True color night vision correlated imaging based on intensity correlation of light

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Night vision imaging is a technology that converts non-visible object to human eyes into visible image in night and other low light environments. However, the conventional night vision imaging can only directly produce grayscale image. Here, we propose a novel night vision imaging method based on intensity correlation of light. The object’s information detected by infrared non-visible light is expressed by visible light via the spatial intensity correlation of light. With simple data processing, a color night vision image can be directly produced by this approach without any pseudo-color image processing. Theoretical and experimental results show that a color night vision image comparable to classical visible light imaging quality can be obtained by this method. Surprisingly, the colorfulness index of the reconstructed night vision image is significantly better than that of the conventional visible light image and pseudo-color night vision image. Although the reconstructed image can not completely restore the natural color of the object, the color image obtained by this method is more natural sense than that obtained by other pseudo-color image processing methods.

I. INTRODUCTION

Darkness is a non-visible barrier, which greatly limits the scope of human vision. In order to broaden the scope of human vision, night vision imaging has emerged. Night vision imaging is a kind of imaging technology, which can transform the non-visible scene into visible image by using photoelectric detection and imaging equipment under the condition of low light environments [1]. Night vision imaging technology, which like turning night into day, has greatly expanded human vision. Now, night vision imaging has been widely used in military reconnaissance, security monitoring, automobile assisted driving and other fields.

Since 1934, the first infrared image converter tube was invented by G. Holst et.al, night vision imaging technology has developed for nearly a century. Because of its irreplaceable role in military affairs, night vision imaging has been widely concerned since its birth. However, the conventional night vision imaging technology still has some insurmountable difficulties, e.g., the performance of infrared focal plane array (IRFPA) is quite lower than that of charge-coupled device (CCD) and complementary metal oxide semiconductor (CMOS); only grayscale image can be generated directly. Consequently, the imaging quality of night vision imaging is far from that of visible light imaging.

In this letter, we propose a novel night vision imaging method. In theory, this method is based on the second-order intensity correlation of light field [2-7]. In the experiment, one infrared laser and one visible laser are coupled together to form a mixed laser beam that is modulated by a spatial light modulator (SLM). Then, the modulated light is separated into two beams by a dichroic mirror (DM). The infrared laser illuminates the object and the reflected power is collected by a photomultiplier tube (PMT). The visible laser does not interact with the object and is directly detected by a conventional CCD camera. One monochromatic image is reconstructed by cross-correlating the output signals of the two detectors. Thus, the object’s information detected by infrared non-visible light is expressed by visible light via intensity correlation of light. Similarly, the other monochromatic image can be produced by another pair of infrared laser and visible laser. A colorful night vision image can be obtained via simple data processing. In fact, the image of the object is produced by the CCD rather than the PMT detector. Moreover, the IRFPA is not used in this method. Consequently, a night vision image with high quality comparable to classical visible light image can be produced by this method in theory.

Conventional night vision imaging techniques directly output grayscale images. Then, the grayscale night vision image is transformed into monochrome or color image by using image fusion processing to make it easier to observe [8-11]. In conventional color night vision imaging, image fusion processing and visible light reference image are essential [12-14]. However, a accurate visible light reference image can not be obtained in some environments, which reduces the effect of pseudo-color. In this approach, two monochromatic images can be directly output via two pairs of infrared laser and a visible laser. These two monochromatic images present different details and features of the object. Through simple data processing, a color night vision image can be directly produced without any pseudo-color image processing and visible light reference image.

II. THEORY

We depict the method of true color night vision imaging based on intensity correlation of light in Figure 1. Through the band-pass filters installed on two filter
wheels, the light illuminates on the SLM surface can be selected arbitrarily. In this scheme, only one wavelength visible laser and one wavelength infrared laser illuminate SLM at each time. For simplicity, we take an infrared laser $E_1$ and a visible laser $E_2$ as examples to illustrate the imaging process. The quasi-monochromatic infrared laser $E_1$ and the quasi-monochromatic visible laser $E_2$ are coupled together by DM3 to form a mixed beam. This mixed laser beam illuminates a SLM, and the modulated light is separated into two beams by DM4. The object is illuminated by an infrared laser, and the reflected light is detected by a PMT. The light detected by the PMT can be expressed as

$$E_1(x_{pmt}, t) = \int d\omega_1 dq_1 e^{-i\omega_1 t} V(q_1) E_1(\omega_1) H_1(x_{pmt}, q_1; \omega_1) T(x_o).$$

(1)

The quantities $x$ and $q$ represent transverse position and wave vector, respectively. The SLM produces spatial amplitude modulation of the light represented by the random spatial mask function $V(q)$, which is taken to be the same for $\omega_1$ and $\omega_2$ [15,16]. The functions $H_1$ is transfer function that describe propagation through the DM4 to PMT. The function $T(x)$ represents the object. The visible light reflected by DM4 does not interact with the object and is directly detected by a conventional CCD camera, which can be expressed as

$$E_2(x_{ccd}, t) = \int d\omega_2 dq_2 e^{-i\omega_2 t} V(q_2) E_2(\omega_2) H_2(x_{ccd}, q_2; \omega_2),$$

(2)

where the function $H_2$ describes propagation through the DM4 to CCD camera. For later convenience we subtract the background, which comes from the average intensities of light received by the PMT and the CCD by a DC block [17,18].

