Li, Byung Hyung Kim, and Anastasios I Mourikis. 2013. Real-time motion tracking on a cellphone using inertial sensing and a rolling-shutter camera. In *Robotics and Automation (ICRA), 2013 IEEE International Conference on*. IEEE, 4712–4719.

[17] Chia-Kai Liang, Li-Wen Chang, and Homer H Chen. 2008. Analysis and compensation of rolling shutter effect. *IEEE Transactions on Image Processing* 17, 8 (2008), 1323–1330.

[18] David J Nelson. 2007. Projector with enhanced security camcorder defeat. (May 22 2007). US Patent 7,221,759.

[19] Christopher Odgers. 2004. Method for spoiling copies of a theatrical motion picture made using a video camera and recorder. (April 20 2004). US Patent App. 10/828,036.

[20] Robert Wilhelm Schumann, David G Grossman, and David Glenn DeGroote. 2005. Visual copyright protection. (Sept. 27 2005). US Patent 6,950,532.

[21] Hamid Shojanazeri, Wan Azizun Wan Adnan, and Sharifah Mumtadzah Syed Ahmad. 2013. Video watermarking techniques for copyright protection and content authentication. *International Journal of Computer Information Systems and Industrial Management Applications* 5 (2013), 652–660.

[22] William J Wrobleski. 2000. Method and system for preventing the off screen copying of a video or film presentation. (Jan. 25 2000). US Patent 6,018,374.

[23] Takayuki Yamada, Seiichi Gohshi, and Isao Echizen. 2010. Preventing re-recording based on difference between sensory perceptions of humans and devices. In *Image Processing (ICIP), 2010 17th IEEE International Conference on*. IEEE, 993–996.

[24] Guangtao Zhai and Xiaolin Wu. 2014. Defeating camcorder piracy by temporal psychovisual modulation. *Journal of Display Technology* 10, 9 (2014), 754–757.

[25] Lan Zhang, Cheng Bo, Jiahui Hou, Xiang-Yang Li, Yu Wang, Kebin Liu, and Yunhao Liu. 2015. Kaleido: You can watch it but cannot record it. In *Proceedings of the 21st Annual International Conference on Mobile Computing and Networking*. ACM, 372–385.