The object’s image is produced by measuring the intensity cross-correlation function [19,20]. We thus obtain

$$G(x_{ccd}, x_{pmt}; t) = \langle |E_1(x_{pmt}, t)|^2 | E_2(x_{ccd}, t)|^2 \rangle - \langle |E_1(x_{pmt}, t)|^2 \rangle \langle |E_2(x_{ccd}, t)|^2 \rangle$$

$$= \int d\omega_1 dq_1 d\omega_2 dq_2 \int d\omega_1 dq_1 e^{-i\omega_1 t} V(q_1) E_1(\omega_1) H_1(x_{pmt}, q_1; \omega_1)$$

$$\times \int d\omega_2 dq_2 e^{-i\omega_2 t} V(q_2) E_2(\omega_2) H_2(x_{ccd}, q_2; \omega_2)$$

$$\times e^{-i(\omega_1 - \omega_2)t} H_1(x_{pmt}, q_1; \omega_1) H_2(x_{ccd}, q_2; \omega_2)$$

$$\times C(\omega_1, \omega_1', \omega_2, \omega_2', q_1, q_1', q_2, q_2'),$$

(3)

where

$$C(\omega_1, \omega_1', \omega_2, \omega_2', q_1, q_1', q_2, q_2') = \left< E_1(\omega_1) E_1(\omega_1') \right> \left< E_2(\omega_2) E_2(\omega_2') \right>$$

$$\times \left< V(q_1) V(q_1') \right> \left< V(q_2) V(q_2') \right>$$

is the intensity cross-correlations function in the spatial and temporal frequency domain evaluated at the output surface of the SLM [15]. Here, the mask function $V(q)$ is taken to possess spatial correlations that follow Gaussian statistics [15,16]. Thus, the image expression can be rewritten as

$$G(x_{ccd}, x_{pmt}) = I_1 I_2 \int dx_{ccd} dx_{pmt} W(x_{ccd}, x_{pmt}; \omega_1)$$

$$\times H_1(x_{pmt}, x_{ccd}; \omega_1) H_2(x_{ccd}, x_{ccd}; \omega_1) O(x_o),$$

(4)

where $I_a = \left< \int d\omega E_a(\omega) \right>^2$ with $a = 1, 2$ being the product of the average intensities of the detected light and the calculated light, respectively. The function $W(x_{ccd}, x_{pmt})$ is the spatial Fourier transform of

$$\langle V(q_{pm}^*) V(q_{cd}) \rangle.$$ 

The transfer functions $H$ is written in position space. $\langle T(x_0) T^*(x_0') \rangle = \lambda O(x_o) \delta \left( x_o - x_o' \right).$

Equation 5 shows that one night vision image is reconstructed via a pair of infrared laser and visible laser. According to the color formation mechanism of correlated imaging [16,21], this reconstructed night vision image show the color of visible light rather than grayscale image produced by conventional night vision imaging technology. Correspondingly, the other visible laser and infrared laser can also produce a monochromatic night vision image. A color night vision image can be obtained by processing these two monochromatic night vision images. In this process, the indispensable pseudo-color image processing in the conventional color night vision technology is not used in this method.

### III. Experiment

The experimental setup is illustrated in Figure 1. Two near-infrared lasers with $\lambda_1 = 785nm$, $\lambda_2 = 830nm$. 

![Image](image-url)
(Changchun New Industries Optoelectronics Technology Co., Ltd. MLL-III-785, MDL-III-830) are coupled together to form a mixed beam by DM1 (Thorlabs, DMLP805). Then, this mixed beam is filtered by two filters (Thorlabs FL05780-10, FL830-10) mounted on a filter wheel (Daheng Xinjiyuan Technology Co., Ltd. GCM-14). Similarly, two visible lasers with $\lambda_3 = 532\text{nm}$ and $\lambda_4 = 635\text{nm}$ (New Industries MLL-III-532, MDL-III-635) are coupled together to form a mixed beam by DM2 (Thorlabs, DMLP605). The output beam is filtered by two filters (Huaxusheng NBP535, Thorlabs FL635-10) mounted on a filter wheel (Daheng GCM-14). In this experiment, only one wavelength visible laser and one wavelength infrared laser are illuminate on the surface of SLM at each time. In this scheme, $\lambda_1 = 785\text{nm}$ and $\lambda_3 = 532\text{nm}$ as a pair of beams, while $\lambda_2 = 830\text{nm}$ and $\lambda_4 = 635\text{nm}$ as a pair of beams participate in imaging. In the following, we take the infrared laser $\lambda_1 = 785\text{nm}$ and the visible laser $\lambda_3 = 532\text{nm}$ as an example to illustrate the imaging process. The infrared laser and the visible laser are coupled together by the DM3 (Huaxusheng LP690) to form a mixed beam. This mixed beam is converged on the surface of two-dimensional amplitude-only ferroelectric liquid crystal spatial light modulator (FLC-SLM, Meadowlark Optics A512-450-850), with 512×512 addressable $15\mu\text{m} \times 15\mu\text{m}$ pixels. The wavelength modulation range of SLM is 450nm-550nm. Then, the modulated light is separated into two beams by the DM4 (Huaxusheng LP690). The infrared laser beam illuminates an object and its reflected power is detected by a PMT (Hamamatsu H10721-20). However, the visible light beam does not interact with the object and is directly received by a conventional visible light CCD camera (the imaging source DFK23U618). One green night vision image is produced by cross-correlation the SLM signal and the output signal of PMT. Correspondingly, we can obtain a red night vision image with $\lambda_2 = 830\text{nm}$ and $\lambda_4 = 635\text{nm}$.

Figure 2 compares the night vision image reconstructed by the novel method, the conventional night vision image, and classical visible light image. Figure 2a1 and Figure 2a2 present the experimental result of two reconstructed monochromatic images of different wavelengths with 200000 sets of data. Figure 2a3 is the color night vision image processed by the above two monochromatic images. Figure 2b1 is a night vision image produced by conventional near infrared camera (Intevac MicroVista-NIR). Figure 2b2 is a pseudo-color night vision image generated by CbCr lookup table method [22]. Figure 2b3 is a classical visible light image output by a CCD camera (the imaging source DFK23U618). Figure 2a3 shows that color night vision image can be directly produced by our approach. Figures 2a3 and Figure 2b2 obviously show the color night vision image produced by our method does not completely restore the natural color of the object, but the color night vision image obtained by this scheme is more natural and friendly to human eyes than conventional software pseudo-color method.

**FIG. 2.** top row: two reconstructed monochromatic night vision images with different wavelengths, (a1) $\lambda_1 = 785\text{nm}$ and $\lambda_3 = 532\text{nm}$, (a2) $\lambda_2 = 830\text{nm}$ and $\lambda_4 = 635\text{nm}$, (a3) the reconstructed color night vision image. bottom row: (b1) conventional night vision image, (b2) conventional color night vision image produced by CbCr lookup table method (lookup table is shown in the upper right corner), (b3) color image with visible light source.

The image quality of this imaging method is significantly dependent on the amount of data. Figures 3(a1-a4) present the reconstructed color night vision images with different frames of data. To quantitatively analyze the quality of the reconstructed image with different number of data, peak signal to noise ratio (PSNR) and structural similarity index (SSIM) are used as our evaluation index. Figure 3b shows that the image quality is significantly improved by increasing the number of data. Certainly, the amount of data used in reconstructing image can be greatly reduced by using image processing and other methods [23-30].

**FIG. 3.** Top row: The reconstructed color night vision images with different realizations. The numbers of frames are (a1) 10000, (a2) 40000, (a3) 70000, (a4) 100000. Bottom row: The PSNR (b1) and SSIM (b2) curves of reconstructed image with different realizations.
Figure 4 compares the images obtained by visible light imaging, the novel color night vision imaging, and conventional color night vision imaging based on pseudocolor image fusion. Figures 4(a1-a3) show the three visible light images. Figures 4(b1-b3) show that the three color images produced by this night vision method. Figures 4(c1-c3) show the three color night vision images obtained by pseudocolor fusion processing with CbCr look-up method [22]. The color colorfulness index (CCI) is used to quantitatively compare the colorfulness of these three methods. It is surprising that the CCI of the new color night vision imaging is significantly better than that of conventional color night vision imaging and conventional color visible light imaging. Figure 4(A-a) and Figure 4(A-b) show an interesting phenomenon that some materials appear monochromatic in visible light, but the night vision images obtained by this method can be color. Although the night vision images produced by this method are only red, yellow and green to human eyes, as shown in Fig. 4d, these different colors can be distinguished in computer vision.

IV. SUMMARY

In summary, true color night vision imaging based on intensity correlation of light has been demonstrated in this article. Through the spatial intensity correlation of light, the object’s information detected by infrared non-visible light is expressed by visible light. A color night vision image comparable to classical optical imaging can be directly reconstructed without any pseudo-color image processing and visible light reference image. Although the reconstructed image is not completely restore the natural color of the object, the color image obtained by this method is more natural and friendly to human eyes than that obtained by other pseudo-color methods. Theoretically, this scheme can obtain night vision images with the same quality as conventional visible light imaging because the IRFPA is not used in this scheme. A surprising found is the CCI of the reconstructed night vision image is significantly better than that of conventional visible image, which seems incredible because visible light image is generally considered to have the richest colors. This new true color night vision imaging method provides a promising solution to military reconnaissance, security monitoring and automatic drive.

V. FUNDING

This project was supported by the National Natural Science Foundation of China under Grant Nos. 11704221, 11574178 and 61675115, Taishan Scholar Project of Shandong Province (China) under Grant No. tsqn201812059.

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